Ted G. Lewis

Book of Extremes

Why the 21st Century Isn't Like the 20th Century

Springer

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California Central Coast: Courtesy of Jim White

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Preface

Even though the twenty-first century is still young, it is already marred by the dot-com crash, terrorism, financial system collapse, war, unsettling climate change, rise of new viruses—both animal and cyber—and an evolving socio-political shift caused by lightening speed advances in technology. Compared with the twentieth century, the first decade of the twenty-first century was as eventful and significant as the last 50 years of the previous century. Why?

We live in an age of rapid-fire change because over the past 200 years the comparatively straightforward Industrial Revolution has morphed into an era of nonlinear change punctuated with tipping points. The machinery of the current century is a collection of interconnected complex, rather than smooth-running, systems. Gradual and linear change no longer happens. Instead, "progress" moves in bursts—fits-and-starts marked by waves of unimaginable flashes, sparks, booms, bubbles, shocks, extremes, bombs, and leaps. Half probabilistic and half nonlinear deterministic, the twenty-first century is defined by intersecting long-tailed distributions, rather than independent and isolated Normal distributions. Episodic phenomena behave erratically and have no average or expected values.

Social, economic, physical, and cyber systems operate near their tipping points—perched on the edge of chaos, because they are optimized for maximum utility. Modern society has wringed out all surge capacity and backup reserves. After 60 years of stretching resources and budgets, governments have reached their limits. Traditional problem solving methods no longer work. Old ways of understanding our world no longer explain the current observed reality. Systems at all levels are out of bounds most of the time and increasingly collapse.

We need a new way to think about this new open, transparent, disruptive, and long-tailed world. We need tools for understanding the complexity of everyday things. Unfortunately, few of us understand complexity theory and nonlinear cause-and-effect, and even fewer of us are able to comprehend the implications of collapses, transformations, and revolutions currently taking place. Why did the global economy collapse? What are the principles underlying punctuated complexity? How can we begin to understand the nonlinear dynamics of global climate change, political upheaval, economic extremes, and the inevitable collapse and disaster confronting our society?

This sequel to Bak's Sand Pile, the author's earlier book, continues to explore society at its boundaries. From bursts of waves at the Asilomar Beach, to economic collapses, globalization of a tilted globe, and flashmobs precipitated by the Internet, Book of Extremes examines society's nonlinear outer limits.

Finding answers to these questions was the task I set for myself when I wrote *Bak's Sand Pile* in 2011. *Bak's Sand Pile* borrowed ideas from complexity theory, while this book applies nonlinear mathematics, catastrophe theory, big data, social network analysis, and biology to go a step further. This book proposes theories to explain extremes—why punctuated reality is bursty; why systems that have worked for decades suddenly fail; and why the wellbeing of entire nations is no longer in the hands of their leaders.

I begin with a gentle introduction to "wave theory"—the basis of punctuated reality. The theory explains social movements like the Arab Spring as well as online social media movements like Occupy Wall Street. Then I show how networks enhance nonlinear bursts—everything is connected to everything else—and hence a relatively small perturbation in one part of the space-time continuum ripples through the ether and impacts other parts. Unlikely events are made more likely by connected events. And connected events lead to conditional probabilities and the Bayesian theory underlying predictive analytics. [How we can forecast the future].

I have borrowed many ideas from biology and applied them to other fields such as economics. One of the most powerful ideas is the *Paradox of Enrichment*, which explains bubbles, shocks, and disruptions in financial markets. When combined with network science and nonlinear chaos theory, the unexpected crashes and disruptions in the global economy begin to make sense. For example, in Shocks, I show how comparative advantage leads to a highly interconnected global supply chain, which in turn determines the fortunes of entire nations.

Is reality completely random and unpredictable? Are we perched on the edge of disaster? Our understanding of mega-events such as the formation of social-political movements online leading to political instability in the Middle East, collapse of supply chains following the Fukushima nuclear disaster, global meltdown due to the 2008 financial crisis, impending ecological disasters from climate change, and plain old risk from terrorism and pandemics begins to crystallize as these mathematical concepts are placed in the context of social, political, and economic reality. This is perhaps the main contribution of this book—the application of rigorous methods to explain seemingly unexplainable events.

Book of Extremes is a work-in-progress, but it is a beginning.

March 2014 Ted G. Lewis

Contents

Waves

1

Abstract

Terrorist attacks, floods, nuclear power meltdowns, economic collapses, political disruptions and natural events like earthquakes come and go in waves—they are bursty. Why? The modern world differs from previous generations mainly due to vast network connections that replace independent random events with highly dependent conditional events. The 21st century is an age of lop-sided long-tailed probability distributions rather than the classical Normal distribution. Like episodic waves striking the beach, modern day events come and go in bursts—most are clustered together in time and space, but occasional bursts are separated in time, space, and consequence. This model of reality is called *punctuated reality*, because of the wave-like behavior of the complex systems found everywhere in modern life.

1.1 A Day at the Beach

Pacific Grove California is one of nature's most beautiful places. The world-renowned Monterey Bay Aquarium located at the end of David Avenue attracts millions of visitors to the jellyfish, seahorse, and sunfish exhibits. Down the street from the aquarium is Asilomar State Beach—a rustic wind-swept compound of Julia Morgan buildings where Silicon Valley mavens like Steve Jobs and Larry Ellison often met to decompress and rejuvenate the troops.

I trekked to the Asilomar beach on a sunny day in June to observe the waves as they crashed onto the rocky shore. Wave after wave crashed against a certain bolder I had picked out as a landmark. For the next 20 min I recorded the time intervals between subsequent waves using the timer on my *iPhone*. The first two waves were separated by 36 s; the next wave quickly arrived one second later; and the next two swept over the landmark bolder after a lapse of 11 and 14 s,

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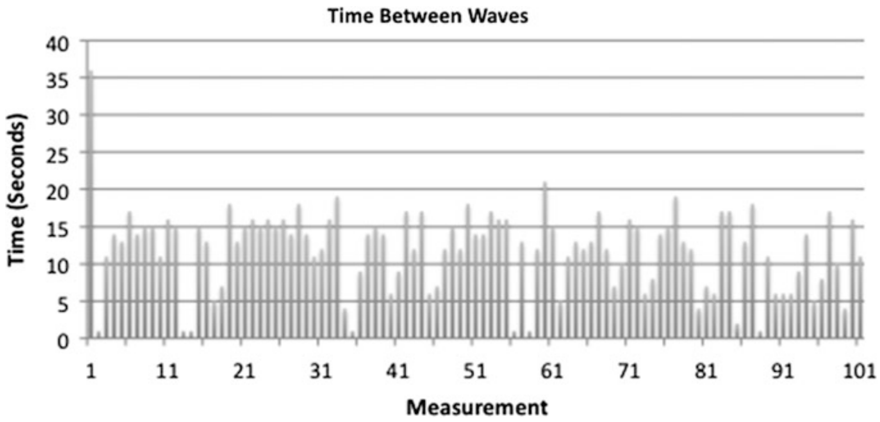

Fig. 1.1 Time intervals between waves appear to be random noise. Measurements were taken sequentially over a period of time

respectively. In 20 min I recorded over 100 time intervals on my notepad for analysis later on. Figure 1.1 shows my data—plotted as elapsed time *between waves* for the entire 20-min period. Notice any pattern?

I returned home and entered the time intervals into my computer and constructed the frequency plot shown in Fig. 1.2. The raw data in Fig. 1.1 looks like random noise but the processed data in Fig. 1.2 shows a distinct pattern. The distribution of time intervals plotted in Fig. 1.2 forms what is called a *long-tailed distribution*. When plotted as a histogram, the time intervals between waves no longer look like noise on a TV screen. Seemingly random wave motion turns out to be somewhat predictable.

If the pattern of wave action was truly random, its frequency distribution would form a symmetrical mound-shaped curve—a *Normal distribution*—with most measurements falling on either side of a representative value and others trailing off to either side. Random waves *should* form such a bell-shaped curve, so the long-tailed pattern came as a surprise. Even more surprising is the fact that long-tailed distributions like the one in Fig. 1.2 have no meaningful average value. While it is mathematically possible to calculate an average value and standard deviation from the data, neither value represents anything physically or practically meaningful, because long-tailed distributions extend to infinity. What is the average value over an infinite collection of points? That is, there is no such thing as an average wave interval! Every wave is considered an atypical *outlier*. [Wave intervals turn out to be an extreme valued statistic].

So, what does the lop-sided distribution tell us about waves? The distribution of Fig. 1.2 says that most waves reach the shore in closely timed intervals, while fewer and fewer waves washed ashore after relatively long lapses of time. Waves arrive in *bursts*—rather than rolling onto the shore in rhythmic patterns. Arrival times are irregular—almost chaotic—but with a distinct pattern as shown in Fig. 1.2. These simple Asilomar Beach waves contain a hidden order as revealed

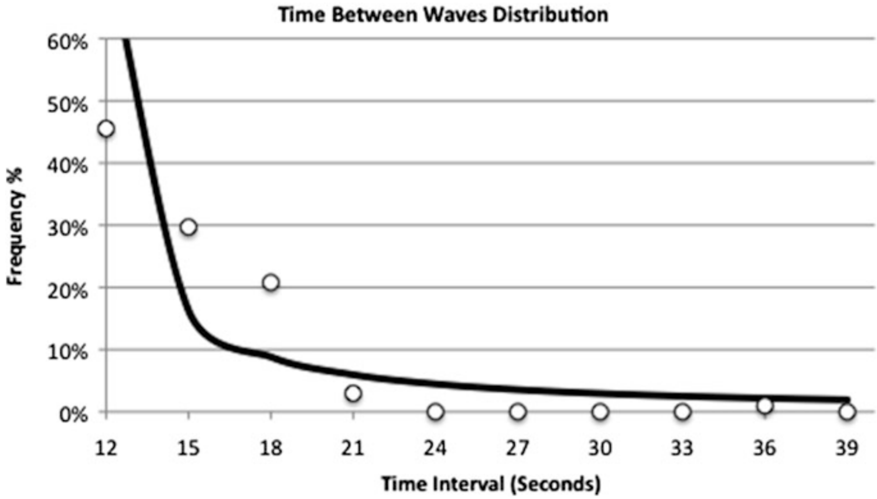

Fig. 1.2 Time intervals obey a long-tailed distribution. Dots are data points obtained from measurements in Fig. 1.1, and the solid line is a best-fit power law of the form, $f = t^{-q}$, where f is the frequency of elapsed times, t, and q is a constant that best-fits the data

by the long-tailed distribution. Waves are simple, and yet they are complex. They behave somewhat randomly, but also with some amount of predictability—specifically, we can expect them to be bursty or punctuated. Just when we think we know the pattern, it changes. Perhaps this is why waves mesmerize idle scientists with time to waste on Asilomar Beach.

I was unable to predict when the next wave would reach the bolder I had picked out as my landmark. Nor was I able to predict how big the wave would be. Bursts of incoming waves were followed by indefinite periods of inaction. Sometimes two or three crests arrived at nearly the same time. Other times, the sea was rather calm and tranquil. Instead of the smooth rhythmic motion I had come to expect from my high school science teacher (waves are caused by the rhythmic gravitational pull of the moon), I found that wave reality is rather *punctuated*. Even worse: it occurred to me that bursts and punctuations are metaphors for modernity.

Wave behavior is like many 21st century phenomenon—a combination of rhythmic and chaotic patterns. A systematic rhythm is established for a relatively long period of time only to be disrupted by an outlier—a miniature tsunami or longer-than-expected calmness. Sound familiar? Worldly events chug along at an orderly pace for months only to be disrupted by a burst of extreme events. For example, the Soviet Union collapses, setting into motion a series of social-political events that eventually die down. The world enjoyed a relatively peaceful and uneventful mid-to-late 1990s until the dotcom bubble burst, setting off another chain reaction of political and financial upsets. Fortunes are followed by reversal of fortunes. Bursts of political anxiety are followed by unusually tranquil periods of calm. And then the unexpected happens, without warning.

1.2 Life Has a Long Tail

Like the waves of change sweeping over our society as I write this book, nature is a combination of regular predictability and irregular unpredictability. But even nature's chaotic behaviors obey certain basic rules. In the case of ocean waves, the chaotic collisions between water and rock conceal a deeper pattern. The long-tail distribution of Fig. 1.2 models this combination of predictability and unpredictability—it is impossible to precisely predict the arrival time of the next wave, and yet the frequency of time intervals between subsequent waves isn't entirely erratic and unpredictable—it follows a well-defined distribution.

The predictable part of wave intervals is easy to understand. Most intervals are short, while only a few are long. The unpredictable part is more challenging. The precise number of seconds that pass between subsequent waves is somewhat random. Thus, wave intervals are both predictable and unpredictable. In the large, they obey a lop-sided long-tailed distribution as shown in Fig. 1.2, but in the small, it is impossible to predict exactly when the next wave will arrive.

Figure 1.2 was obtained from the raw data displayed in Fig. 1.1. However, instead of plotting the wave intervals sequentially, the frequency of intervals of equal size is plotted versus elapsed time interval. The horizontal axis of Fig. 1.2 is divided into bins of equal size and the number of wave intervals falling into each bin is tallied to obtain a histogram. Then, normalize the histogram by dividing each bin count by the total number of measurements. This process yields a frequency distribution as shown by the dots in Fig. 1.2.

The solid line shown in Fig. 1.2 is obtained by fitting a long-tailed power law to the binned data. As you can see, it is lop-sided—short wave intervals are more likely to occur than long intervals. Extremely long intervals are even more unlikely, although they are not too rare. This is the point: the distribution of elapsed time between wave intervals is biased. If it were not, an equal number of data points would fall on either side of an average value. Instead, to my surprise, most points fell on the left side of the frequency diagram. And, there is no average value separating short and long intervals.

Long-tailed distributions like the one shown in Fig. 1.2 indicate a degree of predictability even as there is an element of randomness. Short intervals are more likely than long intervals, and so a betting person would bet that the next wave interval is shorter, rather than longer. But, the wager is still a gamble, because an occasional long interval is still likely. Thus, Figs. 1.1 and 1.2 both contain an element of predictability as well as chance.

This is where my story begins: why is the modern world often governed by long-tailed distributions instead of the well-known Normal Distribution? Why do we observe so many events that are composed of both predictable and unpredictable elements? Is the world truly punctuated—a series of erratic bursts followed by relative calm? How can something as simple as tidal wave action be complex? And on a grander scale, how is it that society is both simple and complex at the same time?

As it turns out, this is the first clue to how the 21st century operates: both small and large events exhibit properties of predictability and unpredictability. Some things can be anticipated with regularity, while other things seem to defy comprehension. The real world is defined by long periods of time where nothing very important happens, followed by a rapid series of events close together in time and space. And typically, the unpredictable bursts matter a lot, because they change the world. This is called *punctuated reality*.

1.3 The Fractal Structure of Reality

Initially I was worried about how to measure the time-between-waves, because some waves were small while others were big. Should I sort out the intervals according to how large or small they were? As it turns out, it doesn't really matter, unless of course, the wave is a tsunami! [In that case, I should run!]. Big waves and small waves illustrate another fact of modern life called *scale*. If I had flown over the beach in an airplane, I would have been able to count only large waves. If I had gazed into the ocean from a mere 6 inches, I would have been able to count very small waves. The aerial view obscures the small waves, while the 6-inch close-up view obscures the big waves. Scaling does not seem to matter, however.

Scale is another property of the punctuated 21st century—both big and small events are subject to the same long-tailed fingerprint. Aerial and close-up wave-counting experiments both produce long-tailed distributions, but at different scales. We say that wave intervals *scale*, because whether I measure the intervals from near or far, both measurements produce a long-tail distribution. This curious fact is profound, because it says something about the similarity of earth-shaking events versus insignificant events—earth-shaking events are a lot like everyday small events—only bigger. It is a matter of scale.

Long-tailed distributions like the one in Fig. 1.2 are called *scalable*, or *self-similar*, because they are *fractals*. In simple terms, a fractal looks the same at all scales. Take a magnifying glass to a long-tailed distribution like the ones shown in this book, and you get another long-tailed distribution! They all look identical regardless of how near or far away they are observed. Ocean waves and many worldly events such as changes in stock market indexes look similar at different scales—that is, they exhibit self-similarity. The underlying patterns are the same regardless of how far or close we observe them.[1]

This is the second lesson of the 21st century that makes it different from the 20th and earlier centuries. Many more events in modern life obey fractal or self-similar distributions than ever before in history. [This is a big claim that will take the rest of this book to justify]. Big waves (tsunamis) are just like small waves (Asilomar Beach), in terms of frequency of time intervals. The time scale (or size scale) may change, but the underlying phenomenon is the same. Big events mimic small events,

[1] Changes in a stock price obey a long-tailed distribution and so do wave intervals.

and vice versa. For example, big events like the Arab Spring in Tunisia and Egypt in 2011 mimic self-similar small events like Occupy Wall Street, and the American Tea Party movement. Even small *flashmob* events that pass with little notice are fractals—disturbances operating at a relatively small scale. Similarly, protests in China occur at all scales, but when aggregated into a frequency distribution, they obey a long-tailed distribution just like the waves in my experiment.

> Fractal nature of nature: Observations made at different scales often belie the same underlying structural dynamics—punctuated, self-similar, and long-*tailed.*[2]

Some say that history repeats itself, but I say history obeys fractals. In many cases, the fractal is a long-tailed distribution like the ones shown in this book. Thus, large-scale hurricanes, terrorist attacks, nuclear power meltdowns, financial collapses, and earthquakes are simply scaled-up small hurricanes, attacks, nuclear power hazards, financial disruptions, and earth tremors. Incidents like these happen all the time, but most of them go unnoticed (fall on the left end of the long-tailed distribution), while a small number of rare-sized events blow up in our face (and fall on the right end of the long-tailed distribution). Instead of repeating itself, history repeats a self-similar pattern at different scales.

The dimension of self-similar events may differ, however. If the frequency distribution of worldly events fits a power law as shown in Fig. 1.2, the exponent in the power law represents the *fractal dimension* of the phenomenon. A large fractal dimension, q, means the distribution is very lop-sided and short-tailed. A small fractal dimension means the distribution is relatively flat and long-tailed. For example, the frequency of earthquakes obeys a long-tailed distribution with fractal dimension near 1.5.[3]

Long-tailed fractal distributions tell us a lot about small and big events in the course of people's lives. Principally, the lesson is this: change is constantly bubbling under the surface of day-to-day reality. Most bubbles are ordinary. But, on rare occasions change is so large and disruptive that it takes our breath away and fascinates entire nations for a long period of time. In fact, major changes such as the terrorist attacks of 9/11 not only get our attention, they foment a period of *chaotic adaptation* or adjustment to a "new world order". Then, after a while life returns to a smaller scale—the so-called "ordinary life".

What would life be like if we could take note of the small constantly bubbling punctuations or surges happening in everyday life? What if we consciously monitored the stock fluctuations of a favorite company, the political fluctuations of national politicians and their policies, or the economic fluctuations of businesses around the world? Would it be possible to anticipate and prepare for the big shocks? If we knew the significance of small events, might we be able to anticipate and even exploit the inevitable big surges? Is it possible to anticipate the future?

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[2] As I will show, the rules governing much of modernity are non-parametric, non-linear, scalable, conditional, and regulated largely by extreme statistics.

[3] Caneva and Smirnov (2004).

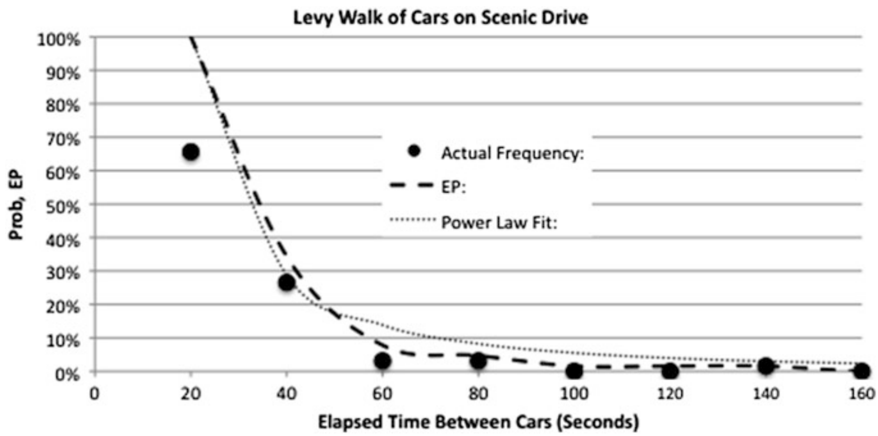

Fig. 1.3 Cars are like waves: they come and go in bursts. Actual counts turned into a frequency histogram are compared with the same data converted into an exceedance probability distribution along with its best-fit power law

1.4 Accidental Tourists

Ocean waves crashing against the rocks below me were not the only punctuated events happening while I was counting waves. Tourists driving their rental cars and riding their bicycles past my lookout point along Sunset Drive also fascinated me. So I turned my attention to counting the elapsed time between cars! Sure enough, cars passed by me in waves—sometimes in a cluster of 3 or 4 together, other times only one car at a time. In rare instances, the bursts were separated by relatively long intervals of time. But most of the time the elapsed time between cars was short. In fact, the distribution of time intervals were much like the long-tailed distributions shown in Fig. 1.2, see Fig. 1.3.

Figure 1.3 introduces a new measure of punctuated reality—the *exceedance probability distribution*. Like the frequency distributions of Fig. 1.2, the exceedance probability distribution of Fig. 1.3 is long-tailed. At each point along the horizontal axis, x, the exceedance probability, EP, represents the probability of an interval as big or bigger than x. For example, EP(40) is the probability that an interval of time equal to or greater than 40 s will occur. Think of EP as a worst-case measurement—it is the likelihood of intervals of size 40 or more seconds between cars passing by me as I count them.

Theoretically, the time separating random cars driving along any road should be a short-tailed distribution—a lop-sided mound called the *Poisson distribution*, which has an average time interval aligned with the mound's peak. If tourists really appear randomly out of thin air—as if by accident—the distribution of cars would not only look different than shown in Fig. 1.3, but it would have an average value just like the Normal distribution. But my measurements produced a distribution nearly identical to the one describing intermittent ocean waves. Surprisingly, the cars traveling along Sunset Drive are punctuated, too. They obey the same bursty rules of as the famous Asilomar beach waves.

Why? For one thing, tourists traveling along Pacific highways of California do not pop into sight purely by accident. They are influenced by forces beyond their control. Slower cars cause packs to form, an unscheduled deer-crossing or otter sighting can make a tourist pause, and local residents come and go at rather predictable times of the day. And then there is the occasional Butterfly Parade of costumed children that stops traffic for hours!

Accidental tourism isn't entirely accidental. Instead, people and events of historical note are like waves approaching the beach. They come and go in bursts. These are called *Levy walks* or *flights*—a term coined by Benoît Mandelbrot in honor of the French mathematician Paul Lévy (1886–1971). People, animals, and some contagious diseases move about the surface of the earth along paths that obey the long-tailed fractal shown in Fig. 1.3. That is, most displacements in space are close together, while a few are far apart. People, animals, and many events of great importance occur on the surface of the earth separated by distances distributed as a long-tailed curve.

Furthermore, Levy walks are characterized by long-tailed exceedance probabilities that model worst-case displacements. EP is a measure of extreme behavior—one of the observed properties emerging in the 21st century. We should replace the outmoded Normal distribution and its average value, with the non-parametric, lopsided, extreme-valued exceedance probability distribution, because it models reality better than the smooth, well-behaved Normal distribution.

1.5 Levy Walks

Is the shift from average to extreme-valued distributions an accident or is there a deeper meaning to these long-tailed phenomena? Are long-tailed fractals simply a mathematical trick that applies only to pathological cases like counting cars and waves?

As I sat next to the Pacific Ocean counting waves, my mind began working out an explanation for punctuated reality. Far across the Pacific, but not very far away in time, another wave had recently struck with deadly force. A tsunami created by an earthquake under the ocean northeast of the Japanese islands swept over the northeast coast of Japan, overwhelming the retaining wall protecting the nuclear reactor at Fukushima dai-ichi. [Reactor number one in Fukushima Prefecture]. A chain reaction that began in the Pacific Ocean propagated disaster through miles of Blue Ocean, seashore, retaining wall, and very thick cement walls into the heart of one of Japan's nuclear power plants. This was the immediate consequence of the Great *East Japan Earthquake* (also known as the *2011 Tohoku earthquake*).