

Profile of Benoit B. Mandelbrot

by Monte Davis

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"You're wasting your time," this mathematician was told by his peers, until his monstrous, bizarre fractals, with their strange dimensions, began taking over the world. As one scientist says: "We hope to explain the universe in a single formula you can wear on your T-shirt." But the task of describing the stuff of matter is not easy. For example, who can explain the rising and falling of the Nile, or the shapes of clouds and craters?

Benoit Mandelbrot can. Amid charges of heresy, the IBM mathematician and philosopher proposed a theory of fractals to explain phenomena that would not fit into the abstract purity of Euclidean geometry. This theory changed the way scientists view reality.

Introduction by Monte Davis

As a staff mathematician at IBM in 1958, Benoit B. Mandelbrot was asked to address an intractable problem of random irregularities intrinsic in signal transmission. His colleagues had an explanation for it. It's guys working with screwdrivers somewhere in the network. "

"I don't want to hear about theories now," Mandelbrot responded. "There are always guys with screwdrivers; we'll never know their schedules. Besides, how could men with screwdrivers generate that kind of systematic structure?"

Mandelbrot realized that noise was, in fact, deeply embedded in nature and impossible to drive out. Thus, he doomed many burgeoning attempts to predict, suppress, or eliminate it. The noise issue was an early example of the strange logic of *fractals* - the unruly collection of irregular geometric phenomena that only Mandelbrot seemed to comprehend at the time. However, he won his case, and was instrumental in halting a multimillion-dollar research project that would have gotten IBM nowhere. "Whether or not IBM understood the problem," he now says, "they couldn't change it, and the technology they were trying to build around it couldn't possibly work."

Noise, with all of its weird manifestations, contributed to Mandelbrot's mighty inspiration - the genesis of fractal geometry. From problem solving in electronics and economics, from long-ignored corners of geometry and probability theory, and from a passionate conviction that there is order in the most irregular phenomena, Mandelbrot created a new world of thought. Twenty-five years ago, fractals - not yet named by him - were his private obsession. Today, they are standard tools in some branches of science, exciting new approaches in many more. As the "father of fractals," Mandelbrot has established fractals' scale and direction and proved their relevance to the real world when others had dismissed them as uselessly abstract or - worse - as pathological monstrosities.

Born in Warsaw in 1924, Mandelbrot moved with his family to France in 1936. His early mathematical education was irregular, much of it based on outdated classics of the nineteenth and early twentieth century. Even at a young age, his methods were as unusual as his preparation. In the rigorous entrance examination of *École Polytechnique* in Paris, he repeatedly solved problems by geometric approaches instead of the prescribed analysis.

At Caltech, where he studied aeronautics, Mandelbrot encountered the daunting complexity of turbulence, the wildly tangled fluid motions that, above a critical speed, replace streamlined flow. Today, fractals are central to two of the three main approaches to turbulence, permitting precise descriptions of shapes that seemed utterly chaotic a few years ago.

Why was it necessary to conceive and develop a new geometry of nature? Until recently, all the curves and surfaces presented to school children and used by scientists in their theories of nature were smooth. Such shapes can bend, but they must bend gently. If such a smooth curve is sufficiently magnified, it looks more and more like a straight line. For example, the spherical surface of the earth looks almost flat on some scales, and the

illusion of flatness is good enough to cause some controversy even today. In other words, the traditional smooth curves all look alike from some perspectives. And the features that make them differ are apparent only on certain scales of measurement.

This is too bad if you want to understand nature, because many of her faces possess structures on a very wide range of scales. Consider the bark of a tree. On the usual human scale, it looks rough. If it is magnified, it still looks rough. The larger scale crinkles are themselves crinkled on a smaller scale, and there is a whole hierarchy of subcrinkles and sub-subcrinkles, right down to something close to the molecular level.

Or consider a stretch of coastline. What appears on a map to be a smooth, curving bay does not look smooth close up. Even at high magnification a coastline's shape is crinkly and irregular. Mountain landscapes, the craters on the moon, the fine structure of Saturn's rings, the folded surface of the lung: all possess structure on a great many scales. It follows that the traditional smooth curves and surfaces of science proved inadequate as models of these features of nature. A different geometry of nature was needed, but none was available.

At about the turn of the century, a few mathematicians had come to study such "infinitely crinkled" curves. For example, the "snowflake" curve due to Helge von Koch consists in a triangle with smaller triangles stuck on its sides, and yet smaller triangles stuck to these new sides until every small piece of the curve is infinitely "prickly." What motivated these mathematicians? By no means had they set out to study the bark of trees, the coastlines of islands, or the lining of the lung. They thought they were fleeing from nature, and that the sole function of their contraptions was to prove the creative power of the most abstract mathematics. As a result, these curves were called pathological, both by their creators and by everyone else.

It is only since 1975 or so that it has been widely recognized that, on the contrary, suitable curves of these types should be considered natural and can be used as models of natural processes. This recognition is largely due to the work of Mandelbrot, who coined the term *fractal* to describe such curves, created new fractals, and energetically pursued them at a time when it was not fashionable to do so.

A fractal curve can be viewed as an intermediary between a traditional curve and a traditional surface. A curve is one dimensional; a surface is two dimensional. The fractal dimension of a fractal curve in the plane is a number that lies between 1 and 2 - a typical coastline can be 1.213 dimensional. Whoever heard of a seacoast having a fractional dimension? But it has. Fractals arise in many problems: the distribution of galaxies, the patterns of errors in transmission through telephone lines, the behavior of liquid crystals, and the scattering of radar beams by mountains. The massive, single-minded achievement of Mandelbrot is to have exhibited an entire new regime of mathematical modeling applicable to a wide range of natural phenomena.

Since 1974, Mandelbrot has been an IBM Fellow, an official recognition of his influence on ideas that at one time seemed wild tangents. He does not have the proverbial corner office, though. In the smoothly curving glass of the Thomas J. Watson Research Center at Yorktown Heights, New York, there aren't any. That doesn't matter to Mandelbrot, because he knows he's at the center of a rapidly branching web of science and mathematics. Branching web is an inadequate description for a structure only a fractal - or Mandelbrot himself, in his gleefully kaleidoscopic style - could describe. So writer Monte Davis asked him to look over the shape of his career for *Omni*, and to describe the importance of being tessellated.

Omni: Your first fractal simulations were of graphs. Why was it important that they look so realistic?

BBM: When scientists need to convince others, they use words and formulas. So do I, but I also use pictures. This used to be sternly discouraged. In fact, I first became aware of the power of the eye very late, around 1968, when I was working on the "Joseph effect." This is the name I gave, in jest, to the persistent fluctuations in the levels of the Nile, like the "seven fat years and seven lean years" described in the Bible. The foremost Nilologist of all time, an Englishman named Harold Edwin Hurst, had spent the bulk of his career in Cairo analyzing the records of the Nile's high- and low-water levels and had made important, but highly mystifying observations about the river. A friend described these observations to me and challenged me to do something about them. On the foundation of Hurst's data, I developed a statistical model that includes the basic feature of the Nile and of other rivers. I later went on a kind of pilgrimage to meet Hurst, nearly one hundred years old at that time.

The main feature of the Joseph effect is that the Nile's successive yearly discharges are extraordinarily persistent, but people had long since stopped trying to predict a river's level next year. A statistical approach was needed, but none of the textbook models of hydrology and statistics remotely fit Hurst's observations. My model did fit the basic fact but at the cost of breaking certain accepted mathematical assumptions. The substitutes I offered looked abstract, were hard to understand, and thus, hard to accept.

So I teamed up with a hydrologist to develop my model and make it more acceptable. One thing we did was to plot the actual fluctuations, using not only the original data of Hurst, but also a collection of deliberate forgeries - records of nonexistent rivers constructed to obey my model. Everyone who tried to sort out our collection of graphs had to agree that my model was extraordinarily effective in mimicking nature's erratic fluctuations. At long last, the model I'd constructed was taken seriously because it looked like reality.

Omni: Did that mean you found there were longer droughts or more discharges than expected, for example?

BBM: Compared with earlier models, mine implied much longer droughts or floods.

Zigzagging fluctuations make dams fail to perform their assigned task, because too often they are either full or empty. In Egypt, the lengths of droughts are not limited to short time-spans (like the reign of a pharaoh or the term of office of his chief minister), but often extend to the total length of a dynasty - millennium-length fluctuations. Records of the Nile's discharges include no flags marking the beginning or the end of a drought. Each record seems to look like "completely random" noise superimposed on a background that is also noisy. The background seems cyclic, but you can't extrapolate from its cycles for predictive purposes. They are not periodic. This is why dams for long-term water storage are so hard to design.

Omni: There was no long-term average that all the Nile data converged upon?

BBM: No. The records look like a hierarchy of random noise on random noise. We showed our collection of graphs to a small group of hydrologists. We mixed up unlabeled graphs of all kinds: actual records of the Nile and other rivers, graphs drawn either from my model, from modifications of my model, graphs drawn from the models that hydrologists had tried previously. We challenged a particularly famous hydrologist to distinguish the real data from the fake ones. He immediately dismissed the graphs made from the old models, saying, "Rivers just do not act like that." But he failed to distinguish the real graphs from those drawn by my models, even after we read the labels on the back and told him which were the real ones.

That was a revelation. Before that, I could not persuade practical people to consider the "crazy" mathematical idea behind my model. But after the expert acknowledged that my model showed river-like behavior, I realized that the power of the eye to discriminate shapes was much greater than anticipated. This was extraordinarily pleasurable, because my way of thinking is almost completely visual. I can hardly count, but recognize geometric forms by their shape, not by mathematical formulas.

Omni: Didn't this research lead into economics, where experts like to break down stock or commodities data into a trend, a few cycles and noise?

BBM: To the contrary, that's another chapter of my checkered career. Before the Nile I had worked out a model of financial prices, stock-market and commodities such as cotton. Later on, impressed by the power of persuasion of my hydrological fakes, some people at Bell Labs performed a similar double-blind test on my stock-market fakes. They used my formula to generate some artificial price charts. Then they generated further charts after they had deformed my model by deliberately changing an important number. Finally, someone showed the resulting mixed batch to an eminent stockbroker, and challenged him to prove he knew his business and could identify the real thing among the imitations. He had no hesitancy in picking the charts drawn by my model. He rejected all the others as being either "too smooth or too unsmooth." "The real thing is in between," he said. "Its special nature is very subtle, but I can recognize real charts when I see them."

I had identified the particular feature of reality that makes stock-market charts look the way they look. My model could fake charts of either high or low volatility. The stockbroker had a clear visual impression of what charts should look like, because stockbrokers spend their lives looking at these things. Anyone who could fool him had to be doing something right.

Omni: How did you move to modeling physical shapes?

BBM: Soon after my work on the Nile and on cotton, I wrote a paper on the geometric shape of coastlines. I challenged myself to account for some obscure observations of a visionary English scientist, Lewis Fry Richardson. A real coastline is, of course, never circular; most are very wiggly. But not every wiggly curve looks like a coastline. What is the special property that makes some wiggly curves look like coastlines and others not? Richardson had pointed out that if you try to measure a coastline length with increasing precision, you must take into account increasingly small bays and promontories. As a result, the measured length is bound to increase. Again, I was successful in identifying the proper mathematical trick that allows a curve not to have a true absolute length, only relative lengths that depend on the method of measurement! Another trick allowed the degree of wiggleness of a curve to be measured objectively, just the way that temperature measures the degree of heat, by one number. This number later came to be called *fractal dimension*.

Under the title, “*How Long is the Coast of Britain?*” my paper came out in *Science*. It was okay but did not satisfy me. It was too abstract, too much in the style of meter readings. I wanted to obtain a gut feeling for the shape of coastlines and decided to find ways of performing forgeries. I thought up a suitable equation, and in 1973 persuaded colleagues to rig up a very clumsy plotter to produce artificial coastlines. They were much harder to draw than graphs of the Nile. Someone had to sit up all night with the plotters. But when the first coastline finally came out, we were all amazed. It looked just like New Zealand! Here was an elongated island, there a squarish one, and, off to one side, two specks resembling Bounty Island. The next time, we got different islands.

Smaller parameters in the same equation made the shapes become smoother and rounder. First they formed blobs like Taiwan, and eventually they became so regular that everyone would say, “No real island can be that round.” Increased parameters made the coastlines become increasingly irregular. It soon broke up into complicated archipelagoes, like the Aegean, then like science-fiction Aegean with more tiny islets. But in the right range of the parameters, we got shapes typical of real islands and continents.

Seeing them had an electrifying effect on everyone. The parameter in this equation is also called the fractal dimension, and at last, people understood what I meant by this term. The idea had been around for a while but had remained abstract, hence elusive. Now, after seeing the coastline pictures, everyone agreed with me that fractals were part of the stuff of nature.

Omni: What was the role of computer graphics in your investigation of fractals?

BBM: The theory of fractals had started in my mind before I knew it was to become a theory, and well before I thought of computer graphics. However, without graphics, the theory would have moved very slowly or not at all. But it happened in 1974 that my friends located a computer graphics device that we could train to draw artificial mountains. Again, the device was very cumbersome, but when the shapes came out, what a revelation! The pictures were poor: black and white and drawn on coarse grids. Shadowing was not feasible. Even so, there was an overwhelming feeling that what we had drawn was right. Even though the pictures looked like old-fashioned worn photographs, they looked like mountains. Having seen them, no one no one could say that I was barking up the wrong tree. Their eyes convinced them. Since then, of course, the equipment improved and the pictures by IBM's Richard Voss are stunning. It seems that we win all the computer graphics contests.

Before, people would run a mile from my papers, but they could not run from my pictures. In the beginning, I used the graphics purely for this reason - to illustrate my ideas and to force people to accept them. But I soon realized that this method enabled me to go further and integrate into a single theory a collection of things that otherwise would have seemed unrelated. Now, very complex geometric shapes could be compared with one another and with reality. The equations behind the shapes were abstract, but the shapes themselves looked alive.

Omni: What is the difference between the meter-reading kind of science and the fractal kind?

BBM: By “meter-reading,” you must refer to the reduction of shapes to numbers and to measurements. This is a universal trick in science and a very successful one in physics. This trick, however, has been enormously impoverishing. Scientists simplify. They are not interested in the smell or color of gas in a vessel, only its temperature and pressure.” In physics and a few other mature and successful branches of science, this approach has been extraordinarily successful. But the phenomena left aside, to which I attached myself, first by accident,

and then with enthusiasm - are those for which that abstraction has not worked well. If water resources had been as simple to understand as gas, water management would have been well in hand well before 1965.

Science had ignored a large residuum of phenomena in which many factors are mixed together and can't easily be separated. These involve some of the most interesting and natural questions. Instead of the temperature of a gas or collisions between atoms, children wonder about the shapes of trees, clouds, and lightning. These questions are among the hardest which is why Physics just left them aside. But I tackled them. The delight is that fractal geometry has answered many such questions in a single swoop over many years. It involves extracting something interesting about coastlines, clouds, and lunar craters.

Omni: But do these ideas *explain shapes*, or do they just let you create similar shapes? If your model of the Nile does not include rainfall, silt, or drainage basins, are you not just doing what scientists call curve-fitting - tinkering with the equation until the line runs through the data points?

BBM: You are needling me. You know very well that the term *curve-fitting* has many bad connotations. I too have nothing good to say about those who would curve-fit each phenomenon separately, only to be left with a grab bag of unrelated and conflicting equations. On the other hand, there is a view, which is very extreme, that the whole of science is not a search for understanding, but for one big equation that has relatively few parameters, and can be curve-fitted to account in one swoop for many seemingly unrelated phenomena. I am not defending this as being a completely satisfactory description of science, but there is some truth to the notion that science is a search for a small number of central ideas that describe how various parts of nature fit together. Fractal geometry faithfully follows this approach. It centers on several very powerful principles that tell us how the world is put together.

When you look at the traditional approach, you see that physicists have been careful to seek out problems they could solve by reducing them to accepted principles. But many other scientists allow themselves to undertake heroic, if not hopeless tasks. Before they can say what a cloud's shape is, meteorologists want to know how varying the humidity affects the shape of clouds. In fact, they often cease to think of a cloud as a shape, only as one or a few numbers extracted from observations. Physics should have taught us all that in the search for an explanation it is awfully convenient to start with a description.

Omni: What about turbulence, which is notorious for being difficult to measure?

BBM: Turbulence was perhaps the greatest thorn in the flesh of certain areas of nineteenth-century physics. Fluid mechanics found it very irritating that turbulent motions should be so incomprehensible, whereas the other motions were easily understood. And it went on being ill-understood. However, by using a certain kind of scaling and fractal argument from other contexts, I put forward a bold conjecture about the nature of turbulence. Originally it was quite abstract, but it gradually became the most concrete thing imaginable.

Omni: What was your idea?

BBM: The wind does not blow regularly but comes in bursts, each one divisible into finer bursts. In due time, this led me to think that turbulent activity might be like the wind: not spread all over space, but concentrated upon a fractal shape of a complicated but well-specified kind. The reason people had not thought of that possibility is that they didn't know that fractals existed. Let me take that back; some people knew vaguely, but were convinced that these were abstract shapes no one could encounter in the hard world outside.

Omni: Would fractals be useful in studying pollution, where traditional methods give an average pollution level, or assign a probable level of concentration in an area?

BBM: For something distributed by turbulence in wind or water, the average is totally meaningless. Suppose that pollution is very low on the average but concentrated in a very patchy fashion. If it hits you, it may well hurt or kill you. The common measures of dispersion around the average tend to view those patches as special cases that confuse the measurements. One censors the data. Instead, fractal geometry provides a natural measure of lumpiness. Measures of the fractal dimension are repeatable, whereas ad hoc measures of lumpiness tend to vary badly from sample to sample. If you know the lumpiness of pollution, you can begin to assess effects of policy. Uniform dilution is the solution to pollution.

Omni: Still, a fractal model seems abstract. Do scientists resist it?

BBM: Many did and still do. In long series of cotton prices, my fractal model was able to match the important upward and downward jumps in the historical record. Economists, however, kept telling me that to follow just one price series was not ambitious enough. They were seeking ways to influence prices, to profit by predicting them, and to explain them through theories of demand and consumption. It was an uphill fight to convince them that my model did not compete with the giant econometric models running to hundreds of series. The giant models tried to do everything at the same time and hoped for results a bit better than those achieved by tossing a coin.

Omni: Was the resistance caused by just plain stubbornness?

BBM: No. I never felt the victim of pigheadedness or stupidity. The critics recognized that my methods implied a departure, and it is right that departures should be sternly criticized. One economist proclaimed that if I were correct, "it would indeed create a very difficult situation in economic statistics."

Omni: But was it an article of faith that someday explanatory mechanistic theory would expand enough to encompass complicated, irregular phenomena?

BBM: Yes, but in many cases it has not expanded. *I love theory*. But what do you do while a theory is slow in developing? I was proposing a qualitatively different kind of science in which the description of the phenomenon is an important question in itself. My persistence has been rewarded. As soon as a good description became available, many fields started moving on to excellent theories, sometimes due to my hand, more often to the hand of specialists I had drafted into my camp.

Omni: Your model for the distribution of galaxies is changing our ideas about the universe. Using fractal geometry, astrophysicists have shown that the larger the volume of space, the smaller the density of matter in it, and that stars cluster into galaxies, clusters of galaxies form megagalaxies, *ad infinitum*. How did you get started on this model?

BBM: Again, it began with a challenge brought to me by a friend. I developed an early model of the galaxies to account for some bizarre observations about the nonuniformity of the universe. For a time, there were no suitable mathematical tool to represent the clustering of galaxies, and the more one knew about space, the harder it became to formulate such a model. My equations, which take just a few lines to write, provide amazingly realistic models of the sky. They are becoming widely accepted.

Omni: They look right to the eye?

BBM: The eye is attuned to texture, but there is no ready-made theory of texture. In all these cases, the eye was much more effective than meter readings, which were trying to tell us that two things were identical, when in fact they were different.

Something very similar happened with concert-hall acoustics. There was the famous debacle of the Philharmonic Hall, the original design of Avery Fisher Hall at Lincoln Center, in New York City. That design matched a certain measurement of the time of resonance to the value found in the best older halls. But everyone's ears said that, in fact, the acoustics of Philharmonic Hall were dreadful. A measurement that was supposed to provide a good summary of a concert hall's acoustic properties had turned out to focus on something that differs from what the ears care about. Our senses and brains have a feeling for shape that's extraordinarily finely honed by evolution and experience.

Omni: As an outsider coming into so many specialized fields, was it hard to find a sympathetic response?

BBM: Yes. It's astonishing how much science is reduced to a sport. The value of a scientific work is judged by the amount of competition in a chosen "event." You're not a real athlete until you've won the hundred-yard dash, not the one hundred and forty-three. I did not. The reason I chose problems in which competition was nonexistent was not that I'm afraid of competition. I picked mountains and coastlines because I found the topics exciting. Lacking specialists in the study of these problems left a whole field to myself. Having no competition was an asset. Now everybody is watching over my shoulder, and I get referees who go into great detail because they're competent to do so.

Omni: Do you approve of the referee system for reviewing technical papers?

BBM: No one loves to referee, or to be refereed, but in most established fields the referee system works. Anyhow, it is better than allowing one all-powerful editor or foundation executive to decide on a whim whether to accept or reject a paper or a proposal. But for years I had an impossible time with every established form of peer review. To state the problem bluntly, since I was all by myself, I had no peers. I had the personality to be able to work alone but did not enjoy having to argue with referees who did not even pretend to be my peers. They had to be broad-minded to agree to read my papers in the first place but did not really care, and their decisions were not to be trusted.

Omni: I have heard you use the term *technical mathematician*. What do you mean?

BBM: A professional mathematician can be compared to a professional chess player. To be a real chess player, you must have studied quite deeply all the great games of the last century or more. You aren't in the big league if you make mistakes that somebody made a hundred years ago and everybody else knows how to avoid. As a child I was a chess champion. I retired at age eleven, because I went from a place where everybody played chess and there was a championship for kids, to a place where nobody played chess. In retrospect, I was lucky, because I played intuitive chess. I had a feeling for spatial relationships of pieces and so on. I had stamina. I was a fighter. But I hadn't read everything about all those old games.

To do well in mathematics, in addition to having talent and skills, you must be able to instantly recall the way various technical problems have been solved. People who do this supremely well become known as great technicians. I am not at all a technician. It is not a skill one can maintain on a part-time basis. However, I know many admirable problem solvers, and I often seek them out to offer them my half-baked ideas on difficult problems.

Omni: Would you describe yourself, then, as an applied mathematician?

BBM: No. I have never indulged in the activity that ordinarily goes under this name. The caricature of the applied mathematician is that of a consultant who takes mathematical techniques he has not developed and applies them on request to problems he has not posed.

So what should I be called? Some people do call me an experimental philosopher, because I am a philosopher at heart. There is no question about this but in one sense, I'm a "mathematician-without-hyphen," neither a "pure-mathematician" nor "applied-mathematician," nor a "mathematical-physicist." And I am one of the few people plying this trade today. For Who's Who, I put down MATHEMATICIAN AND SCIENTIST or even MATHEMATICIAN, SCIENTIST, SCHOLAR, AND ARTIST, which upsets editors, who prefer one word. I was once a visiting professor of physiology at a medical school (unpaid, I hasten to add, and I saw no patients). After my host and I had worked together, he wanted to make a gesture of acknowledgement. He said, "It is obvious that your life's ambition is to retire as a professor of divinity after having been a professor of aesthetics; so to help you on your way, I'll make you a professor of physiology."

Omni: Where does aesthetics come in?

BBM: Quite unexpectedly. Once fractal shapes were drawn correctly, they were viewed by many as being beautiful. Some of them were old, even a hundred years old. Yet they were never looked at carefully before, perhaps because they had been introduced as monstrous, counterintuitive, bizarre, and impossible. Faced with these shapes, mathematicians and scientists covered their eyes. They were prepared to visit the freak show on rare occasion, but not to live on a daily basis with monsters. The old pictures were very few, astonishingly inaccurate,

poorly executed, and haphazardly chosen. When computer graphics made it possible for me to draw them correctly, a striking harmony was suddenly revealed.

Omni: Harmony in what sense?

BBM: Many years before I formulated fractal geometry, I had heard the famous mathematician and physicist Hermann Weyl lecture at Princeton. These lectures eventually gave rise to his marvelous book *Symmetry*. Weyl emphasized that the ancient pre-Classical Greeks held an idea of symmetry far richer than today's narrow notion of mirror images. For them, symmetry expressed a kind of harmony between the parts and the whole.

Many of our monstrous maids whose married name is fractal are self-similar; that is, they are structures in which each part is the same as the whole, only smaller. Hence, the old Greek notion calls them symmetrical to the most extreme degree. This may be why it happens so often that fractal pictures are perceived as being extremely strange, yet wholly familiar. They are much stranger than deliberate special effects in science fiction, because science fiction is in most cases remarkably humanoid.

Having done time with self-similar fractals, I moved on to fractal dragons, in which the parts are obtained from the whole by a certain mathematical deformation. These dragons are generally perceived as even more beautiful - still very strange, yet somehow familiar.

Omni: Can fractal art be minimalist?

BBM: Yes, to an unusual degree. Given a piece of the "conventional" minimal art, try to describe it precisely enough to allow anyone to reproduce it exactly. To do so would require an extremely long description in words. The equation that generates a fractal dragon, on the other hand, is one line long, and if you give it to someone with the right intellectual and computing equipment, he will be able to reproduce it exactly. So this art is the most minimal of all. It is astonishing that something that is logically so minimal can contain such a wealth of characteristics. The interesting thing isn't that flamboyant, baroque behavior can be generalized from complicated formulas, but that attractive shapes are "easily" obtained from very simple formulas.

Compared with other work shown in exhibits of computer art, I find that our fractal mountains are not only the best art intrinsically, but also the most novel, because we deliberately put in the least possible amount of willful intervention. We do not improve upon our simple formulas by imposing our mediocre skills as landscape painters, and the art presently achieved in this fashion is much purer. On the other hand, I'm sure that once artists become familiar with the new fractal medium, some are going to do great things with it. Pure geometry can look beautiful by accepted standards of beauty.

Omni: Most people would think of scientific art as stark and austere, rather than flamboyant and baroque.

BBM: When people say that modern buildings are soulless and not on a human scale, what do they mean? I've never heard anyone say that the Paris Opera is not on a human scale, yet it's an enormous building. Why doesn't it elicit that feeling? Because the architect Charles Garnier incorporated features of every scale. Wherever you stand - at the end of the Avenue de l'Opera or right smack in front of the building - there is something you can see that is at your scale. It has symmetry in the old Greek sense: harmony between the parts and the whole. But buildings designed by Mies van der Rohe are aggressively nonsymmetrical, even if they are reduced to a one-room box. I started making these remarks around 1970; they were viewed as bold, but today they have become tame. Today, we are surrounded by Bauhaus renegades, who leave no long line unbroken and no large blank surface anywhere.

In old masters' paintings or in Beaux-arts architecture in its heyday, I see a deliberate and successful imitation of nature's elements of scale. Fractal designs recall the beaux arts style, and even baroque. But they avoid the rococo manner of filling every available space with decoration, a kind of aesthetic overkill. The surface of an old master's landscape is filled mostly by the sky, never filled with detail. The surface of an old master's portrait is mostly given to drapes or perhaps a robe. This balance between what is filled in and what is left blank provokes a feeling of plenitude. Fractal geometry has shown that a similar feeling can be evoked by shapes drawn according to a simple formula. This is a genuine aesthetic discovery. Similarly, Scandinavian furniture uses the rosewood

grain as part of the design. The same furniture made with a bland wood looks dreary. It doesn't have the detail to balance it.

Omni: Can you make a fractal equivalent of the “Auditory Penrose Staircase,” the illusion of a steadily descending tone, by zooming in on a fractal as it branches?

BBM: I find M. C. Escher's drawing of the “Penrose Staircase” monotonous, the same thing going around and around endlessly. But zooming in endlessly on a fractal landscape is something else. You think you're going to crash, but you don't. You get more detail.

Omni: Why is it that fractal mathematics can be applied to living forms to create artificial trees and animals?

BBM: The complexity of many fractal shapes suggest snails, jellyfish, or other forms of life. This cannot be accidental. It raises a basic question of biology: How much genetic coding is needed to obtain the diversity and richness of shape we observe in living beings? If you compare all the tiny and irrelevant differences in two species of lobster, you ask yourself why nature would have evolved such an exuberance of form without obvious use? I mentioned that fractal shapes of great complexity can be obtained merely by repeating a simple geometric transformation, and small changes in the parameters of that transformation provoke global changes. This suggests that a small amount of genetic information can give rise to complex shapes, and that small genetic changes can lead to a substantial change in shape.

Omni: Why do you claim that parts of the human body are fractal?

BBM: Consider the mammalian lung, which is an extremely complicated structure of tubes, air sacs, and blood vessels. It would take an enormous amount of information to specify its development in detail. But the significant instructions are very short. During the development of the fetus, a simple budding process is repeated over and over, twenty-three times. The packing of soft tissue within a confined volume creates the final structure. If the diameters of the bronchi were decreasing any faster as one moves away from the nose, the lung would be loosely packed - a bad design. If the diameters of the bronchi were decreasing more slowly, the growing buds would be too closely packed and would interfere with one another.

Omni: Did you suspect from the beginning that all these applications of fractals would form a unified whole?

BBM: It was a very gradual development, with many intermediate stages. Early on, what you call a unified whole did not cover much territory, but I have always been on the lookout for structures of broad general validity. Nevertheless, the actual search for these structures involved a gamble - a gamble on which I staked everything. Friends kept warning me against involving myself in so many disparate fields, but I felt that getting into a large enough number of different fields would end by making my life easier. I was fortunate to win the support of Ralph Gomory, who remained my boss for many years.

The logic of what I was doing did not really become apparent until 1973. I had been invited to summarize my work in a lecture at the Collège de France. As I prepared the lecture, I began to see a very effective way to order my material. After I spoke, there was an hour-long question-and-answer session, in which people in a dozen different disciplines asked questions. I had an answer in every case. This led to an unpublished article, which grew into my 1975 book.

That book needed a title. Clearly, it could not be called *Applications of the So-called Mathematical Monsters to a Miscellany of Practical Phenomena*. That is when I coined the word *fractal*, the title becoming *Les objets fractals: forme, hasard et dimension*.

There is a Latin saying: “To have a name is to be.” Now the word is in several dictionaries, and people flatter me by misspelling it, indicating that it has become a part of their thinking, not a new word they must be careful about. I've gone from wasting time on something nobody could see the point of, to belaboring the obvious!

My Ph.D. thesis was completed in 1952. The first decade was one of groping. The next ten years were spent in formulating a broad enterprise with no distinction between the social and physical sciences. Later years have been a period of consolidation.

Omni: Do you no longer consider yourself to be on the eccentric fringe?

BBM: The element of solitude is gone. The element of noncompetition is gone. The element of amazement is gone, although the pleasure remains. What will the next years bring? I don't know; I've only scratched the surface of everything. Ultimately, it's a matter of how much unity can be created by this one idea. The true test is the test of time.

'I identified the particular feature of reality that makes the stockmarket charts look the way they do. By changing a number, my model could fake charts of high or low volatility.'

'If average pollution is very low but concentrated in a patchy fashion and it hits you, it kills you. However, if something has a fairly high toxicity but a low lumpiness, it may be bearable.'

'It's astonishing how much science is reduced to a sport. The value of a scientist's work is judged by the amount of competition he's encountering, the number of people in his event.'