G E O P H Y S I C I S T S

Benoit B. Mandelbrot (1924–2010)

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Benoit B. Mandelbrot, who advanced the concept of power law scaling as a fundamental property of a broad range of natural processes and patterns in geophysics, economics, mathematics, and virtually all of science, died on 14 October 2010 in Cambridge, Mass., at the age of 85.

Mandelbrot, known as the "father of fractal geometry," was a mathematician who developed the scaling concepts of self-similarity and self-affinity and found examples in spatial, temporal, and size patterns across a broad spectrum of disciplines. He coined the term "fractal" (from the Latin noun "fractus," meaning fragmented) for shapes and patterns that exhibit self-similarity, meaning that they are statistically scale independent. Such shapes are characterized by fractional power law exponents, between the integer (Euclidean) dimensions. He is best known through his books, including *Les Objets Fractals: Forme, Hasard et Dimension*; *Fractals: Form, Chance and Dimension*; *The Fractal Geometry of Nature*; and *Multifractals and 1/f Noise: Wild Self-Affinity in Physics* [*Mandelbrot,* 1975, 1977, 1982, 1999].

Benoit Mandelbrot was born in Warsaw, Poland, of Lithuanian Jewish descent on 20 November 1924. His family immigrated to France in 1936. He graduated from École Polytechnique, Paris, in 1947. He received an M.S. in 1948 and a professional engineering degree in 1949, both in aeronautics from California Institute of Technology, Pasadena. He received a Docteur d'État ès Sciences Mathématiques from Faculté des Sciences, Paris, in 1954 and then joined the School of Mathematics at the Institute for Advanced Study in Princeton, sponsored by John von Neumann. He returned to France in 1955 and worked at the Centre National de la Recherche Scientifique. He married Aliette Kagan, with whom he had two sons, both now physicians.

In 1958 he began work as a research staff member at the IBM Thomas J. Watson Research Center, Yorktown Heights, N. Y. He became an IBM Fellow in 1974 and an IBM Fellow Emeritus in 1993. His status as a Fellow enabled him to pursue his own research interests, to have multiyear stays as a visiting faculty member at Harvard and Yale, and to travel extensively to scientific meetings in many disciplines worldwide. At Yale he was Abraham Robinson Adjunct Professor of Mathematical Sciences (1987–1999), Sterling Professor of Mathematical Sciences (1999–2004), and later Sterling Professor Emeritus of Mathematical Sciences.

He was a longtime member of AGU and was elected Fellow in 1986. He cochaired, with Leon Knopoff, the first AGU session (Union) on fractals in 1982 and was a founding member of the AGU Nonlinear Geophysics Focus Group in 1998.

He received 21 prizes, medals, and awards, including the Franklin Medal in 1986, the Wolf Prize for Physics in 1993, the Honda Prize in 1994, the Lewis Fry Richardson Medal of the European Geophysical Society in 2000, and the Japan Prize in 2003. He was inducted into the U.S. National Academy of Sciences as a Foreign Associate in 1987 and became a U.S. member in 2001. He received 18 honorary doctorates.

In the 1970s and 1980s the nonlinear paradigms of deterministic chaos, renormalization, and fractals were rapidly changing the way patterns and processes were viewed. Mandelbrot recognized that disparate and apparently unrelated observations and phenomena, often at vastly different spatial and temporal scales and disciplines, shared a common feature: power law (self-similar) scaling. Although mathematical fractal objects were formulated in the nineteenth century, they could not be visualized until the advent of modern computers, and thus real-world applications were intermittent. The empirical demonstration of the power law scaling of the length of coastlines by L. F. Richardson was pivotal, and building on this, *Mandelbrot* [1967] famously interpreted Richardson's exponents in terms of dimensions.

Numerous examples of power law scaling in the Earth sciences are provided by topography, lakes and islands, river networks and runoff, sedimentation, earthquakes, precipitation patterns, turbulence, weather and climate, petroleum deposits, fragmentation processes, fracture and fault networks, and flow and percolation through porous media.

Mandelbrot and Wallis [1968, 1969a, 1969b, 1969c] widely applied the concepts of fractional Gaussian noises (Gaussian noises subjected to a power law filter) and their running sum, fractional Brownian walks, for time series of all kinds. They also systematized the rescaled range approach developed by H. E. Hurst in his studies of the hydrology of the Nile River. This approach to long-range statistical dependency in time series has found a broad range of applications from hydrology to space physics to finance.

Building on earlier ideas (Richardson) and models (the Russian school of turbulence) of cascades, *Mandelbrot* [1974] pointed out that turbulent energy could be concentrated on a fractal set. This fractal intermittency was later generalized into multifractal intermittency. He also pointed out that turbulent cascades of energy from large to small scales can generate power law distributions of extremes, a property they have in common with P. Bak's self-organized criticality (a cellular automaton model that produces avalanche-like extreme events with fractal temporal and spatial distributions), although in a different context. Describing geophysical turbulence required a further generalization with anisotropic scaling.

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As with all paradigm shifts, sober assessments can be made only retrospectively, after the new ideas have been clarified and integrated into the body of established theory. By this measure, the fractal and multifractal scaling of geophysical patterns and processes continues to transform geophysics.

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—CHRISTOPHER C. BARTON, Wright State University, Dayton, Ohio; E-mail: chris.barton@wright.edu; SHAUN LOVEJOY, McGill University, Montreal, Quebec, Canada; DANIEL J. SCHERTZER, École des Ponts ParisTech, Université Paris-Est, Marne-la-Vallée, France; and DONALD L. TURCOTTE, University of California, Davis