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SIMPLIFYING COMPLEXITY

LIFE IS UNCERTAIN, UNFAIR AND UNEQUAL

Bruce J. West

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Simplifying Complexity: Life is Uncertain, Unfair and Unequal

Bruce J. West
US Army Research Office
Research Triangle Park
Durham
NC 27709
USA

Simplifying Complexity: Life is Uncertain, Unfair and Unequal

Authors: Bruce J. West

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FOREWORD

We in Western culture like to believe the world, especially its human corner, is a reason-driven place. We perceive the universe to operate in accordance with fixed laws. For most of us, science has caught up to, if not replaced, religion as a primary mover. The urge to seek and excavate nature's operating rules dates back more than a millennia, inspired by Aristotle and codified into the scientific method by Roger Bacon. People trust in the scientific method partly because we trust scientists to bracket off their initial biases so that they may engage in a uniform system of inquiry.

But what if scientists are unable to bracket off initial biases? What if cognitive biases about the world are actually built into the way science is conducted? If so, then empirical results are not wholly objective, but instead are partially rigged from the start. And what if the population at large unwittingly shares in these biases, often without realizing it?

This is precisely the state of affairs Bruce West reveals in his ground breaking book, Simplifying Complexity. In order to test hypotheses empirically, all research, no matter what the discipline, is shaped and even driven by the framework of its underlying mathematics. As West suggests, scientists' choice of mathematics goes hand-in-hand with their underlying "cognitive maps" that color reality according to various unconscious slants. These cognitive maps are necessary, for their facts and presumptions allow us to simplify the incredible complexity that surrounds us, so that we may function with purpose and free from overwhelm.

For centuries, Western science has relied primarily on linear statistics, whose "normal" bell-shaped curve and regression to the mean yield strong central tendencies. The normal distribution characteristic of linear statistics operates by collapsing variability to a point in the middle, which is then used to characterize the whole. In conjunction with Newtonian mechanics, linear statistics paint nature and her contents in clockwork fashion. Just like the mechanism of a clock can be disassembled and reassembled without surprise, under the influence of linear statistics, so too does Newton and Laplace's world move predictably in small, additive steps. The resulting statistics give the universe the appearance of being both fair and equal. In general, this choice of mathematics serves to tame nature's wild, uncertain, unpredictable, and unjust side.

West likens the mathematics a scientist selects as the formal medium for experimentation to an artist's choice of medium for self-expression. In both science and art, the medium conveys the message, as Marshall McLuhan would claim. Yet, the clockwork picture supported by linear mathematics is only one, highly simplified view of the world—one which easily leads to confusion. As a child raised in the 1960s, I recall learning an important statistic: the "norm" for the number of children growing up in families in the United States was said to be 2.5. Being rather literal-minded, I found it hard to wrap my mind around this notion. What exactly does it mean to have 2.5 children? When it comes to real families, it seemed to me that no one had 2.5 children. Looking back, I can see that wrestling with these ideas presaged my current interest in nonlinear science.

As West explains, we easily take for granted the story created by our mathematics of choice, largely due to familiarity. Normal statistics work well for sampling height or weight in the general population, because variability among people is relatively small; differences are additive; and underlying elements remain independent from one another. Yet, these conditions do not apply to most complex systems as they operate in the real world. Most natural distributions show wide spreads that include extreme if not catastrophic events. Indeed, catastrophic events occur far more often than most of us would like to believe. In general, nonlinear statistics reveal nature's wild side—her uncertain jolts, abrupt transitions, unpredictable turns, and dynamic variability in general.

With respect to real people in the real world, life is not clockwork nor is it mechanical, and families are not normative. Some people have 1 child; others have 10. When taking into consideration generation after generation that precedes the current one, each family looks different. The more families we sample, the greater the variability we find. Life thrives on variability. And the faster contemporary society changes with the advent of new technology and communication devices, the more dynamic the surrounding variability. Through nonlinear lenses, variability is the new norm, and for this reason, the time is right to shift our cognitive maps.

In this book, West presents a different kind of metric with which to understand nature's complexity and refine our underlying assumptions about the world. He offers nonlinear statistics that capture variability in the distributions of objects in space as well as events in time. In contrast with linear statistics that apply primarily to simple systems whose constituents are independently organized, nonlinear statistics apply to complex systems whose interdependent elements shift in multiplicative or exponential ways. This type of statistic goes by several names—1/f distributions, inverse power laws, pink noise, Pareto's law. West outlines as many as 9 different mechanisms giving rise to similar surface distributions.

One consequence of variability at the heart of such distributions is the importance that extreme events take. This is consistent with how the human mind works: we hardly take notice of tiny fluctuations in ordinary life, but do pay attention to extremes. Every time I successfully pull my car out of the garage, it is a non-event; meanwhile, the time I smash the side of my car is the single instance that matters most. Society at large works the same way.

Consider the stock market: minor fluctuations hardly make the news, but a market crash carries reverberations for years, if not decades, to come.

We human beings are complex creatures. Our brains have more interconnections among their neurons than the entire number of atoms in the universe. Our brains teeter on the edge of chaos, displaying some amount of order, yet enough variability for quick adaptation to an ever-changing environment. As West demonstrates, there is even variability at the center of our beating hearts—quite literally. Whereas traditional Western medicine asserts health in the form of predictable stability and regularity, when examined at the micro level, the dynamics of a beating heart reveal quite the opposite state of affairs. In between each and every heart beat is a tiny bit of variability that keeps us resilient and healthy.

This kind of variability is the stuff of life. As a clinical psychologist, I am steeped in it. I have probably seen hundreds of depressed people in the course of my 30+ year career. While linear statistics might put them all in the same diagnostic box, to me in real life, no two have ever looked exactly alike. Indeed, if they did, I would have been bored out of my mind and not skilled enough to treat them. The closer I look at each person—whether depressed or not—the more unique that individual appears. Welcome to the realm of the nonlinear.

As you turn the pages ahead, prepare to go through Alice's rabbit hole. For once you understand the characteristics of nonlinear statistical distributions, some ordinary assumptions about certainty, fairness, and equality in the world will be turned upside down. When it comes to being complex systems living in a highly complex, interdependent world, dynamics are ever-changing and the future is uncertain. We may use tricks like distraction or mindful awareness to tolerate the anxieties and preoccupations that living with ambiguities and uncertainties entails. Meanwhile, the democratic ideal of everyone having a fair and equal shot at becoming rich, famous, or President, is statistically opposite to the real state of affairs. The rich keep getting richer; the poor keep getting poorer; those already famous keep getting more famous; while scientists whose work is most cited will keep getting more credit, even if they had little to no hand in the underlying research.

From my perspective as a psychotherapist, the linear version of the world appears to be a nice fairy-tale people paint to ease the scariness, unfairness, and inherent injustice of life. To me, this cognitive map of the universe is akin to how parents appear to young children—bringing up the sun and moon and in control over everything. The illusion of certainty and control yields a safe and predictable world that protects little ones from harm and worry. Perhaps this naïve story of our environment, both inside and outside, serves a similar purpose within the developmental trajectory of science. Maybe during the early phases of scientific exploration, scientists similarly needed to keep things simple, by warding off the highly complex and unpredictable side of life.

West's book teaches us an important lesson: it is time for humankind to grow up and wipe the fairy dust from our metaphorical eyes. Simplifying Complexity reveals fascinating facts that connect separate disciplines with the same underlying mathematics. West even introduces a candidate for the first universal principle to govern the interaction of complex systems. West's complexity management cube applies to diverse phenomena—from habituation in a brain that encounters a strong smell to the de-habituation in a brain that becomes riveted on a beautiful piece of classical music. His new principle even addresses issues related to modern warfare and global warming, at points to yield surprising, if not controversial, results.

Most of us have been so thoroughly steeped in linear, reductionist assumptions about how the world works, we act like fish happily swimming in the calm waters of our protected bowls, oblivious to the turbulent waters in the real world outside. But we can't live in isolated environments (including ivory towers) forever. Just as it is dangerous to remain a child sheathed in the false comfort of a predictable, controllable, and fair future, so too is it dangerous to remain naïve about nature's implicit inequities and injustices. By understanding nature's true complexity, as rendered transparent by West (impressively without the use of a single mathematical equation), we prepare ourselves to address the complex problems we each face, both individually and collectively.

Terry Marks-Tarlow, Ph.D.
Santa Monica, CA
USA

PREFACE

The present book is an extensive revision of the previously published "Complex Worlds, Uncertain, Unequal and Unfair" and the title was changed to reflect that change. I believe an ebook publication will increase the likelihood of reaching an audience that is curious about what science can offer the first generation born into a mature information age.

A general polishing of the presentation has been made throughout the revision, but the most significant changes involve incorporating suggestions made by readers. One such change is the emphasis on using the powerful methodology of network science to guide the making of individual and corporate decisions in our complex society. There is also additional discussion on how a new way of thinking is required to fully utilize the results coming out of the new intellectual maps of the complex world of the 21st century.

Bruce J. West
Research Triangle Park
Durham
NC 27709
USA

CONFLICT OF INTEREST

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PROLOGUE

One of our strongest urges as human beings is to know the future in order to control our destiny and the destiny of those in our charge. Therefore, proposing the notion that life is uncertain, unequal and unfair seems to undercut a basic human need. But my intention in writing this book is not to subvert that primal need, but just the opposite. My belief is that the more clearly a person understands how the world actually works, the more effective they can be in achieving what they want in life. My experience is that individuals are ineffective, in large part, because they fail to distinguish between how the world is and how they want it to be.

I am not a psychologist, sociologist or social worker. I am a physicist and as such I am more comfortable with mathematical equations and experimental data than I am with words. So this is not a self-help book. It is a somewhat personalized account of what the average college graduate in western society has been systematically taught about the scientific understanding of the world that is not true. The greatest myth that has been delivered with all the pomp and circumstance of scientific truth is that for most purposes a linear view of the world is more than adequate. This is where the book begins, tracking down some of the less obvious implications of a linear world view and how that view conflicts with available data.

I heard somewhere that an editor told a would-be author of popular science books that with each equation she would lose half her intended audience. I do not know if this is true, but to be on the safe side I have not included any equations in the book, but there are charts and graphs along with ample interpretive discussion to replace them. This is a book about science and the role science plays in our technological society, both on stage and behind the scenes.

A brief review of the historical evidence that the mental maps of the world we construct for ourselves consist primarily of elements that are linearly connected provides a context to understanding why some people refuse to act in their own self-interest. Even when uncertainty is introduced into the description of events, as a way of including the influence of the broader world into their development, that uncertainty takes the form of small, additive, random fluctuations. The world's ambiguity is represented by a bell-shaped distribution of fluctuations in the outcomes of experiments and the variability of observations. The bell-shaped distribution reveals certain general properties of the world's influence on simple predictions, whether it is your broker's estimate of the likelihood of a market crash, your doctor's estimate of the severity of your disease, or whether you should have received a raise rather than the new guy.

I examine how the neatly constructed linear world view has been challenged by the complexity of modern society. It is not the case that humans have changed how they construct their mental maps of the world. It is that the linear assumptions made in the past are no longer as useful, as they once were, in guiding decisions made, particularly when social interactions are long range, multiple, and anonymous. I will indicate how the disintegration of simplicity disrupts our lives and leads to such things as the mismanagement of the health care system, particularly through the dominance of extreme events, when the assumption of Normal statistics no longer suppresses outliers. Specifically I am concerned with the form in which the notions of fairness and equity, born in the social unrest and industrialization of the nineteenth and early twentieth centuries, survive in the data of the twenty-first century; or more accurately how they do not survive or have been transformed.

Much of the fear that is generated by those that misapply the notion of complexity is based on extrapolating recent fluctuations into the future. Such extrapolation is invariably done using linear models that almost never have anything to do with the phenomenon being extrapolated. This was done using the "science" of eugenics at the turn of the twentieth century, and was the scientific basis for the "Aryan race" so loved by Hitler and still considered fondly by "white supremacists" and "skin heads" today. A similar kind of scientific basis was made in the 60s and 70s for overpopulation and "global winter". These things are mentioned in passing, but what is important is that we must abandon the idea that complex phenomena lend themselves to simple linear predictions.

Such a strong conclusion requires an abundance of evidence regarding the value of replacing linearity with complexity. The implications of a complex representation of the world are immediate and profound. One inherent advantage is that the complex vantage point provides a single coherent view of disruptive mechanisms in complex phenomena; mechanisms ranging in physical science from earthquakes to floods; in social science from stock market crashes to the failure of power grids; in medical science from heart attacks to flash crashes in health care; and in biological science from the extinction of species to allometry relations. Extrema are more frequent in the complex world than they are in the linear world. The effects of extreme events are certainly unfair, and fortunately they do not occur every day. But when disruptive events do occur they introduce crossroads, and the selection of which road to take determines the subsequent course of events in a person's life. Consequently, understanding the source of extremes enables an individual to take back control from the hands of fate.

The transition of our mental models from a simple to a complex world view, entails the breakdown of bell shaped statistics and necessitates the adoption of inverse power-law distributions. This is nowhere more evident than in the distribution of wealth. The long tail in the inverse power law implies that there is a fundamental imbalance in how wealth is distributed and this imbalance was identified by Pareto, the engineer that first identified the effect over a century ago. We shall explore whether or not such imbalance is necessary in a stable social society. This is done by studying other, less emotionally charged, phenomena that share many of its properties. To compare physical, social and biological systems it is necessary to have a common language and for this the idea of an information-dominated system is introduced and developed. The appropriate quantities to measure in complex dynamical systems are not easy to identify, in fact, what we choose to measure may well be determined by how we define information and how that information changes in time. How information flows in complex networks, or how information moves back and forth between two or more complex networks, is of fundamental importance in understanding how such networks or networks-of-networks operate. This information variability is shown to be determined by inverse power-law distributions, which in turn are generated by a number of generic mechanisms that couple contributing scales together. We identify different mechanisms that produce empirically observed variability; each one prescribing how the scales in the underlying process are interrelated.

Science is about finding order in the panorama of the world and embracing a perspective that includes the falling of apples and the motion of planets; the behavior of the individual and the actions of groups, large and small; the information content of an encyclopedia and the wikipedia; in short, science does not, and should not, have any boundaries with regard to content. The terrestrial and the cosmic are part of the give and take in science, with the goal of uncovering the principles and laws that determine how the universe functions, along with the individuals within it. For most people, science appears to be separate and apart from the world in which they live. The principles and laws of science do not seem to apply to the general interactions among people; due, in part, to the fact that principles have not been found for everyday decision making; laws have been notoriously absent from mundane thinking; rules have been sought in vain in the growth of society; and indeed canons go begging in the multiple complex phenomena within the human sciences, despite over two hundred years of effort to either invent or find them. A possible exception to this pessimistic summary of history is given by the Principle of Complexity Management, whereby a system with greater information, but perhaps lesser energy, can dominate a system with lesser information, but greater energy. The principle is a recently proven generalization of an observation made by the mathematician Norbert Wiener, and may be one of these long sought universal principles.

The final chapter contains my understanding of the formal justification for complexity in the real world. In turn, it is an examination of what complexity implies, about the difference between how we react to what we have, as opposed to reacting to what we want, but do not have. People always respond to events according to their mental maps of the world. Consequently, when they find the response to be inappropriate, the most reasonable thing to do is change the map. However, people are not always reasonable or logical. My hope is that the potential for understanding presented in this book can initiate the wisdom that St. Francis addresses in his brief prayer:

God, grant me the serenity
To accept the things I cannot change,
Courage to change the things that I can,
And the wisdom to know the difference

At the suggestion of an anonymous reviewer to present additional discussion on the interpretive strength of nonlinear models I have elected to include an epilogue.

CHAPTER 1

How Scientists Think

Abstract: We begin by focusing on the ways we record the myriad of events that make up our lives, using simple models that are intended to capture the dominant features of those events and to provide coherent interlinking of events. If the world did not change in time, more and more detail could be added to these models, with each repetition of an event. Eventually we would have an accurate reconstruction of a successful economic relationship, of a nurturing family, or of a supportive organization. But things do change, even if our reactions to them do not. To understand these changes scientists have developed techniques that quantify and communicate objective models of these subjective events. Without presenting the technical details of how scientists construct such models, I use a combination of personal history and discussions of the science hidden by a variety of social problems, to lay the foundation for the understanding and resolution of these problems in subsequent chapters.

Keywords: Chaos, Exponential growth, Grand visions, Mental models, Multiple saturations, Saturation, Technology evolution.

Science, as well as the typical scientist, has changed along with society. From its slow paced agrarian roots, to the faster paced industrial form, to the nearly instantaneous informational society, the concerns of science and scientists have steadily expanded. The basic science describing the mechanical motion of the planets orbiting the sun, matched the relatively simple social forms that were directly supported by farms and farmers. The increased complication of the statistical description of the interaction of large numbers of particles in a gas was more compatible with industrial mores and the networks necessary to support them. Finally, tipping points and global interdependence spawned the analysis of complex phenomena in harmony with the information society. This historical tagging of the concerns of science indicates that we tend to think of these distinct

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social modes as being separated by large intervals of time, say centuries. Although historically accurate, such a picture distorts the influence that these distinct social modes have on individual scientists. So it is not without value to include some personal history in my presentations, since all three social modes have influenced my own development as a scientist.

So I begin with my father, who was brought up on a five hundred acre farm in upstate New York; the oldest of thirteen brothers and sisters. The farm was without benefit of electricity or indoor plumbing, except for a hand pump providing water with which to wash and cook. He graduated eighth grade when he was 12, but there was no high school in his rural community, so he had a choice to either leave school and work the fields with his step father, or stay in school and read every book in the library including two encyclopedias. He choose the latter. Like many young men his vision of the future did not coincide with that of his parents. The world beckoned to him and he left the farm when he was 16; it was the depth of the depression.

My mother was raised on an even smaller farm in upstate New York; the oldest of seven brothers and sisters. Her town did have the luxury of electricity, as well as, a high school from which she graduated. The daughter of Italian immigrants, she was the first in her family to receive a high school diploma. I have one book she kept from that time, *The Logic of Epistemology*, not the kind of high school reading seen today.

My parents were married when my mother was 21 and my father was a few years older. They gave birth to seven boys, three before the Second World War and four after my father came home after serving in the Army on an island in the Pacific. The ages of my brothers were spread over seventeen years; the youngest was in a crib in my room when I left home at 17. I shared my room with four younger brothers. Like my father I was restless and did not share my parents view of the future. I was the third oldest of seven sons, born into a labor class family, and this circumstance contributed significantly to my decision to be a scientist.

My first memory of wishing to be a scientist is associated with a eulogy I wrote on Albert Einstein for an eighth grade English assignment. Thinking about it now

I can see how the idea must have been swirling around in my head for some time, but it took the death of this great man to focus the desire. It was 1955 and once a month there were school drills in which students were guided to duck under their desks in response to an imagined, but no less real, bright flash of light in the sky. We were periodically shown films of cities being destroyed by atom bombs and every Catholic mass ended with the phrase "Savior of the world, save Russia". At that age the 'how' of things seemed much more important than the 'why'. It is only after years of study that I began to understand the reasons underlying the 'why' and to appreciate their entanglement with the 'how'.

Modern science, or more precisely physics, began with Sir Isaac Newton (1642-1727), who famously wrote in response to critics who wanted him to 'explain' the causes of gravity, that he constructed no hypotheses. Newton believed that what could not be directly inferred from experiment constituted hypothesis and he was having none of it. A hypothesis is a refined version of the vague impressions, half-backed ideas, ill-conceived assumptions and intuition that are often generated during the scientific investigation and solution of complex problems. The hypothesis summaries what is learned in the feverish attempt to understand a mystery, but only after the fever has subsided. Scientists typically formulate a hypothesis near the end of a study to make clear to others exactly what it was they were attempting to prove, but only after they are pretty sure they know the answer.

Only extremely simple problems have solutions that can be put into the form of a hypothesis before any research has been done. So when I refer to how scientists think it is not about the formation and testing of hypotheses, but it is about how we acquire knowledge from experiment. What a scientist works to avoid in this acquisition of knowledge is confirmation bias. Such bias was identified by the mathematician/philosopher B. Russel:

> "If a man is offered a fact which goes against his instincts, he will scrutinize it closely, and unless the evidence is overwhelming he will refuse to believe it. If, on the other hand, he is offered something which affords a reason for acting in accordance to his instincts, he will accept it even on the slightest evidence."

CHAPTER 2

Uncertain: A Simple World View

Abstract: Everyone knows the future cannot be predicted and yet fortune cookies are invariably received with pleasant anticipation. In this chapter we review how science came to terms with uncertainty, through the invention of statistics and probability, but perhaps more importantly, how this world view was made compatible with the clockwork universe of Newton. If the changing events of one's life are treated as being linear, then response is proportional to stimulus, with perhaps a little error. But the error in this view is subject to law, and is therefore controllable. The linear world view, with Normal statistics to explain uncertainty, is the model of reality adopted by most people, either implicitly or explicitly. It is this world view that promotes the idea that equality and fairness are not only what is true, but more importantly they are what ought to be true.

Keywords: Adrian, Drunkard's walk, Gauss, Handicapping, Linear, Medicine, Normal statistics, Prediction, Probability, Psychophysics, Scaling, Simple models, Sociophysics, Uncertainty.

At the opening of the nineteenth century a new scientific view of the world, based on statistics, was introduced by the German polymath Karl Fredrich Gauss (1777-1855) [23]. In the same year an identical view was independently published across the ocean by the American mathematician Robert Adrian (1775-1843) [24]. These mathematicians solved a great mystery that had confounded scientists since the acceptance of Sir Francis Bacon's (1561-1626) assertion that the best way to answer questions was through experiment. Bacon is credited with fathering the scientific method; an inductive logical procedure for isolating the cause of a phenomenon through the judicious use of experiment. For example, humans were curious about the nature of lightning since the beginning of recorded time, but it remained for Benjamin Franklin (1706-1790) to initiate experiments on lightning

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in 1749, see Fig. (**2.1**). As pointed out in the Encyclopaedia Britannica Franklin's deductions based on his carefully designed experiments remained the best information on lightning for 150 years. In spite of their quality Franklin's experiments on electricity suffered from small uncontrollable variations in the results; a vexing situation common to all other experimenters of the time.

Fig. (2.1). Sir Francis Bacon (1561-1626) the inventor of the scientific method is depicted on the left. Benjamin Franklin (1706-1790) used Bacon's method with considerable success.

Gauss and Adrian were the first to explain why the vacillation in results from experiment to experiment occur, and never produces the same value of a given variable twice. This academic discussion did not influence the horizons of the farmer planting his crops, nor did it change the vision of the landlord over- seeing his holdings, but in the cities where innovation was flourishing the intelligentsia was listening. What captured the imagination of the nineteenth century philosophers and scientists (natural philosophers) was that unpredictable random variations obey a law in the same way that predictable physical phenomena obey laws. What is unique and unpredictable is not completely arbitrary. The law of randomness was expressed through the interpretation of the bell-shaped curve of Normal statistics depicted in Fig. (**2.2**). This curve peaks at the center where the largest number of experimental values occurs. Most results are in the immediate vicinity of the mean, so that the center contains the greatest concentration of results. The greater the distance a value is from the peak the less often it is observed in the experimental data.

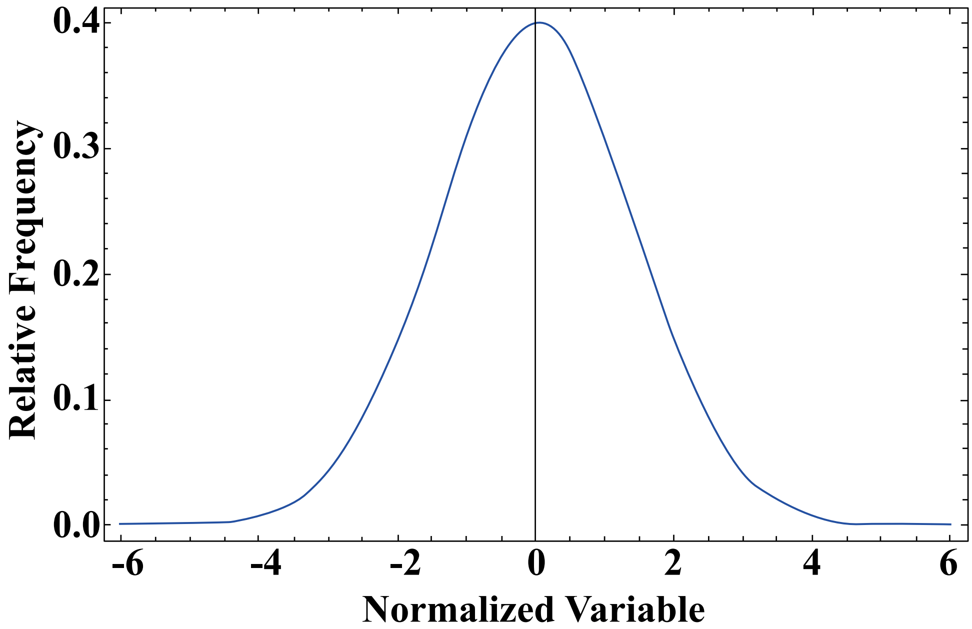

Fig. (2.2). The bell-shape curve of Gauss, Adrian and Laplace concerns errors. Consequently the average of the experimental data is subtracted from each data point so the curve peaks at zero, and the data are divided by the standard deviation of the data (width of the distribution) so that the normalized variable is dimensionless. The peak occurs at the point of zero error, that is, the average of the data. The region two standard deviations above and below the average value contains 95% of the errors (the deviations from the average value).

The bell-shaped distribution was interpreted as the law of frequency of error, since it was believed that measurements ought to have a correct value; one fixed by the underlying dynamics of the phenomenon being investigated. For convenience let us agree to refer to this as the law of error. This view of physical phenomena was and remains consistent with Newtonian mechanics that determines the ballistics of cannon and rifles, the inertia of horse and carriage, and the orbits of the planets. The world was understood to be a clockwork mechanism and therefore variables ought to be quantifiable and predictable, even those

CHAPTER 3

Unfair: A Complex World View

Abstract: The linear additive world view, in which uncertainty is described by Normal statistics, is replaced by a nonlinear multiplicative world view in this chapter; the simple yielding to the complex. One consequence of the complex world view is that uncertainty is characterized by inverse power-law, rather than Normal, statistics. The implications of this complex representation of the world are immediate and profound. One inherent advantage is that the complex vantage point provides a single coherent view of disruptive mechanisms in complex phenomena; mechanisms ranging in physical science from earthquakes to floods; in social science from stock market crashes to the failure of power grids; in medical science from heart attacks to flash crashes in health care; and in biological science from the extinction of species to allometry relations. Extrema are more frequent in the complex world than they are in the simple world of Normalcy. The effects of extreme events are certainly unfair, and fortunately they do not occur every day. But when disruptive events do occur they introduce crossroads, and the selection of which road to take determines the subsequent course of events in a person's life. Consequently, understanding the source of extrema enables an individual to take back control from the hands of fate.

Keywords: Bursting, Complexity, Crashes, Extrema, Fractals, Hospitals, Intermittency, Nonlinear dynamics, Non-normal statistics, Power grids, Quakes, Tipping point, Unfairness.

One of our strongest urges as human beings is to know the future and through that knowledge control our destiny and the destiny of those in our charge. In the first two chapters I reviewed some of the historical evidences that the mental maps of the world we construct for ourselves consist primarily of elements that are linearly connected. Even when I introduced uncertainty into the description of events, as a way of including the influence of the broader world into their development, that uncertainty took the form of small additive random fluctuations. The world's

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ambiguity is represented by the distribution of the fluctuations in the outcomes of experiments and the variability of observations.The functional form of the distribution revealed certain general properties of the world's influence on simple predictions whether it is my estimate of the stopping distance, when tail gating at 60 *mph*, or how students react to a change in testing procedures.

In this chapter I examine how the neatly constructed linear world view has been challenged by the complexity of modern society. It is not the case that humans have changed how they construct their mental maps of the world. It is that the linear assumptions made in the past are no longer useful in guiding decisions made when social interactions are long range, multiple, and anonymous. I will indicate how the disintegration of simplicity disrupts our lives and leads to such things as the mismanagement of the health care system, particularly through the dominance of extrema when Normalcy no longer suppresses the outliers. Specifically I am concerned with the form in which the notions of fairness and equity, born in the social unrest and industrialization of the nineteenth and early twentieth century, survive in the data of the twenty-first century; or more accurately how they do not survive.

3.1. THE IMBALANCE

The Italian engineer/economist/sociologist, the Marquis Vilfredo Frederico Damoso Pareto (1848-1923), as the nineteenth century drew to a close, determined the empirical distribution of income within western society for the first time. Pareto had worked as an engineer in business until he was middle aged and with the death of his father and shortly thereafter his mother, he left the business world and after a brief hiatus took a faculty position in Political Science at the University of Lausanne, Switzerland. Being trained as an engineer he was convinced that the social sciences were amenable to the same logical-experimental reasoning as the Natural Sciences. Late in life he justified his perspective in *The Treatise on General Sociology* [48] with the following:

> "Driven by the desire to bring an indispensable complement to the studies of political economy and inspired by the example of the natural sciences, I determined to begin my Treatise, the sole purpose of which - I say sole and I insist upon the point - is to seek experimental reality, by the application to

the social sciences of the methods which have proved themselves in physics, in chemistry, in astronomy, in biology, and in other such sciences."

Fig. (3.1). Marquis Vilfredo Frederico Damaso Pareto (1848-1923), engineer, sociologist, economist and philosopher. He made several important contributions to social science, especially in the analysis of individual choice and in the study of income distribution, which he found to follow an inverse power law for high incomes.

Pareto, see Fig. (**3.1**), was among the first to have the modern vision of society as a network of reciprocal and mutually interdependent elements. Consequently, he viewed social change as a process of action and reaction to maintain the social order, analogous to the then emerging concept of homeostasis in medicine. He reasoned that all social systems are composed of individuals with a distribution of moral, intellectual and physical differences, together, with what he considered to be non-logical actions, resulting from psychic states of sentiment. He consequently determined that the distribution of wealth in western society was not completely random, that is not Normal, but followed a different, but consistent pattern he determined to be inverse power-law. He called the inverse power-law distribution "The Law of the Unequal Distribution of Results" [49] and referred to

CHAPTER 4

Unequal: A Matter of Scale

Abstract: The transition of our mental models from a simple to a complex world view, entails the breakdown of Normalcy and the necessary adoption of Pareto's inverse power-law distribution. The complexity measure in this new world view is the inverse power law index, whose magnitude determines whether or not variability of the underlying process can be described by a finite variance. It is often the case that in such phenomena the focus shifts away from continuous dynamics of mechanical systems, such as the trajectory of a person's life, to the time intervals between discrete events, such as having a heart attack or receiving a message. This shifting is particularly evident in information-dominated systems, whose time series may not even possess an average time between events. The appropriate quantities to measure in such fractal dynamical systems are not easy to identify, in fact, what we choose to measure may well be determined by how we define information and how that information changes in time. How information flows in complex networks, or how information moves back and forth between two or more complex networks, is of fundamental importance in understanding how such networks or networks-of-networks operate. This information variability is determined by the inverse power-law distributions, which in turn are generated by a number of generic mechanisms that couple contributing scales together. We identify different mechanisms that produce empirically observed variability; each one prescribing how the scales in the underlying process are interrelated.

Keywords: Allometry, Contagion, Criticality, Decision making, Frequency, Inequality, Inverse power laws, Networks, Rank order, Scaling mechanisms, Space, Time, Universality.

Science has historically been concerned with the search for universal principles and laws to describe and understand the world; relationships that capture wide ranges of experimental results with a minimum number of assumptions. This has been particularly true in the physical sciences. Sometimes a physical law is

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straightforward, as is the first law of thermodynamics; the conservation of total energy. But once the law is articulated, its implications are remarkable in the extreme. Conservation of energy implies that changes in kinetic energy are compensated by changes in potential energy and the exchange of one form of energy for another, such as in a swinging pendulum, provides a way to understand the dynamics of the mechanical part of the world in which we live. The clockwork universe of Newton, shown by Hamilton to be based on this conservation law, satisfactorily explained how things work for a large fraction of the civilized world. But others, who were more qualitatively minded, maintained that this was not adequate for characterizing the dynamics between people; it did not and does not encompass the human sciences. They wanted something more.

As a scientist I try to represent phenomena in simple forms, or some might think in simplistic ways. I think about such physical concepts as space and time in terms of how many times I can lay a ruler end to end to measure the dimensions of my room, while time is measured in terms of the number of ticks of the clock sitting on my desk. However, as a person, the dimensions of my room are much more than the number of square feet enclosed by the walls. The size of the room is also determined by the books that fill the shelves along each wall; the light shining through the windows overlooking the front lawn; and the connection to the outside world through my computer. Time goes faster or slower depending on whether an exciting insight is revealing itself in writing the right word or phrase, to explain a central idea, or is being stubbornly elusive. In this chapter I discuss the quality of life experienced in personal space/time, in terms of operational definitions introduced in the sociophysics of the nineteenth century. This discussion provides some of the insights necessary to understand the source of some of the inequality in the human realm.

Musicians and physical scientists understand how the vibrations of a violin are produced, but the aesthetic appeal of music is put into a category outside the science of acoustics. The human sciences of psychology and sociology lack the universality of physics: symmetry principles and the laws of thermodynamics have no human science analogs, with the possible exception of information flow. This lack of universality arises, in part, because the appropriate metrics are lacking, that is, scientists do not understand what they ought to be measuring, or whether what they believe is important in a given context can be measured. In a physical interaction there is always the exchange of something tangible: momentum, energy, matter, or the element of an appropriate field, such as a photon or phonon. However, in a social interaction the far more elusive quantity of information is exchanged. Of course the intended message of the sender, contained in the words used to construct the message, can be very different from the understanding of the message, as interpreted by the receiver. In the real world the history of the sender and receiver are involved in the formation and interpretation of messages, including such things as posture, hand movements, facial expression, choice of words and so on. Note that this is not the information exchange proposed by Claude Shannon shortly after the Second World War. His working hypothesis abstracted sender and receiver to featureless points that contribute nothing to the message. All the human qualities mentioned, as well as others, are important in determining the information transmitted in a social interaction, but these are explicitly excluded from Shannon's definition of information. However, the notion of information used herein is more general than that postulated by Shannon over a half century ago and which is still used by communications engineers.

Consider how little information is transferred in terms of words used when, for example, a youth wants to impress a member of the opposite sex. Compare the information content of the words to the information contained in an awkward stance, a nervous tick, an inappropriate laugh, and the myriad of other uncontrollable things, that despite their best efforts, emerge in the exchange. Only in literature do words: outweigh how people carry themselves; impress more than how a person is dressed; or focus the attention more than the warmth of a smile. So how is this collection of indicators about a complex person transmitted and interpreted by another person. These concerns replace the simplifying assumptions made about the nature of information by Shannon, which started as his working hypothesis over a half century ago and are, for the most part, still used today.

I have been asked by a number of people in the course of my research,including the Directors of the Army Research Office and the Army Research Laboratory, why the elaborate formal methods of statistical physics are not sufficient to

CHAPTER 5

Complexity Management Principle

Abstract: Science is about finding order in the panorama of the world and embracing a perspective that includes the falling of apples and the motion of planets; the behavior of the individual and the actions of groups, large and small; the information content of an encyclopedia and the Wikipedia; in short, science does not, and should not, have any boundaries with regard to content. The terrestrial and the cosmic are part of the give and take in science, with the goal of uncovering the principles and laws that determine how the universe functions, along with the individuals within it. For most people, science appears to be separate and apart from the world in which they live. The principles and laws of science do not seem to apply to the general interactions among people; due, in part, to the fact that principles have not been found for everyday decision making; laws have been notoriously absent from mundane thinking; rules have been sought in vain in the growth of society; and indeed canons go begging in the multiple complex phenomena within the human sciences, despite over two hundred years of effort to either invent or find them. In this chapter we examine the Principle of Complexity Management, whereby a system with greater information, but perhaps lesser energy, can dominate a system with lesser information, but greater energy. The principle is a recently proven generalization of an observation made by the mathematician Norbert Wiener, and may be one of these universal principles.

Keywords: Complexity management principle, Global warming, Habituation, Inverse power law, Laws, Leaky faucet, Memory, Network-centric warfare, Universality Norbert, Wiener.

The goals of economists studying global financial markets; the objectives of sociologists scrutinizing terrorist organizations; the intent of neuroscientists to understand neuronal networks and the aims of others in the human sciences, are no less worthy than those pursued by the physical scientists. Some would argue that understanding these non-physical phenomena are, in fact, more important

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than are their physical counter parts, because they are so closely related to the every day events of people. Therefore, it is exciting that even though the muse has not pulled back the curtain on the principles of human science, it appears that the first glimpse of scientific laws of human conduct, may have been made.

The recent surge of interest in networks and the effort to develop a network science has provided a foundation for general principles outside the physical sciences. It should be understood that network science does not yet exist. There are various theories and models, but nothing that has risen to the level of science that is distinctly dependent only on networks. Network science is a hope for how science may develop in the future. It should be clear that if network science is to exist, it will stand outside the traditional disciplines, in recognition of the common aspects of various disciplines coincident across complex phenomena. The common features across phenomena result in the interchangeability of their network representations. Inverse power-law statistics and pink (1/f) noise capture complementary aspects of complexity in dynamic behavior through the mechanistic effects discussed in the last chapter. Without identifying the common features, it would seem unreasonable to compare music to a dripping faucet, or an oil spill to the milk in a cup of hot coffee.

The first step in formulating a principle of network science has been taken, through the collective scientific insights of what constitutes a complex network, provided by scientists over the past decade. The next step in formulating a principle for understanding the complexity of human phenomena is to explain how complex networks influence one another. The influence can be deterministic by means of direct physical control, as in leaning a motorcycle through a turn, or trying to convince your teenage son or daughter that having sex, whether protected or not, has dramatic unintended consequences. On the other hand, the influence can be statistical, where the fluctuations in one network gently perturb those of another, producing an unexpected variety of responses. The transfer of information by weak coupling of one network on another, may be absorbed by the second network resulting in no long term response. On the other hand, the influence may be cumulative and the perturbing network may eventually completely dominate the network being perturbed. The transfer of statistical influence through information is more subtle than that through energy perturbation, but may be more common in the interacting complex networks that nature designs, than are the deterministic controls designed by engineers.

A traditional way to frame our understanding of the question of how complex networks influence one another is to construct the separate equations of motion for the two networks and then allow them to couple, usually through a linear term. An engineer would design a coupled system in this way and therefore this is the first way science tries to understand how nature does it. If this does not work, we can always go back to the empirical approach; that being, to put the two networks of interest into direct contact with one another and record what happens. Of course, the empirical approach is almost always costly, often not feasible, and, when dealing with human beings, is frequently limited by considerations of ethics. However, nature is filled with examples of species that feed off one another, when they are allowed to freely interact, as we discussed earlier.

Before turning to the social context let us look at how individuals react to various kinds of stimuli. The initial shock to the skin of the icy water of a stream is attenuated to a warm tingling sensation; the strong odors that command attention, soon fade, leaving an undetectable scent; the annoying traffic noise outside the motel window is replaced with the comforting quiet of sleep. All these stimuli start clearly in consciousness, but in a relatively short time their influence on what is experienced dissipates. This is the phenomenon of habituation in which a simple stimulus first attracts attention and then relinquishes it over a relatively short time, without the stimulus changing form. Therefore, people fall asleep in front of the television, or reading a book, or in the middle of reading a scientific paper. Habituation is examined here in terms of a complex signal exciting the brain, using a suitable function to measure the level of response of one complex network being stimulated by another. This examination reveals how complexity, in the form of information, is transferred and controlled by complex networks. My colleagues and I call this transfer and control of information the *Principle of Complexity Management* [71]; it is interesting because the complexity of the sender and receiver are crucial in determining how much information is actually transferred.

One thing that has become apparent in discussing the transfer and control of

CHAPTER 6

Apology for Complexity

Abstract: This chapter provides a summary of the material discussed; highlighting what is important and connecting those parts of the story that might have been obscured in presenting the details. This apology is my understanding of the formal justification for complexity in the real world. In turn, it is an examination of what complexity implies, about the difference between how we react to what we have, as opposed to reacting to what we want, but do not have. People always respond to events according to their mental maps of the world. Consequently, when they find the response to be inappropriate, the most reasonable thing to do is change the map. However, people are not always reasonable or logical.

Keywords: Chapter summaries, Complexity, Epilogue, Fractional reasoning, Highlights, Illogical, Individuality, Linear, Mental maps, Nonlinear, Organization man.

The final chapter of a book of fiction should be climactic; pulling together all the various plot lines in creative, fulfilling and even unexpected ways. When the final synthesis is done well the reader puts the book down with a feeling of satisfaction; when done by a master the reader is reluctant to put the book down at all. I maintain that a truly interesting work of non-fiction should aspire to the same end. Therefore this final chapter is a challenge for me. It is similar to retiring to the library, after a dinner with friends, for good company, cognac and, if you are so inclined, a good cigar. That good company is herein provided by a brief summary of what has been discussed in the first five chapters. The cognac, or brandy, takes the form of an introduction of a mathematical infrastructure, with which to clarify why the inverse power law is ubiquitous. The mathematics is that of the fractional calculus, in which non-integer integrals and derivatives appear, and that provides

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a single perspective, from which the nine different mechanisms that generate inverse power laws discussed in Chapter 4, can be understood. Of particular interest is the cigar smoke that ties the critical dynamics of complex networks to the fractional calculus; thereby reducing a many-body system to a one-dimensional rate equation.

6.1. SUMMARY OF CHAPTERS

This essay began the discussion of complexity in the first chapter, with the assertion that scientists think about complexity differently from most people. They do this in part because they are trained in method; but perhaps more importantly they do this because they are drawn towards quantitative models that enable them to think systematically about complexity, without passion or bias. It is not that scientists do not have passion or bias, for they most certainly do, but they can step beyond those limitations in their reasoning and come back to them once the reasoning is complete. Scientists, like other people, mentally store experiences that sprawl into a cognitive landscape forming a mental map of the world. This map is used in qualitative assessments and quantitative reasoning to provide an individual's unique lens, through which they see and understand the unfolding of events. The essay's narrative voice offers one scientist's point of view on how people understand the complexity of every day phenomena and how their mental maps mitigate their response choices.

The life-long process of developing mental maps begins at the earliest stages of childhood and determines whether the context in which all subsequent experience is stored is hostile or friendly, detached or engaged, coherent or confused. The formation of these maps are made explicit and analytic by youths who grow into scientists. These consciously developed maps modulate how scientists think about difficult problems and morph into quantitative models, which can be shared with like-minded individuals and whose predictions are amenable to experimental testing. The weaknesses of mental maps are revealed through systematic comparisons with real world data and these mental maps converge on reality by continuously changing them to eliminate inconsistencies. Chapter One finishes with the realization that what we think we know, but which is not true, is the highest barrier to understanding the nonlinearity and complexity of everyday experiences.

Chapter Two maintains that western civilization and the industrial revolution fostered adopting a particular map of the world; one based on the clockwork universe of Newton. Even when things become complicated and unpredictable, they do not differ too much from the mechanical world view. Uncertainty is described by Normal statistics, the mean characterizes the process and the scatter around the mean is not very large. This is the linear additive world view where fairness can be quantified and inequality can be measured. In this world industry flourishes, everyone has a job and failure can be controlled. The Utopian dreams of social order by people such as Marx, even if not a natural outgrowth of social evolution, from their perspective, can and should be imposed.

The historical reasons for the linear additive world view are sketched out and its consequences are explored. The fundamentals of uncertainty, probability and statistics are explained without burdening the reader with extraneous mathematical formalism. However, the discussion of the background concepts discloses the empirical evidence supporting the acceptance of Normalcy and traces the underlying reasons for Normal statistics, as well as, the theoretical reasons for its development in the physical sciences and its inclusion in the human sciences. This chapter explores those areas of science that have come under the spell of Normalcy and its compatibility with the great nineteenth century social thinkers.

Chapter Three examined the symmetric behavior of the Normal distribution and finds it to be inconsistent with data from such everyday phenomena as the distribution of income, the variability of prices in the stock market, and the intermittency in time intervals between emails or letters. A fundamental imbalance in the distribution of income was discovered empirically at the end of the nineteenth century by the political scientist/sociologist/engineer Vilfredo Pareto. The Pareto distribution has subsequently been found whenever the process examined is complex; from the number of earthquakes [127], to the number of sexual liaisons; from the size of a person's paycheck to the length of their email messages [59]. The real world is nonlinear, multiplicative and terrorized by extreme events, such as flash riots, crashes of the stock market, congestion of

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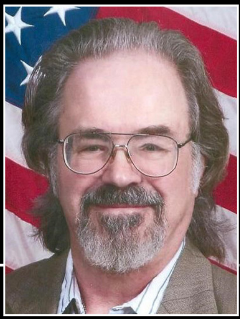

Bruce J. West

Dr. Bruce J. West is the Senior Scientist Mathematics (ST) in the Army Research Office of the Army Research Laboratory. He received a B.A. cum laude in physics at SUNY@ Buffalo in 1965; an M.S. (1967) and Ph. D. (1970) in Physics from the University of Rochester.

Before coming to ARO Dr. West was the Professor of Physics, University of North Texas, 1989-1999; Chair of the Department of Physics 1989-1993. During his time at the university, he did research into the quantum manifestations of chaos (energy level repulsion, ionization rate enhancement, breakdown of the Correspondence Principle), the foundations of statistical mechanics (getting random fluctuations without statistics, failure of the Green-Kubo relation, Lévy statistics), and nonlinear processing techniques applied to biomedical phenomena. He received the Decker Scholar Award (1993) and the UNT President's Award for research (1994). Prior to the university Dr. West was the Director, Division of Applied Nonlinear Science, La Jolla Institute, 1983-1989. During this period, he worked on the development of nonlinear dynamical models of biomedical phenomena, physical oceanography and the statistical mechanical foundations of thermodynamics. Specifically he helped developed ways to use renormalization group concepts to extract pattern information from biomedical time series. He was the Associate Director, Center for the Studies of Nonlinear Dynamics, La Jolla Institute, 1979-1983. He applied some of the newly emerging concepts in nonlinear dynamics systems theory to nonlinear water wave fields and turbulence. He also examined how the branching structure of the lung and other physiological structures could be described by scaling.

He has worked on the development of the fractional calculus for the modeling of complex phenomena and his book Physics of Fractal Operators (with Bologna and Grigolini, Springer, 2003) received the Army Research Laboratory Award for Publication in 2003. His recent research has also been in the area of modeling nonlinear networks and biomedical phenomena leading to 5 books the 3 most recent being Complex Webs: anticipating the improbable (with Grigolini, Cambridge University Press, 2011); Network of Echoes: Imitation, Innovation and Invisible Leaders (with Turalska & Grigolini, Springer, 2014); Fractional Calculus View of Complexity: Tomorrow's Science (CRC, 2015). He authored over 300 peer reviewed journal articles and 17 books garnering over 16,000 citations resulting in an h-factor of 61. Dr. West has held the position of Adjunct Professor of Physics at Duke University since 2000.

Dr. West was elected a Fellow of American Association for the Advancement of Science in 2012; and received the Presidential Meritorious Rank Award in 2012; Army Samuel S. Wilks Memorial Award 2011; Army Research and Development Achievement Award 2010; ARL Publication Award in 2003 & 2010; Professional of the Year in Applied Physical Science & Mathematics 2009 & 2011, Cambridge Who's Who; Chair 2010-12 Army ST Corps; Commander's Award for Civilian Service 2010; Founding Editor-in-Charge of Frontiers in Fractal Physiology 2010; Department of the Army Superior Civilian Service Award 2005; Fellow of the American Physical Society since 1992; past chair of the ARL Fellows; Member of the American Association for the Advancement of Science, American Geophysical Union, American Physiological Society and the American Physical Society.