Empirical Paradox, Complexity Thinking and Generating New Kinds of Knowledge

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By

Bruce J. West, Korosh Mahmoodi and Paolo Grigolini

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Preface

As scientists it is gratifying when a theory, with which we are associated, is shown to be consistent with newly obtained experimental data. This reaction to success fades into near insignificance, however, when it is compared with the response to an experimental result that contradicts a fundamental assumption of the same theory. The reaction to failure is much stronger than the reaction to success as any experimental psychologist will tell you. When confronted with such conflict any scientist worth his salt becomes strongly motivated to determine where the theory is deficient, or where the experiment did not measure what they thought it was measuring. This is the normal evolution of scientific knowledge and it ratchets upward due to a cultivated social desire, embraced by most scientists, to understand the why of the world, as well as, the way.

However, a scientist's strongest reaction occurs when the failure is doubled, which is to say when an empirical result not only contradicts a tenet of the theory, but is also at odds with other well established experimental data. Such conflicts do not occur very often, that is, one rarely finds results contradicting both a validated theory and standardized data, by reproducible experiments, but when they do, they invariably lead to fundamental insights. The insights are a consequence of the fact that such a double contradiction constitutes an *empirical paradox* and its resolution constitutes not only new knowledge, but quite often a new kind of knowledge.

For example, Charles Darwin was the first to identify the altruism paradox, which he subsequently resolved with a conjecture. His conjecture remained unproven for over a century and required the formation and maturation of the new discipline of sociobiology in order to satisfactorily resolve the controversy. A century earlier, a similar paradox was identified in an economic context by Adam Smith. We briefly discuss these and a half dozen or so other kinds of paradox that arise in organizations, in the bonds people form in social groups and some that are unique to the information age.

The working hypothesis of this essay is that empirical paradox is entailed by complexity. We choose the word entail with conscious intent to emphasize the notion that empirical paradox is necessitated by complexity and a system, or network, is truly complex only when it gives rise to paradox. Herein we use this as an operational definition of complexity and by so doing finesse the necessity of having to prove a hypothesis. For those reluctant to accept a hypothesis without proof let us suggest that it is evident that every empirical paradox emerges from a complex phenomenon, for if there is a paradox the system cannot be simple and is therefore complex. This is less formal than a hypothesis, but for our purposes it comes to the same thing in the end.

There are a number of examples of empirical paradox from physics, one being the transition of water to ice. The interactions of H_2O molecules in water are short range, that is, they are local interactions. However, the interactions of H_2O molecules in ice are long range, since the molecules form an interconnecting web. Any theory of phase transition must therefore contain these contradictory properties of how H_2O molecules interact in various phases. Kenneth Wilson was awarded the 1982 Noble Prize in Physics for the mathematical resolution of the empirical paradox of criticality and phase transitions in physical phenomena. As anticipated above, the mathematical theory he developed for its resolution led to a new way of understanding many-body behavior of physical processes independently of the detailed underlying dynamics. Central to this new way of knowing is *scaling* and *universality*, concepts that we use in this essay to understand all manner of empirical paradox in the physical, social and life sciences.

Although we subsequently introduce a mathematical model to guide our discussion for resolving empirical paradox, we gloss over the mathematical details, since these have been presented in the scientific literature. Our intent here is to interpret the mathematics in a way that makes the implication of the model accessible to the reader relying only weakly on their degree of mathematical literacy. It is however important to verify that this model exists and that its detailed dynamics do not matter, because it is the emergent properties that are of consequence and these we discuss at some length.

This essay contains the discursive content of the first complex dynamic model of empirical paradox and the clarity of the presentation will hopefully reduce the number of responses claiming: 1) that it is not even nonsense and should never have been published; 2) that it is not nonsense, but it is trivial; 3) it is brilliant, but I knew it years ago and never got around to publishing it.

Nomenclature

AP: altruism paradox
EP: empirical paradox
DMM: decision making model
EGM: evolutionary game model
EGT: evolutionary game theory
IPL: inverse power law
LFE: law of frequency of error
PDG: prisoner's dilemma game
PDF: probability density function
RTP: rapid transition process
SEM: selfishness model
SUM: success model
SOC: self-organized criticality
SOTC: self-organized temporal criticality
TLB: two-level brain

Chapter 1

Paradox is Fundamental

In this chapter we argue that the emergence of paradox is the opportunity to develop new knowledge and more often than not, a new kind of knowledge resulting from the resolution of the paradox. Typically, contradictions arise from applying existing understanding of a phenomenon about which new experimental data has become available and which contradicts the accepted interpretation of prior data. It is the contradiction that constitutes the paradox. The earlier data was interpreted in terms of simple models, but as the phenomenon becomes more complex (less simple), or its fundamental complexity became visible, using more refined experimental tools, the previous models lead to logical inconsistencies. In physics, the resolution of the paradoxical data indicating that light is both a wave and a particle, ushered in quantum mechanics and introduced a revolutionary way to understand physical reality. However, the discussion is not restricted to physical paradox, but includes visual paradox as well, allowing the reader ample opportunity to develop some intuitive feel for the fundamental role paradox plays in understanding the world in which we live.

1.1 Getting Oriented

> How wonderful that we have met with a paradox. Now we have some hope of making progress. – Bohr [41]

This essay is a collaboration among three very different authors and even though we are all physicists, we come from different cultures, from different parts of the world and ply our trade in very different ways. But an essay should speak with a single voice and not become bogged down in statements of over-qualification, with this being the experience of one, that being the opinion of the other, with the third having a slightly more nuanced view than the other two. For that reason we adopt the first person singular for nearly every expression of personal experience and hopefully present a coherent, more robust, personality than any of us possess individually, thereby blending our unique voices into one harmony. So with that caveat, let us begin our journey into the exploration of conflict, contradiction, paradox and the generation of new kinds of knowledge.

When I reached my late twenties, or early thirties, I found that the people I knew had more stamina, could run farther, climb faster, jump higher, were in all around better physical condition and were overall more physically capable than I was. The realization that I was probably less athletically capable than were my friends bothered me, so I began to actively investigate the phenomenon, but only decades later did I come up with some remarkable and totally unexpected conclusions. Not the least of which is that the world is filled with paradoxes and I had inadvertently stumbled into one called the *capability paradox*.

The capability paradox apparently arose from the fact that not only were my friends probably more athletically capable than I was, they were probably less athletically capable than were their friends, with me being the exception. This circumstance seemed to imply that everyone in a large group is probably less athletically capable than almost everyone else in the same large group. Therein lies the inconsistency that constitutes the paradox. How can almost everyone in a large group be less capable than almost everyone else within the same group?

This paradox is similar to the *friendship paradox*, or *happiness paradox*, both of which have been argued to be a consequence of the network structure of social media [43]. The friendship (or happiness) paradox asserts that within a social network most individuals have the experience of being less popular (happy) than their friends on average, leaving aside the fact that people are sometimes less than honest in their computer postings. The variability in the connectedness of individuals on social networks has been used to explain the counter intuitive nature of the paradox. We subsequently use statistical arguments to quantify this connectedness and hopefully develop an intuition for the kind of variability that can lead to this kind of contradiction. But before we posit any attempt to explain the cause of paradox, or at least before we develop a mathematical model to provide insight into paradox, let us examine the multiple ways paradox enters our lives and its inevitability in today's society.

Perhaps a more familiar form of paradox is a self-contradictory statement such as: *This sentence is false.* About which many articles have been written for both popular and scientific consumption. The logical paradox is a consequence of the breakdown of linear logical thinking in understanding what has been said. The disruption in the logical understanding of the statement arises because what is presumed true at the outset is contradicted by the end of reading the statement. Consequently, one must start again, with the opposite assumption about the statement's truth, but obtain the same contradictory result, thereby generating an endless cycle of change and contradiction. Suppose we assume the statement is true. We then read it and conclude that the statement is, in fact, false. But if we assume the statement is false then when we read it a second time we conclude the statement is true. This is the cycle, which arises from the logical necessity to change the truth value of the sentence with each reading.

In isolation the inability to assess the final truth of a given statement would be an exercise in logic. But the implications of such statements run much deeper. The sequential building of interdependent statements to construct a logical argument, which is the hallmark of linear logical thinking, is disrupted by the existence of such statements. If a statement of the above form is contained within a sequence of remarks, then it is not possible to go beyond the statement itself with any clarity regarding the truth of the sequence of interdependent statements. Therein lies the truth-value paradox. It is interesting, but the truth-value paradox in itself does not concern us here, although a number of its consequences are certainly of interest.

There are many different classes of paradox. A particularly devastating class is called *antinomy*, which according to the American philosopher and logician W.V. Quine, brings on a crises of thought [195]:

> An antinomy produces a self-contradiction by accepted ways of reasoning. It establishes that some tacit and trusted pattern of reasoning must be made explicit and henceforward be avoided or revised.

We mention this because many, otherwise educated, people view logical thinking as proceeding by an invariant set of rules, such as the syllogism, by which we reason about the world and that have been fixed since the time of Aristotle. Not only is this not true, but a belief in such a rigid system of reasoning prevents such people from developing the cognitive strategies necessary to understand the complex world in which we live. But even less extreme forms of paradox have resulted in the necessary abandoning of once accepted forms of reasoning, an example of which are Gödel's two incompleteness theorems.

You have probably heard of Gödel's proof and may even vaguely recall that it has had a profound effect on what mathematical theorems can and cannot be proven. At one time it was believed to be sufficient to prove that a line of reasoning, assuming the truth of a given theorem, which results in a paradox is a reduction to absurdity (*reductio ad absurdum*), and on its face is sufficient to establish the falsity of the theorem. On the one hand, in the 1920s the mathematician Hilbert championed the idea that all of mathematics could be derived from a finite set of axioms, like those of Euclid that we learned about in high school geometry. On the other hand, in the 1930s Gödel *proved* that one could not prove the truth of all possible statements made within a closed mathematical system, using only the axioms from within the system. Consequently, in a self-referential closed system one cannot prove the truth or falsity of a theorem, the truth value is not decidable.[1]

The incompleteness theorem of Gödel implies that scientists can never be absolutely certain concerning the truth of all the statements made in a closed mathematical system and therefore by extension they can never completely rely on the complete validity of any closed mathematical model of reality [201]. Consequently, the self-referential sentence (*This statement is false.*) is true only if false, and false only if true. Determining the truth of this sentence might give a reasonable person a headache; but then mathematicians can be very unreasonable. Fortunately scientists have experiments from which to determine, if not the truth, at least the consistency of a theorem with the behavior of the world. But experimental observation does not obviate the need for mathematical models of the phenomenon being investigated and therein lies the rub.

The point of this digression into mathematics and mathematical

[1] The results of Gödel's 1931 paper, "On Formally Undecidable Propositions of Principia Mathematica and Related Systems," can be summarized as follows:

> Any consistent axiomatic system of mathematics will contain theorems which cannot be proven.
>
> If all the theorems of an axiomatic system can be proven then the system is inconsistent, and thus has theorems which can be proven both true and false.

logic is to establish the historical precedent, as observed by Quine, that the identification of paradox has, on a number of occasions, entailed the reconstruction of the foundations of thought. This precedent regarding the reformulation of the static rules of thinking may then subsequently facilitate the reader's acceptance of a reformulation involving dynamic rules entailed by the kind of paradox that emerges in scientific theory. It is the latter that is the focus of this essay.

What does concern us is the form of paradox that arises in science when a phenomenon is explained by a theory attributing two or more mutually incompatible characteristics to a phenomenon and yet all the attributed properties are empirically observed. This natural, or empirical, paradox is of interest to us because nature has devised ways to resolve such conflicts, since they are part of objective reality. However when we attempt to reason about phenomenon containing empirical paradox we encounter logical inconsistencies, which we herein seek to resolve. Or as King Lear might have observed: *that way madness lies.*

1.1.1 Physical Paradox

> Every great and deep difficulty bears in itself its own solution. It forces us to change our thinking in order to find it. – Bohr [41]

Physicists, in their attempt to understand the physical world, build models of the phenomena they observe. They follow in the tradition of Isaac Newton, who introduced quantifiable mechanical forces in the form $F = ma$ into *Natural Philosophy* and thereby initiated its transformation into classical physics. His perspective tied the motion of the planets to that of apples falling from trees, all being one in the same through the force of gravity. For over a century the behavior of matter was determined by identifying the force and solving the resulting equations to predict the trajectory of a cannon ball, the speed of sound in air, the time of an eclipse, *etc.*.

On the scale we live our lives things seem to be deterministic and given sufficient information about the state of a material object at any one time enables its behavior to be predicted at any latter time.

Rudolf Clausius in an 1850 paper summarized centuries of physical experiments in the first two laws of thermodynamics. The First Law is that energy cannot be created or destroyed, but only changed in form. This is consistent with the mechanical forces of Newton and all the experiments based on his equations of motion. The Second Law, states that heat only flows from a hot body to a cold body. This one-way flow of heat is not consistent with the time reversibility of Newton's dynamic laws of matter and after 15 years of wrestling with this inconsistency Clausius introduced a new concept into physics, *entropy.* As pointed out by Haw [112], Clausius recognized that energy alone was insufficient to characterize processes involving work and heat, a second physical quantity, entropy, was required to accommodate the unidirectional flow of heat. The Second Law was then recast in the form of entropy remaining the same, or increasing, in any natural process.

But even with the introduction of entropy the Laws of Thermodynamics and those of Newton remain fundamentally incompatible. It is our contention that the resolution of such fundamental incompatibility leads to new ways of knowing and the resolution of physical paradox is no different. So what is the empirical paradox (EP) and what is the new physics that its resolution entails?

The predictable dynamic behavior of matter is a direct consequence of Newton's equations of motion, and consequently its properties are determined by Newton's laws. The equations have the property that if the direction of time is reversed the equations work just as well as they did for time flowing normally. A consequence of this property is that starting from an initial state the equations of motion predict a final state, such that if the direction of time is reversed once the final state is reached the resulting dynamics unwind the previous motion and the initial state is reformed. Both the forward and backward behavior are *predicted* by the equations of motion, so that the equations are reversible in time.

The one-way flow of heat in thermodynamics indicate that the equations of heat flow are not reversible in time. This is incompatible with Newton's force law and therefore constitutes a paradox, for how can a physical process be both time-reversible and time-irreversible simultaneously. This EP is based on two fundamental physical models of the world and we emphasize that over a century and half after this particular EP was identified it remains unresolved. But the search for its resolution and even the partial successes of that search have produced new ways of understanding the world.

Ludwig Boltzmann in a mathematical *tour de force* gave a comprehensive foundation to the kinetic theory of gases in an 1872 paper, deriving the statistical behavior of gas particles from the deterministic equations of Newtonian mechanics. Five years later he published a sequel in which he constructed a statistical interpretation of entropy, which enabled quantification of the entropy in terms of the total number of distinct ways the energy can be shared among the gas particles, thereby resolving the irreversibility paradox. This expression for the entropy is carved on his headstone as shown in Figure 1.1. Although Boltzmann's arguments turned out to be flawed with regard to resolving the time-reversal paradox, they did put statistics on a firm physical foundation and uncertainty became a physical aspect of the world in which we live.

A remarkably entertaining and scientifically accurate historical account of the forgotten science leading from the first mysterious indicators of statistics in complex phenomena to its acknowledged ubiquity in modern science is given by Mark Haw in his book *Middle World* [112]. That particular story started with the seventeen century Scottish botanist Robert Brown and his discovery of the erratic motion of particles in this middle world that in size is between atoms and animals. Brown was searching for the secret of life, which he at first thought he had observed with the unquenchable motion of pollen motes in water. But on carrying out multiple experiments on a variety of inanimate as well as animate particle in the three months of June, July and August of 1827, determined the motion had to do with particle size and not life. Haw goes on to trace

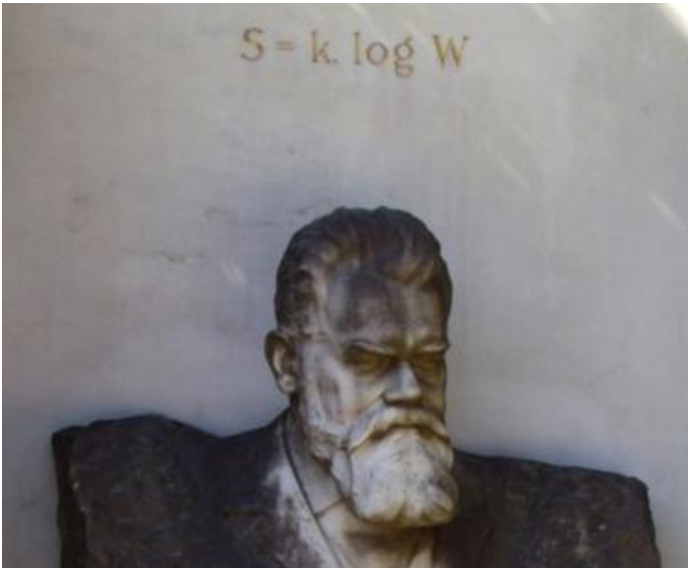

Figure 1.1: This is a bust of Ludwig Boltzmann (1844 -1906) with his equation expressing the relation, between entropy S and the number of microstates W available to the energy, carved into the stone above his head.

the twists and turns of scientific discovery, involving the giants of physics, what they saw and what they did not see, up to the present day statistical treatment of uncertainty.

Wave-particle duality: Physics encountered an equally unsatisfactory state of affairs at the turn of the twentieth century, when microscopic entities, quanta, were observed to have the particle property of spatial localization, as well as, the wave property of spatial extension. It was an established truth, at a time when the Industrial Revolution was shifting into high gear, that light consisted of waves, as verified by nearly two centuries of experimental measurements of interference, refraction and diffraction. Consequently, to say that the community of physical scientists was surprised by Einstein's 1905 paper explaining the photoelectric effect as being due to light being made up of a string of discrete quanta, is a gross understatement. The paper was, of course, properly couched in the language of Planck's quantum hypothesis, but it was only 17 years later that Einstein was awarded the Noble Prize in Physics for this remarkable work.

Note that the phrase quantum hypothesis constitutes a heuristic assumption without a theory. It is referred to as Planck's quantum hypothesis, because one of the towering figures in science at that time, Max Planck, had found it necessary to introduce the idea of energy occurring in discrete packets, called quanta, in order to explain another mystery in physics, that being black body radiation. This hypothesis had been published in 1900, again without an underlying physical theory. Planck was to be awarded the Noble Prize in Physics for his further development of the quantum hypothesis, just four years before Einstein received his. This earlier discussion need not concern us here. Suffice it to say that neither of these giants realized the full implications of what they had become partners in creating.

So what does this have to do with empirical paradox?

Recall that empirical paradox is the result of an observable phenomenon having at least two measurable properties that are logically inconsistent and the logic is the result of our theoretical understanding of the phenomenon. Our understanding of the nature of light constitutes such an EP. The beautiful separating of the colors in the sun's light into a rainbow is explained by the wave mechanism of refraction and the diffuse edge of your shadow on the ground is explained by the wave mechanism of diffraction. These are just two of the literally hundreds of examples of the manifestation of the wave properties of light. So it is firmly experimentally established that light is a wave and therefore has extension in space.

On the other hand, Einstein argued that an electron is ejected from a conductor by shining light on it, because light can be described by packets of energy, that is by quanta having energy given by the product of Planck's constant and the frequency of the light. The energy of the ejected election is an integer number of such quanta. This phenomenon is what enables today's solar panels to transform sunlight into electrical energy and the subsequent development of quantum theory is the foundation of Information Age technology. So it is firmly experimentally established that light is a particle (quantum) and is localized in space.

Can an entity be both extended and localized in space simultaneously? Spooky, eh?

Nature says yes it can be both through thousands of reproducible experiments. This was the EP facing the physicists of the early 20th century. They resolved the paradox by introducing an epistemological argument that came to be called *wave-particle duality* interpretation of quanta. This interpretation of quanta was developed, in the 1920s, by Werner Heisenberg and Niels Bohr, and was subsequently adopted by the majority of physical scientists as the Copenhagen Interpretation of quantum mechanics. In this view of quantum theory, quanta are thought to be neither particles nor waves until they are measured. The measuring process itself induces a collapse of a quanta into either the state characteristic of being a particle, or a state characteristic of being a wave. Prior to measurement a quanta is either both or neither, but the pre-measurement state is not knowable, since it cannot be accessed by experiment. This assumption of unknowability is a statement about the fundamental character of physical reality. The quantum paradox is resolved by maintaining an *either/or* dichotomy of that part of nature that is accessible by experiment, but it is *both/and* for that part of nature that is not experimentally accessible, for a physical scientist that is the best we can do. At least for the time being.

The quantum paradox has been the focus of often heated argument over the last century. The wave-particle duality, or quantum paradox resolution, is now so much a part of the culture of physical science that many students of physics think it is either quaint, or arcane, to discuss the matter seriously, being more metaphysics than physics. But this misses the larger point having to do with paradox in general, how we resolve EPs in the natural, social and life sciences and what that resolution entails.

1.1.2 Complexity

> We are all deeply conscious today that the enthusiasm of our forebears for the marvelous achievements of Newtonian mechanics led them to make generalizations in this area of predictability which, indeed, we may have generally tended to believe before 1960, but which we now recognize were false. We collectively wish to apologized for having misled the general educated public by spreading ideas about determinism of systems satisfying Newton's laws of motion that, after 1960, were to be proven incorrect. – Lighthill [140]

In the middle twentieth century a number of isolated individuals working alone, as opposed to the community of scientists as a whole, began to recognize that the tools of analysis available to them were not up to the job and began to study complexity itself as the focus of research. The concern was over understanding the patterns, order and structures that emerged from nonequilibrium systems having chaotic dynamics, as well as, those that shared matter and energy with their environment, while retaining a low entropy, and whose endogenous dynamics produce self-organized critical states.

Ekeland [78] summarizes one view of complexity in his book about time, mathematics and how they have been used in the formalization of the science of complexity for nearly half a millennium. The book is a discursive popularization of the way in which the simple mathematical laws describing the universe give rise to complexity. He begins with a detailed critique of Kepler's three laws of planetary motion emphasizing their approximate nature. The limits of quantitative methods (accurate but limited in scope) for determining planetary trajectories led the 19th century mathematical genius Poincaré to develop equally rigorous qualitative methods (greater range but less precision) to describe their behavior, thereby questioning the efficacy of prediction in science; commenting that all the perturbation calculations of trajectories, such as those of lunar orbits, are asymptotically divergent. Thus, the stage was set for the introduction of the unpredictable, weaving together order and chaos, leading to complexity and the 'butterfly effect'. This last phrase was the result of an off-hand remark made by Ed Lorenz that his results in meteorology implied that the flapping of a butterfly's wings in Brazil could stir up weather patterns that might ultimately result in a tornado in Texas.

We now step from the complexity of reversible microsystems to irreversible, dissipative macrosystems with the introduction of thermodynamic potentials to determine dynamics. We also introduce catastrophe theory to identify and categorize qualitative changes in a system's behavior, such as phase changes in physical systems and tipping points in social systems.

A very different view of complexity is presented by Morin [170] in a collection of essays on the various metaphysical, as well as, practical implications of complexity. He introduces the notion of blind intelligence, resulting from the simplification of complex phenomena to make them orderly and predictable. In his approach to understanding complex phenomena Morin emphasizes the necessity to transcend the limitations of linear logic to resolve paradox: "The modern pathology of mind is in the hyper-simplification that makes us blind to the complexity of reality." He goes on to attack the notion of *either/or* choices and discusses the formation of alternatives, again emphasizing that our logic-based mathematical models are ill-suited to handle true complexity, which are marred by uncertainty. Thus, he asserts that even more than self-organization, complexity involves self-creation and the paradox that such understanding entails, including the observer being part of what is being observed. He, more or less, ends with the notion of complex thinking; a process that is capable of unifying incompatible ideas by pragmatically affirming that nothing is isolated and everything is interrelated.

The overwhelming significance of complexity in the modern world was first systematically articulated by the mathematician Norbert Wiener in a work that introduced into science a new paradigm, *cybernetics*. In his book of the same name [265], Wiener sets the stage with a brief introduction to contemporary scientific luminaries that had contributed to the formation of this nascent science, capturing a new view of science and society after World War II. Cybernetics is concerned with how a quantity was being exchanged between humans and machines and how this quantity facilitated communication and could be used for control. This newly identified quantity was information and its measure is entropy, as hit upon by N. Wiener, R.A. Fisher and C. Shannon at essentially the same time, albeit for different purposes. Wiener discusses some concepts that have challenged the imagination of thinkers for millennia and others that they were only then becoming aware of; the irreversibility of time entailing uncertainty; the necessity for linear feedback loops for stability in physiological systems, homeostasis; ergodic theory and information, with the implied use of probability density functions (PDFs) to construct the entropy measure of information; the analogy between computing machines and the brain, at a time when the state of the art was the vacuum tube computer *Eniac*.

Wiener was not bashful about speculating concerning the potential utility of his new paradigm of science in areas for which he had no special training, but he had spent his life discussing these ideas with the finest minds in the world. He was convinced, and argued convincingly, that because of an area's scientific complexity, such as psychopathology, that the computing machine and the human brain have much in common and each could significantly benefit by study from a perspective focusing on their complexity. In retrospective I would say that this work [265] ushered in the modern world with the first version of complexity science (Version 0.1) and in so doing was prescient in anticipating our present day dependence on information.

Given the multiple definitions of complexity and the variety of phenomena that have been described as being complex, but bear no mechanism in common, we are going to adopt a strategy successfully employed by the physical/mathematics community half a century ago. In the middle of the last century it became clear that dynamic systems come in two forms, those that are linear and those that are not, and the richness of dynamic structures of the latter bear no resemblance to those of the former. Consequently, the community tacitly agreed to adopt the nomenclature of calling the latter system nonlinear and thereby to define its members by what they are not. This led some to criticize this as describing a "zoo of non-elephants", and in that they were accurate. However, it has turned out that this modest change in nomenclature has bee very useful. We therefore replace the term *complex* with the term *nonsimple* in the remainder of this essay, but in discussions that reference previously done work were the term complex was used we also use that term, in the hope of avoiding confusion.

1.1.3 Aristotelian Logic

> No, no, you're not thinking; you're just being logical. – Bohr [41]

We argue that complex (nonsimple) phenomena, by virtue of being nonsimple, entail paradox and in so doing, violates the two thousand year Western tradition of Aristotelian logic; the tradition being that a statement A and its negation $\overline{A}$ (not A) cannot be simultaneously true. Said the other way around, a simple system cannot contain contradictions, by definition, and is therefore free of paradox. Even the simplest example, such as the logical paradox given previously, has two poles that contradict one another. The fact that the truth of such a statement cannot be determined rules out the notion that such a statement is logically simple, which is part of the surprise, because its construction appears so uncomplicated.

In a nonsimple organization, consider the paradox of having both A and $\overline{A}$ within a common context. This could be viewed as the *Yin* and *Yang* of Taoism; the thesis and antithesis existing together as depicted in Figure 1.2. The combination of A and $\overline{A}$ existing together manifest a duality in opposition to one another, but they are also synergistic and interrelated within the larger system, as in the wave-particle duality of quantum phenomena. The resolution of the paradox that is implicit in Figure 1.2 requires abandoning the *either/or* - thinking of Aristotelian logic that implies A or $\overline{A}$, but not both together, to embrace the *both/and* - thinking of A and $\overline{A}$ together, achieved by balancing the tension of contradiction dynamically. This management of the tension of paradox, whether within individuals, groups or organizations produces flexibility and resilience, while fostering more dynamic decision making [211].

If our contention regarding the essential nature of paradox in nonsimple phenomena is true we would expect to see EP within every scientific discipline as the discipline matures over time. This is, in fact, what is observed. Empirical paradox has been observed in every scientific discipline, examples of which we discuss in some detail are the altruism paradox (AP) in macroevolutionary biology [68] and sociobiology [70, 268], organizational paradox in management [211], strategy paradox in economics [209], and we have already discussed wave-particle duality in physics. The result has been that the resolution of EP, which can be a subtle concept, whose nuanced definition shifts according to the discipline in which it is used, is discipline-specific and consequently often cannot be used to resolve EP within other disciplines. This implies that the mathematical models, designed around a specific mechanism, are often not generalizable to phenomena outside that discipline. We believe that this limitation has been overcome using network theory, as we subsequently explain. But for the time being we focus on the myriad ways paradox disrupts our simple mental pictures of people, society and the world in general and consequently how we are forced to think about them.

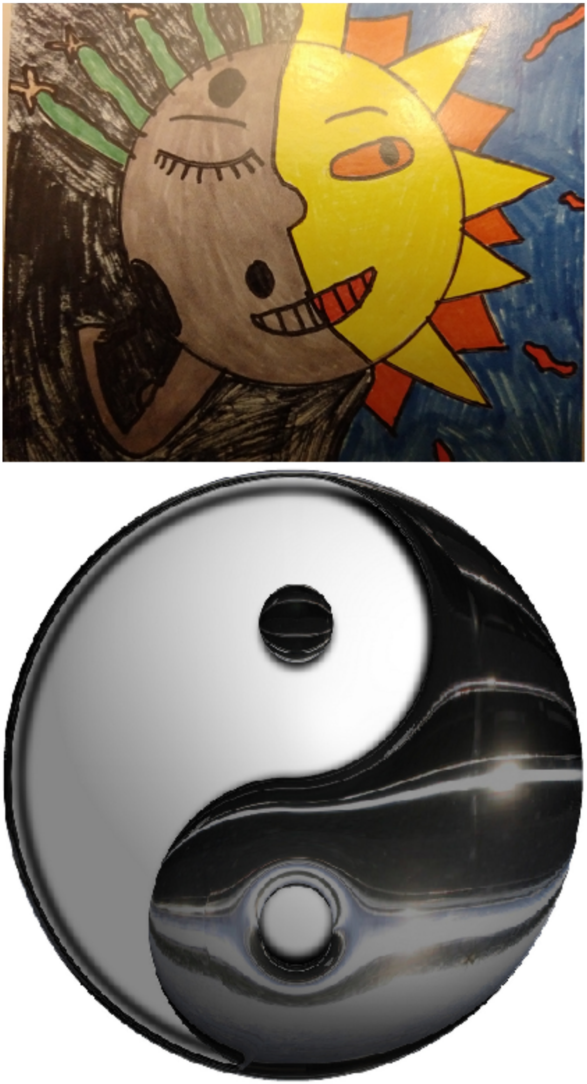

Figure 1.2: top: A nine year old's view of the world (Gabriel West, with permission). bottom: In Taoism the fusion of the two cosmic forces, the light and dark representing respectively Yin and Yang, each containing a 'seed' of the other. This becomes more than a metaphor for paradox when dynamics is properly taken into account. But perhaps with something less than cosmic forces.

1.2 Visual Paradox

> A visual paradox is when you look at something and you see something that can't exist or doesn't exist despite the fact you are looking at it. – Curfs [65]

Most of us believe that we see the world objectively, not distorted by our mental constructs or the way we think the world ought to be. But like most unexamined beliefs this turns out not to be true. The least complicated example of the dependence of what we see on what we believe, turns out to be an optical illusion, also known as an ambiguous figure, or for our purposes here, what we call a visual paradox. An artist who was a master of visual paradox was Escher [82], whose favorite image seemed to be that of a person walking down (up) a flight of stairs only to arrive at the floor above (below) him. After some analysis of the image the deceptive use of how objects occupy space that entails the visual contradiction is found, but the cognitive understanding does not completely quiet the discomfort. His etchings are often so filled with visual contradictions that like in Figure 1.3 only a section of one such print is displayed and this contains approximately half a dozen contradictions. I cannot be more precise as to the number, because what constitutes a contradiction depends on which way is up.

I remember how surprised and intrigued I was the first time I saw a visual paradox in a book I was reading. An image that matches my memory is given by the classical face-vase ambiguous image found in almost every college general psychology book. On first viewing the image one either 'sees' a vase or two faces peering at one another, but whichever registers on the brain first is not important, because that percept is not stable. That percept will not persist over time. Instead the percept, say it is the vase, is replaced by the other, the opposing faces, which is also not stable in time. This forms an unstable, or a multi-stable, perception in which the exchanging of percepts in the brain flickers like the lights in a disco club of the 1970s.