Dimensions of consciousness

Peter T. Walling, MD, FRCA, and Kenneth N. Hicks, CETsr, CBET, GROL

> The way in which knowledge progresses, and especially our scientific knowledge, is by unjustified (and unjustifiable) anticipations, by guesses, by tentative solutions to our problems, by *conjectures*. These conjectures are controlled by criticism; that is, by attempted *refutations*, which include severely critical tests. —Karl Popper (1)

The nature and location of consciousness in humans remain a mystery. The presence or absence of conscious awareness throughout the remainder of the animal world is still disputed. Sitting by a pond with rod and reel, anglers may wonder what is going on in the heads of the fishes, frogs, dragonflies, turtles, and other critters that have inhabited the planet virtually unchanged many millions of years before the appearance of *Homo sapiens*. In Izaak Walton's classic *The Compleat Angler*, first published in 1653, the pike, for example, is described as "the tyrant of the rivers, or the fresh-water wolf, by reason of his bold, greedy, devouring disposition; which is so keen" (2). An apt description, but is the pike aware of any of these attributes? As John Donne noted in a 1628 sermon, "The beast does but know, but the man knows that he knows" (3). Consciousness is indeed strange, straddling the objective and the subjective with no dimension to call its own. The shape of our thoughts does not quite resemble the configuration of the neurons responsible for them, so where are they?

Two difficult problems remain to be solved before consciousness can be explained. First there is the "phenomenal problem." The redness of the rose I see exists in a private domain. I cannot communicate to anyone else what redness is like. Redness and other qualia are subjective phenomena which cannot be described to outsiders (4). Second, there is the "binding problem" (5). How can multiple memories and afferent impulses combine simultaneously to produce a moment of lucid conscious awareness when the data are scattered throughout the brain and there appears to be no central station to coordinate the information? Clues that could lead to a solution for this puzzle may be all around us. Many animal species exist today whose structurally similar ancestors have been memorialized as fossils. If changes in their central nervous systems have been as slight as other bodily alterations, the surviving progeny could serve as time capsules for paleoneurologists. Today's fauna could represent examples of living prototypes of central nervous system development. Perhaps a pattern could be seen within these survivors that might help us to unravel the problem of human consciousness.

In a previous article, we hypothesized that consciousness might be related to phase space, a mathematical construct where the geometry of dynamic systems takes place (6). We conjectured that complex neural function developed within a framework of mathematics just as bones developed around the demands of gravity, that objects in physical space are translated into perceptual space within phase space.

A brief overview of dimensions is presented because that understanding leads naturally to the dynamics necessary to comprehend some aspects of the conscious state model.

THE CONVENTIONS OF DIMENSIONS

A point has no dimensions; a line has 1; a plane, 2; and a solid object, 3. Since Einstein's work in the last century, the concept of 4-dimensional space-time has gained wide acceptance. Time has been promoted to the position of an honorary fourth dimension, so we live our everyday lives in 3 dimensions plus 1, space-time. It has been proposed that light is a vibration in the fifth dimension. When the clumsy-looking theories of subatomic particles are expressed in higher dimensions, they dramatically take on a startling symmetry (7). Recent studies of superstring theory relating to the smallest subatomic particles suggest the possibility of as many as 26 dimensions. Although our brains can imagine objects only in 3 spatial dimensions, some concept of higher dimensions is occasionally possible. For example, a hypercube of 4 spatial dimensions may be appreciated by examining its 3-dimensional shadow (7).

Studies in nature reveal a different picture. Shapes rarely come packaged in a neat Euclidean way. The outlines of mountains, clouds, and coastlines, for example, are highly irregular. Plants and animals often display symmetry, but their shapes are difficult to quantify. In 1904, an advance was made when Koch described his now-famous snowflake *(Figure 1)*. Adding triangles to the sides of triangles ad infinitum produces a mathematical curiosity. The resulting line is infinitely long, never crosses itself, yet remains contained in a finite space. The shape is more than a line but less than a plane; it lies between 1 and 2 dimensions. When the length of the side of each equilateral triangle is one third the size of the previous one, the dimension of the resulting shape is 1.26.

From the Department of Anesthesiology and Pain Management, Baylor University Medical Center, Dallas, Texas.

Corresponding author: Peter T. Walling, MD, FRCA, Department of Anesthesiology and Pain Management, Baylor University Medical Center, 3500 Gaston Avenue, Dallas, Texas 75246.

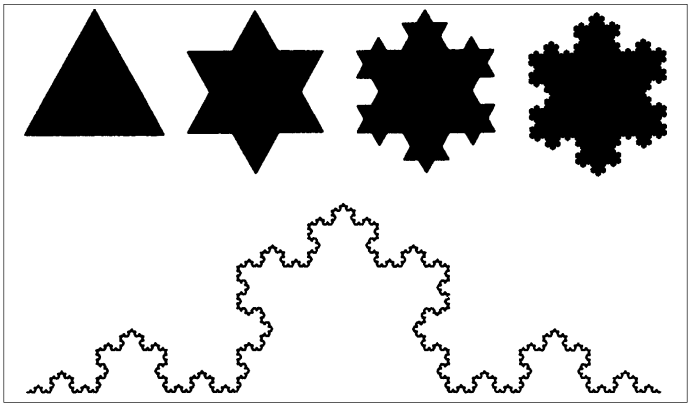

Figure 1. The Koch snowflake. To the sides of an equilateral triangle, add replicas with sides one third the length. An infinitely long line crowds into a finite space, never crossing itself. The fractal dimension is 1.26. The exploded view shows the similarity to a coastline. Reprinted from reference 9 (p. 99) with permission of The William Morris Agency.

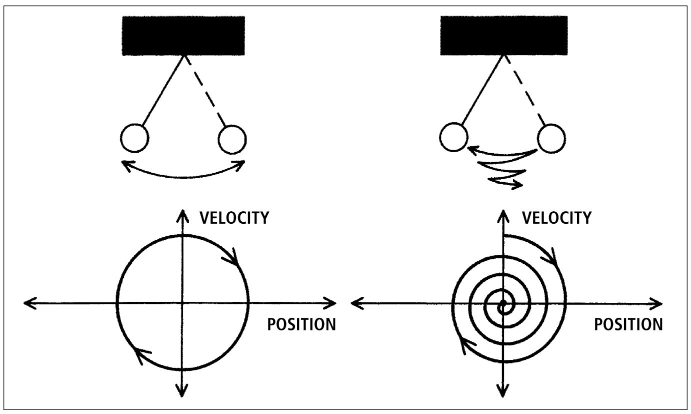

Figure 2. The velocity and position of a pendulum plotted to produce a circle in phase space. At any instant in time, the velocity and position collapse to a single point somewhere on the circle. The continuously scribed circle is a periodic attractor. The pendulum on the right has lost power. The phase space portrait spirals towards a point attractor. Reprinted from Crutchfield JP, Farmer JD, Packard NH, Shaw RS. Chaos. *Sci Am* 1986;254(12):46–48 with permission of Andrew Christie.

In the 1970s, the word *fractal* was coined to describe fractions of dimensions. Like the Koch snowflake, fractals in nature maintain their irregular but distinctive shapes over different scales of magnification, a quality known as nesting. The mathematician Benoit Mandelbrot had been particularly fascinated by the shape of the cauliflower. Cutting the vegetable into smaller and smaller pieces, the different-sized parts demonstrated self-similarity, which was distinctive for that species. The fractal dimension of the outline of a typical cloud appears to be about 1.35; a coastline, about 1.26; and a piece of paper crumpled up into a ball, about 2.5. The fractal dimensions between 1 and 2 measure how wrinkly a line is. The crumpled paper ball fails to completely fill its allotted space, so it scores a dimension of <3. Foamy structures may also have fractal shapes. The universe itself has a fractal shape due to its foamlike structure caused by enormous globular voids between clusters of galaxies.

Fractal geometry occurs throughout nature. In biology it is seen in the sequential branching of ferns, trees, blood vessels, bile ducts, bronchi, and urinary collecting systems into smaller and smaller versions of the original. Our vascular system, when stripped of all other cells, would almost fill the space that our

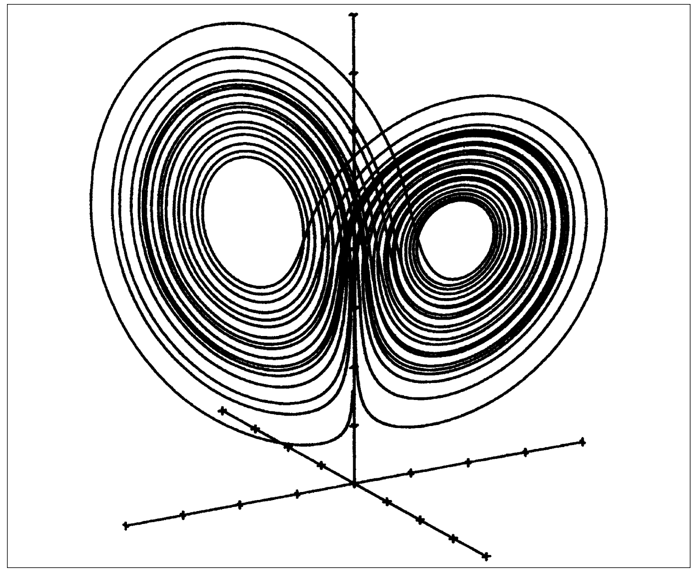

Figure 3. The Lorenz attractor, generated by an equation for turbulence. At any instant in time, the 3 variables fix the location of a point in 3-dimensional space; as the system changes, the motion of the point represents the continuously changing variables. Patterns like this reveal the fine structure hidden within a disorderly stream of data. Reprinted from reference 9 (p. 28) with permission of The William Morris Agency.

bodies occupy. It is estimated to have a fractal dimension of slightly <3. Beautiful fractals may be generated by computers when certain numbers are inserted into selected simple equations. When the results are fed back into the original equation, a feedback loop is set up, and the mathematics feeds upon its own results. It is well known that feedback loops often have the effect of signal amplification, as illustrated by a microphone being placed too close to its own loudspeaker. In the 1940s, Donald O. Hebb, a Canadian psychologist, investigated feedback loops in the brain (8). He realized that successive firing in the same neural loop led to reinforcement of nerve cell connections so that subsequent activation occurred more easily. The embers could thus be fanned into activity by suitable prompting from an afferent stimulus. The nerve networks would have memory.

Fractals and feedback loops are part of a branch of mathematics called nonlinear dynamics. The availability of powerful computers has spurred tremendous growth in the field of nonlinear dynamics over the past 30 years. Nonlinear dynamics has been used to help describe complex processes such as the weather, fluid turbulence, and many aspects of biology. The presence of feedback loops in the brain and in nonlinear dynamics made a compelling argument for attempting to use the latter to explain the former. During the past 30 years, Walter Freeman of the University of California at Berkeley has conducted extensive and elegant research demonstrating that nonlinear dynamics plays a critical part in the working of the mammalian brain, but the link between brain function and consciousness remains elusive (see http://mcb.berkeley.edu/faculty/NEU/freemanw.html).

NONLINEAR DYNAMICS: THE BASICS

Let us start with simple dynamics. Consider the pendulum of a clock. The velocity and position of the pendulum bob change constantly and may be plotted on a graph one against the other (*Figure 2*). The resulting circle describes, in phase space, the changing circumstance of the pendulum. All the information regarding the velocity and the position of the pendulum at any instant is given by a single point somewhere on the circle. If someone bumps into the clock, the pendulum may rattle about but will usually settle into its previous beat. It is as if the circle has attracted the dynamics of the pendulum back into its orbit. This kind of circle is known as a *periodic attractor*. When the clock winds down, the pendulum will slowly come to rest under the influence of external forces, friction and gravity. In phase space, the circle will spiral inwards to a central *point attractor*. In many biological systems, the attractor is the isoelectric state or cell death.

In some nonlinear systems, unlike in the case of a simple pendulum, the attractor is a fractal. One of the best-known and first-discovered fractal attractors associated with nonlinear dynamics is the pair of "butterfly" wings generated by a computer when Edward Lorenz was studying equations relating to weather turbulence *(Figure 3)*.

In biological systems, experimental data are often cluttered with noise and other artifacts. Thus, it is sometimes hard to discern the underlying dynamic processes. A simple device was described in the 1970s that may help distinguish between random noise and the presence of an underlying mathematical rule in a series of raw data (9). The irregular dripping of water from a faucet may be random or associated with an underlying mathematical order. If the drip intervals are plotted sequentially one against the other and the points are widely scattered, the dripping is probably random. If a pattern emerges, a nonlinear dynamical process may be evident. This device is called *delay coordinate embedding*. Many biological measurements are taken at regular time intervals. Embedding is accomplished by plotting the data against itself after the introduction of a suitable time lag. Two staggered columns of data plotted one against the other will produce a 2-dimensional plot. Three data streams will produce a 3-dimensional plot, which can be oriented arbitrarily on a computer screen. Embedding may be extended into multiple dimensions by increasing the number of staggered data streams.

A word of caution is needed here. The higher dimensions involved in string theory are physical and thought to be highly compact. Phase space is a mathematical construct, and motion on an attractor is abstract. In fractal attractors, the orbits in phase space may be stretched and folded like bakers' dough when it is kneaded. In either case, the human imagination is not equipped to contemplate these higher dimensions directly. Suffice it to say that if data from perceptual space may be retrieved, analyzed, and shown to exhibit an underlying mathematical order that correlates sensibly to its source, it probably is real even if it cannot be touched.

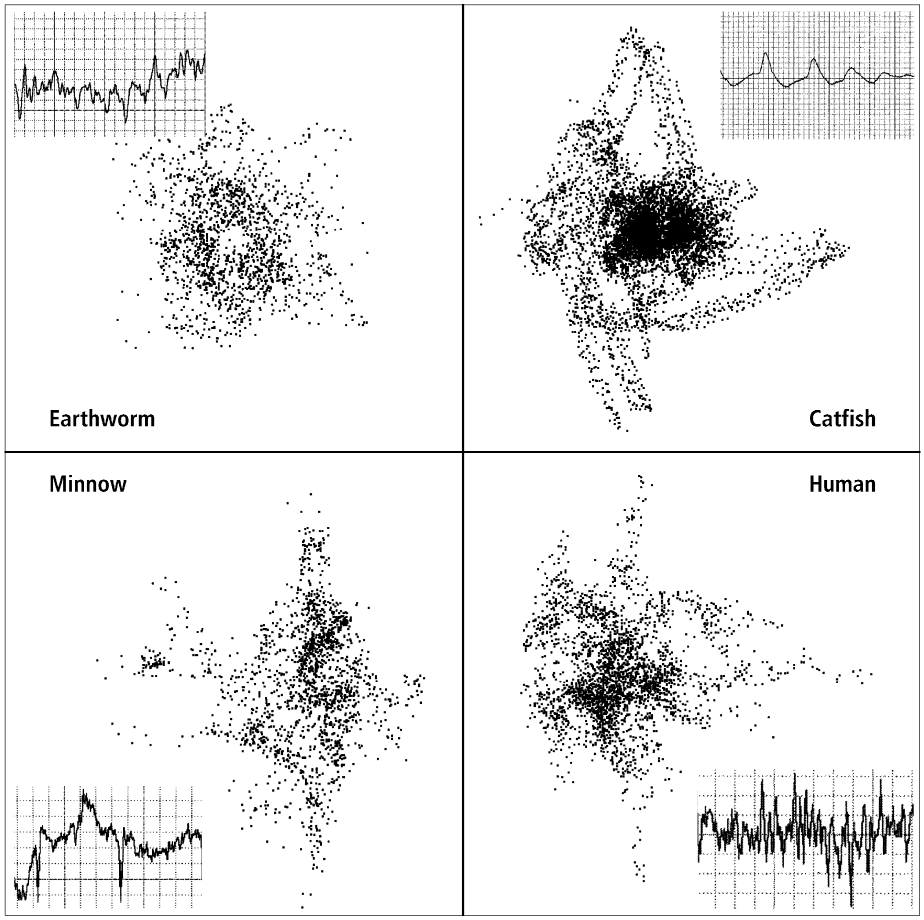

Figure 4. Raw signals with 3-dimensional plots from earthworm, catfish, minnow, and human. The earthworm plot shows symmetry and the hint of a doughnut shape, suggesting a simple periodic attractor. The catfish shows decreasing gill activity; the plot is suggestive of a point attractor. Note the electrocardiogram superimposed on the minnow's electroencephalograph. Plots from the minnow and the human both show symmetry and a slight foamy appearance.

APPLICATION OF NONLINEAR DYNAMICS TO CENTRAL NERVOUS SYSTEM DATA FROM DIFFERENT SPECIES

To look for signs of nonlinear dynamics, we manipulated data from electroencephalographs of 11 different fauna: anemone, starfish, earthworm, moth larva, crayfish, minnow, perch, catfish, frog, dog, and human. We wanted to see whether an increase in mathematical sophistication across species correlated with preconceived notions regarding evolutionary ranking in the central nervous systems of the animals.

Data manipulation was performed by using the Nonlinear Dynamics Toolbox (correspondence, Reiss@qmul.ac.uk, 2002). The data were analyzed to calculate the best delay coordinate using the autocorrelation function. Embedding was performed from 2 through 10 dimensions. The embedded data were examined in 3 dimensions for signs of attractors. Possible attractors may reveal themselves by demonstrating symmetry, patterns, or a foamlike structure. The data were subjected to analysis using the correlation dimension function to identify evidence of higher-dimensional structure.

Corresponding 3-dimensional plots for some of the raw signals are shown in *Figure 4*. Rotating the plots in 3 dimensions failed to demonstrate attractors in the anemone, starfish, or moth larva. A hint of a doughnut shape may be discerned from the plot of the earthworm. This might indicate existence of a periodic

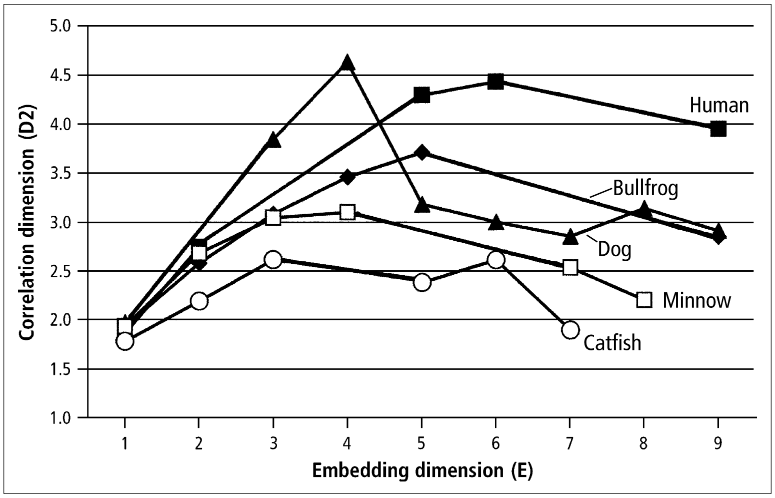

Figure 5. Fractal dimensions plotted at different embedding dimensions, taken from the catfish, minnow, bullfrog, dog, and human. The highest dimensions appear between 3 and 6 embedding dimensions. Note how the curves decrease in value after achieving their maximum value, an indication of the presence of nonlinear dynamics.

Table. Rankings of highest fractal dimensions obtained from the electroencephalographs of 11 species

Species	Highest fractal dimension
Human	4.85
Dog	4.63
Bullfrog	3.71
Minnow	3.09
Catfish	2.50
Perch	2.37
Crayfish	1.65
Earthworm	0
Moth larva	0
Starfish	0
Anemone	0

attractor. None of these creatures demonstrated fractal attractors when calculations were made at any embedding dimensions.

The crustacean, fishes, amphibian, dog, and human all showed evidence of fractal attractors and demonstrated increasing fractal dimensions, possibly commensurate with their status in evolutionary development *(Figure 5, Table)*. Changes in electroencephalograph fractal dimension over time were studied by measuring the correlation dimension (D2). Six animal groups were compared and plotted against their estimated age as calculated from the first appearance in the fossil record *(Figure 6)*. Thus, a few living animals were used as surrogates for evolutionary milestones.

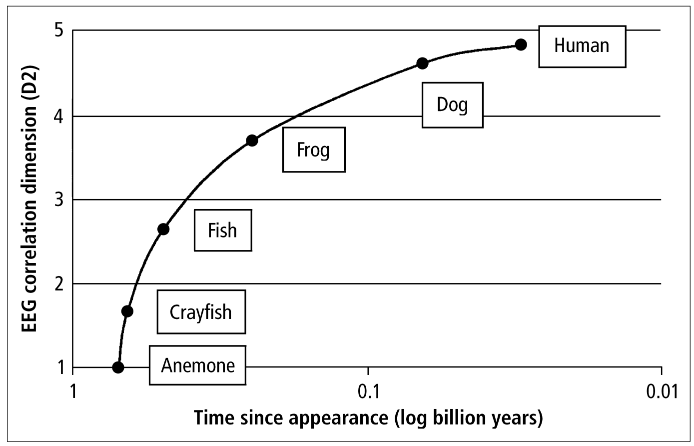

Figure 6. Electroencephalograph correlation dimensions (D2) from 6 animals were plotted against their age as estimated from the fossil record: anemone, 700 million years; crayfish, 650 million years; bony fish, 490 million years (mean of perch, catfish, and minnow, D2 = 2.65); frog, 245 million years; dog, 65 million years; and human, estimated at 30 million years. The shape of the curve is part of the logarithmic spiral.

DISCUSSION

The appearance of consciousness was a revolutionary development, not merely an evolutionary improvement. However, surely the groundwork must have first been laid. It has been suggested that the original stirrings in the journey towards consciousness may have arisen from pressure to secure improved sensory motor coordination. When a crablike critter sees food, computations must be made to coordinate eye and pincer relationships in phase space (10). If gradual improvements in coordination are eventually assisted by the development of awareness, it is not unreasonable that consciousness may also be found associated with phase space. Our results would tend to support this idea, as higher-dimensional fractal attractors first appear in the crayfish. We have demonstrated the beginning of order in creatures as lowly as the earthworm. We believe we have shown the presence of nonlinear dynamics in the crayfish and higher species for 3 reasons: fractal attractors appear in the 3-dimensional plots; the presence of higher-dimensional fractal attractors may be computed from the data; and fractal dimensions, when plotted against their corresponding embedding dimensions, tail off after reaching a maximum value. Linear artifacts and noise are less sensitive to the effects of higher embedding dimensions. Their signals may continue undiminished.

We emphasize that the crayfish is not ancestral to the catfish; they belong to different phyla, which have been separate from the first records of multicellular life (11). If it ever could be shown that awareness arose separately in these phyla, the implications would be most important.

Higher-dimensional fractal attractors have been demonstrated previously in humans. Values of correlation dimension vary with electroencephalograph epoch length, lead position, method of calculation, level of arousal, and age (12).

What is the significance of fractal attractors associated with the brain function of more advanced animals? Attractors are a testament to the presence of nonlinear computation. Remember the phase space of the simple pendulum. The position and the velocity of the pendulum collapse to a single point on the circle. The 3-dimensional Lorenz attractor allows 3 variables to join at a single moving point in phase space. The results reported here show that fractal attractors derived from the human electroencephalograph have dimensions as high as 4.8. The more variables there are in a nonlinear system, the more dimensions are needed to accommodate them. *Conversely*, the higher the dimension of the fractal attractor, the greater the number of variables that are required to represent it. Thus, the fractal attractor we observe could be evidence of a repository for the information required for higher-dimensional brain activity. The attractor may be the knot where the "binding" of information occurs.

Figure 6 was included out of interest and not for its statistical significance. Dimensions increase exponentially. When they are plotted over time on a logarithmic scale, the resulting curve is a section of the unique logarithmic spiral. As the radius of this curve increases, its shape remains unchanged. The curve is self-similar and may be seen throughout nature from the arms of spiral galaxies to the arcing shape of the shell of the chambered nautilus. Studies on more species are planned. If the curve in Figure 6 achieves significance by the addition of corroborating data, it is predicted that a new and better understanding of the evolution of the brain may result.

In conclusion, a prerequisite for an explanation of consciousness is a mechanism by which separate bits of information may be analyzed and synthesized. We believe that traces of this mechanism should be increasingly evident through the evolutionary scale. We have shown evidence of nonlinear dynamic activity in the brains of animals, activity that increases in complexity through species in a logical progression. In humans, we have shown that nonlinear dynamics may exist in the form of higher-dimensional fractal attractors up to a value of 4.8 dimensions. A 4.8-dimension attractor may combine more than 4 variables in phase space. It is possible that the synthesis necessary for a partial explanation of consciousness occurs in the phase space associated with the nonlinear dynamics of the brain. It is suggested that objects in physical space enter our perceptual space via phase space. A hyperspace is a phase space with more than 3 dimensions (10). It is our conjecture that consciousness is better described in its relationship to hyperspace than to an anatomical place.

Attempted refutations are expected and welcome. Watch this (phase) space!

Acknowledgments

The authors gratefully acknowledge the help of Dr. Joshua D. Reiss of the Department of Electronic Engineering, Queen Mary, University of London, without whose computer program this paper would not have been possible and without whose constructive criticism this paper would not have been plausible.

1. Popper K. *Conjectures and Refutations. The Growth of Scientific Knowledge.* London: Routledge, 2000:vii.
2. Walton I. *The Compleat Angler.* London: JM Dent and Sons Ltd, 1962:121.
3. Carter R. *Exploring Consciousness.* Berkeley: University of California Press, 2002:143.
4. Chalmers DJ. *The Conscious Mind. In Search of a Fundamental Theory.* Oxford: Oxford University Press, 1997:4.
5. Block N, Flanagan O, Guzeldere G. *The Nature of Consciousness. Philosophical Debates.* Cambridge, Mass: MIT Press, 1997:90.
6. Walling PT. Consciousness: a brief review of the riddle. *BUMC Proceedings* 2000;13:376–378.
7. Kaku M. *Hyperspace. A Scientific Odyssey Through Parallel Universes, Time Warps and the Tenth Dimension.* New York: Doubleday, 1995.
8. McCrone J. *Going Inside.* London: Faber and Faber, 2000:43.
9. Gleick J. *Chaos.* London: Cardinal, 1991:265.
10. Churchland PS. *Neurophilosophy: Towards a Unified Science of the Mind-Brain.* Cambridge, Mass: MIT Press, 1986:420–423.
11. Gould SJ. *Wonderful Life: The Burgess Shale and the Nature of History.* New York: WW Norton, 1990:43.
12. Ferri R, Pettinato S, Alicata F, Del Gracco S, Elia M, Musumeci SA. Correlation dimension of EEG slow-wave activity during sleep in children and young adults. *Electroencephalogr Clin Neurophysiol* 1998;106:424–428.

Invited commentary

In this issue, Walling and Hicks have written a provocative article hypothesizing a concept of consciousness that relates to a system of repeatable and identifiable patterns of electrical activity from the central nervous system of various life forms. They conjecture that this pattern of electrical activity, because it has a basic form, indicates that more than chance is involved, and therefore this might indicate a higher influence that might be "consciousness." They have applied the concept of nonlinear dynamics to neural activity, and where a process can be identified that can be associated with mathematical order, they have identified it as the basis of consciousness. This, of course, is a giant leap of faith, but nevertheless is very intriguing. May we assume that consciousness can be defined in terms of neural activity? Could consciousness be a separate higher function that may require neural activity to access it?

This article raises the question, "What is consciousness?" Consciousness is taken away approximately 27 million times a year in this country in patients undergoing general anesthesia, probably in a similar number of patients undergoing sedation, and who knows in how many people who medicate themselves into oblivion every day. Of course, we all experience a daily loss of consciousness during sleep, but this experience is very variable depending on how far dreams intrude on consciousness. The etiology of dreams is probably controversial enough to spawn another article. Do we know what consciousness is? Certainly we can appreciate that it has much to do with awareness, attention, perception, memory, and cognition, but is it definable? What makes 2 people recount different renditions of the same event? What is the filter that allows some external stimuli to reach the short-term memory circuits and not others? How does this filter fit into our definition of consciousness?

What are you conscious of right now? Perhaps you are conscious of this editorial and are wondering where it is going. You are probably aware of your environment and perhaps your gen-