Decisions in the Face of Risk

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Abstract. The author of a popular book on risk and decision analysis made the statement that “The revolutionary idea that defines the boundary between modern times and the past is the mastery of risk: the notion that the future is more than a whim of the gods and that men and women are not passive before nature.” (Bernstein 1998, 1) While this book was written primarily from the perspective of economics and finances, the premise that the tools for making a reasoned prediction of the future, based on past experience and present decisions, goes to the heart of what it means to “do” systems engineering. This paper examines the nature of uncertainty, risk and decision analysis, particularly as understood within the historical context and the continuing development of the “art and science of decision.”

A Brief History of Risk and Decision

Risk – a Modern Phenomena. Like many of the manifestations of the modern era from modern medicine, to aircraft, and digital computers, risk, and especially the management thereof, is a relatively recent development of the contemporary pursuit of quantifying and controlling the natural world. And just like those other endeavours, involving numerous complexities with many layers of interactions that often generate emergent behaviour, some of which are unexpected, so “risk” is fraught with multifaceted uncertainties and challenges that have yet to submit to our most detailed models and prognostications. To understand the implications of divining risk today, it helps to understand the forces and perspectives which developed over many centuries that form the basis of the current mix for identifying and addressing risk and uncertainty.

Games of Chance and other Rational Decisions. From distant records of human pastimes, not directly related to survival and need, comes the revelation of our infatuation with gambling. The earliest form of gambling was a type of dice game. The die, called astragalus or knuckle-bone, were shaped from the ankle bones of sheep or deer, which are without marrow and thus so hard as to be nearly indestructible. Artefacts indicating the use of astragalus in games of chance can be found dispersed across time and geography from the Americas, to the ancient Babylonians, to Egyptian tomb paintings dating to 3500 B.C. (Bernstein, 13), and to the classical progenitors of the western world, the Greeks. On a coin minted in Athens during the sixth century B.C. is depicted a game of chance being played by young women using astragalus (Koerper 1999).

The Greeks even based their cosmogony on a celestial game of “craps” in which three brothers rolled the dice for the universe, with Zeus winning the heavens, Poseidon the seas, and Hades, the presumed loser, going to hell to rule the underworld (Bernstein 1998, 15). Despite the nearly universal interest in challenging the fates by pitting one’s supposed mastery of good fortune against whatever forces controlled the roll of the die and other games of chance, there was apparently a total lack of concern for describing, probing or understanding the potential results of any particular throw, which is a favourite pastime of any serious gaming aficionado today. While

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the games of chance have fundamentally changed very little down the ages, the desire to predict the outcome is a modern obsession. The question is, what has changed in the human psyche and understanding of the "chance event" over the intervening centuries?

Bernstein expresses some surprise, and perhaps disappointment, that the Greeks did not venture into an exploration of probability. At that time in history, the Greeks were one of the few civilizations in the world not dominated by a priestly cast that guided the lives of the faithful, and, also unusual for the time, they were endowed with an interest and skill in mathematics and logic. They seemed tailor made to delve into the wonders of "what could be" as defined by probabilities. This conundrum characterizes the study of the history of decision analysis and risk management. What seems so obvious today, but not then, perplexes us to the point that we struggle to understand why the great civilizations and their gifted thinkers did not traverse similar ground as our own. Is this merely the consequence of the twist and turns of fate that sometimes guides us down unseen and unanticipated paths, or was some other mechanism at work preventing the best of the ancient world from achieving the spectacular potential of the human race that we have experienced in just the last few hundred years?

We may never know the complete answer. Historians have observed that "At any time in the past, people have held a view of the way the universe works which was for them similarly definitive [as our own], whether it was based on myths or research." (Burke 1985, 9) As Burke goes on to describe in his fascinating study of tectonic shifts in worldview over time, every civilization has an "understanding" of how the universe works, which both defines their "age" and governs their behaviour and thought, and every age (including ours) has been convinced beyond doubt that "Unlike our ancestors, we know the truth." Thus far, however, every age has been supplanted by another that is similarly certain of their convictions, and there is no reason to think that our age is really any different from others in that regard, but we can only operate on the basis of what we have experienced as a civilization, and what is now "known" as a consequence.

Without judging the merits of past and current worldviews, Bernstein noted that "As Christianity spread across the western world, the will of a single God emerged as the orienting guide to the future... life on earth remained a mystery, but it was now prescribed by a power whose intentions and standards were clear to all who took the time to learn them." (Bernstein, 19) In the Greek worldview, "The Greeks believed that order is to be found only in the skies... But the perfection of the heavens served only to highlight the disarray of life on earth." (Bernstein, 17)

Of Chance Today and Tomorrow. Something more, beyond the essential philosophy, belief and attitude of today, is needed, however, in order for the human mind to even conceive of the vagaries of tomorrow as something more than mere fate. There is one seemingly insignificant thing that distinguishes the world of today from those of the past, something that is so ubiquitous, common, and yet essential to the very existence of nearly all that we do, that it is difficult to realize how novel and original it is in all the history of the world. That one thing is numbers.

We are a world immersed in numbers and engrossed with counting. There is apparently nothing to which we will not attach a number, extending from the beauty of a woman, up to and perhaps beyond the stars in the heavens. With such an outlook, even tomorrow must have a number, and the future is not a mystery as much as it is just another turn of the clockwork. But the process of arriving at such a vantage was hardly direct and took many centuries of exploration every bit as filled with adventure and hazard as the first tentative voyages into the open oceans to find new worlds and discover great riches.

The story of numbers in the West, leading to our modern understanding of information and quantification, finds a likely origin nearly a millennia ago in 1202 with the publication of the *Book of the Abacus* or *Liber Abaci* by Leonardo Pisano in Italy. Today, Leonardo is known as Fibonacci who included the short passage in his book that led to a mathematical wonder we still delight in to this day. The passage describes the breeding of rabbits which led to the generation of the Fibonacci series. At the heart of the series is a proportion equal to 1.618, known as the "golden mean" that is found when dividing any number above 144 by its preceding number. This number was known by the ancient Greeks and can be found in the proportions of the Parthenon. Today it is applied in art, architecture, commodity items like playing cards, and credit cards. Perhaps most intriguing, the number is found throughout nature in the proportion of various appendages of plants and animals including the digits on our own hands. (Bernstein, 26) Could there be any more convincing affirmation of our own use of numbers than to find such a pleasing proportion embedded in the very fabric of our existence?

However, in all of recorded history, such a delightful realization was not even possible anywhere prior to about 500 A.D. when the Hindus developed the numbering system we use today (Bernstein, 31). Prior to this invention, numbering systems of any sophistication were always based on the letters of alphabets; however, because such systems do not have a "base" from which all other numbers are derived, calculations are essentially impossible.

There was something the Hindu system possessed, however, that was even more significant than the ability to do calculation and which no other system in recorded history contained. This was the lowly value of "zero." This situation forces a certain cognitive dissonance in the modern mind when trying to contemplate the nature of societies that did not possess the concept of zero or even useful methods of performing complex calculations. While a numbering system that does not include "zero" is virtually inconceivable to us, the concept of possessing zero of "something" would be as equally difficult for a person to grasp that only dealt with "the number of animals killed or the number of days passed, or the number of units travelled." (Bernstein, 32)

The number "zero" is only of value in abstract concepts of accounting, mathematics and the construction of numbering systems with bases for the purpose of calculation. As soon as the West had both a philosophical as well as a practical basis for calculation and accounting, the potential for forecasting was present, but the realization of that potential required many more centuries of gradual growth in awareness and understanding in order to grasp what the new capability enabled.

From a strictly methodological perspective, until there was a numbering system that permitted abstractions and "free-form" associations with temporal events as well as enabling a myriad of calculations and formulations, there could not be any basis for making analytic predictions of the future. However, it is not enough to simply have the means of performing an operation; there must also be the understanding and epistemology of what all the elements of the operation are for, how to use them, and what the results represent. It would be like giving a rifle to an isolated people that only used spears. They would have no context or knowledge of how to use the rifle, or even what it was for. If they attempted to use it within their own context as a spear it would be poorly suited for that purpose and rightly discarded as defective. In the same manner, an understanding of what the new "numbering" tool could do had to develop over a period of time involving experimentation and exploration.

The Power of Counting. It would be more than two hundred years after the publication of the *Book of the Abacus* in 1202 before the next really interesting development would occur in the field of counting and forecasting. In that time, there was a gradual growth in the insight of the use of the Hindu numbering system, but, oddly enough, the real power of numbers could not be exploited until printing became widely available. Not because, as you might expect, printing eased communication and recording, which it did, but because, the new numbering system could not be trusted until printing became widespread. It turns out that in a world based on script writing that the Hindu numerals could be readily modified by a deft hand, turning a 0 into a 6 or 9, 1 into 4, 6, 7 or 9, and a 0 added to the end of any number. (Bernstein, 35) As with numbers before printing, risk represents a measure of how much "trust" one can place in the measure of what is likely to happen – the greater the doubt and the more significant the consequence of making a wrong decision the higher the risk.

With the invention of print in the mid-fifteenth century, the use of the new numbering system was fully accepted, which coincided with another momentous development in history, the Renaissance. As is evident, especially in the art of that period, the people depicted were real people existing in a real space and environs. No longer, as in the Greek cosmology, was the earth a place of disarray and the heavens a place of order and perfection. The Greek world view was turned on its head; now the heavens were the abode of mystery, while the earth and anything it contained could be measured, located and placed in its proportionate and appropriate relationship to all the surrounding elements in space and time.

It was during this period that a most interesting and seemingly innocuous puzzle was posed by a leading mathematician of that day. Luca Paccioli, a Franciscan monk, in 1494 in his *Summa de arithmetic*, wrote "A and B are playing a fair game of *balla* (a popular game of chance). They agree to continue until one has won six rounds. The game actually stops when A has won five and B three. How should the stakes be divided?" (Bernstein, 43) What is significant about this problem is that Paccioli is not asking how to take a fraction of something and divide it but rather: "Based on what has already happened, what is our confidence in deciding what would likely happen if the game had been played to completion?"

From this point onward people began in earnest to investigate the structured analysis of probability, and the eventual quantification of risk that we pursue to this day. According to Bernstein, this is the first occurrence, at least in recorded history, of a question being posed regarding the likelihood of outcome for a game of chance.

The rule of chance, law and decision. The next step in the journey occurred in 1545 with the publication of *Ars Magna* (The Great Art) by Girolamo Gardano, who was a mathematician, an inveterate gambler and Europe's most renowned physician – called on by both Popes and royalty to relieve their ailments.

Algebra was just being developed and Gardano's contribution was the introduction of the now familiar notations "a, b, c" for variables. He also originated the use of the fraction to express probabilities or, as he called the proportion of likely events in dice throws, "the chances." The fractions Cardano used to describe the various possible outcomes of any aeliotory process would comprise "the circuit" for that process, and collectively they would always add to the whole non-zero number: "1." Cardano may well have been the first to attempt to describe and quantify the expected results of single and multiple throws of dice. (Bernstein, 45-53)

The last Italian to wrestle with probability during this period was Galileo who wrote a treatise in 1623 summarizing the discoveries to date of the concepts of probability. He considered the principles as being well enough understood and established that any decent mathematician of the day could grasp and emulate his calculations. However, it had only been a few years earlier, in 1619, that a Puritan minister, Thomas Gataker, had argued in print that natural law, not divine law, determined the outcome of games of chance. (Bernstein, 55)

The concept that even “chance” obeyed clear patterns of behaviour, governed by physical parameters and circumstances, was just being codified in the early 1600s, but by the close of that century all the major problems of probability had been resolved due primarily to the work of two very clever Frenchmen who solved Paccioli’s dilemma over how to split the winnings in a prematurely terminated game of *balla*.

When more things *can* happen then *will*, the Frenchmen Pascal and Fermat, were the first to develop a systematic method for determining what is *likely* to happen. Not only did their method work for *balla*, but for any process involving two options whose outcome were the result of independent and random events of like kind, such as the gender frequency of children in a family, or even who would likely win a baseball world series based on the games already played in the series (assuming evenly matched teams). Together they determined that the coefficients in the expansion of the binomial series, i.e. $(a + b)^n$ where “n” is the number of trials, for different values of “n,” form what is now called Pascal’s triangle, useful for describing probable outcomes.

Pascal is also well known for his Pascal’s Wager regarding belief in God that is framed in terms of a game of chance. Ian Hacking asserted that the Wager marks the beginning of decision-theory, which Hacking defines as “the theory of deciding what to do when it is uncertain what will happen.” (Hacking 1975, 62)

In 1662, Pascal’s associates at the Port-Royal monastery, which Pascal entered after solving the riddle of “the chances,” wrote an important treatise in the annals of decision making, called *Logic, or the art of Thinking*. The author said: “Fear of harm ought to be proportional not only to the gravity of the harm, but also to the probability of the event.” (Bernstein, 71) This work is the first recorded use of the term “probability” in the modern sense. This is also the start of a decision analysis method that is still being applied to this day, known as “utility.” That is, one’s reaction to the occurrence of an event should be in proportion not just to the seriousness of the outcome, but also to the likelihood of occurrence. With this formulation the seemingly unquantifiable variable, “risk,” was on the verge of becoming a useful reality.

It is somewhat surprising that such an apparently basic concept, at least to us, should have been expressed so late in history, being a mere three and a half centuries ago. This shows how quickly our culture has adapted to the concepts of probabilities and risk management to the point that today we apply this basic premise on a daily basis without even realizing it when we drive to work each day in a “box” that could easily be our “coffin,” or we willingly climb into a jet aircraft to streak hundreds or thousands of miles in a “missile” that would have dire consequences for us personally if it were to “plummet out of the sky.” Thus we are constantly evaluating “utility” by balancing probability of occurrence with consequence, and judging the risk of our actions relative to the potential benefit to arrive at an estimated valuation of the outcome of chance events to our overall wellbeing.

The past is the key to the future. Risk, which is the probability of making the wrong decision, and uncertainty, which occurs when the probabilities are unknown, are ever present, because the future is, after all, just a bit murky. There is some hope, however, of seeing dimly past the impenetrable veil between the present and the next moment, if we assume there is some continuity, a vector, originating in the just concluded past, proceeding through the momentary present, and leaping into the undefined future. Risk management and decision analysis is highly, almost wholly dependent on being able to discern the outlines and direction of that temporal arrow. Pascal and Fermat took a giant's step in defining the basic shape of that vector, just as it begins to prick the barrier between the present and the future, and others would soon see more clearly the extent of that vector and widen the conduit from the past to the ever queried future. The objective is the management of risk, which is the manner in which people recognize and respond to the probabilities of the possible.

There is the old saw: "In God we trust, all others bring data." Probabilities live or die on the data. Predicting what has not yet happened can be a bit disconcerting, but information about what is already past can make all the difference in understanding what could happen, especially if what is occurring turns out to be independent, random events. In such a case, the past is a reliable guide to the future under the right conditions. One Jacob Bernoulli, in *Ars Conjectandi* (The Art of Conjecture) which was published posthumously in 1713, discovered that if the sample size is large enough one could begin to speak quasi-definitively of the whole.

The Law of Large Numbers, as his rule is now known, though useful is not foolproof. It merely says that the average of a large number of independent, random events will be more likely than the average of a small number of the same independent, random events to differ from the true average of *all* the independent, random events by less than some stated amount. This is why there is still risk in making a decision, even with "tons" of prior data; there are simply no guarantees of outcome, even when the events are truly independent and random. For these situations, Jacob applied the term "moral certainty" meaning certainty as a practical matter rather than an absolute certainty. (Bernstein, 118-123)

But from these humble beginnings, starting with Pascal in 1662, the management of risk progressed steadily, as with the realization by Daniel Bernoulli in 1738 that the "… utility resulting from any small increase in wealth will be inversely proportionate to the quantity of goods previously possessed." (Bernstein, 105) Thus began the demarcation that, while "the facts" are the same for all, the perception of what those facts *mean* is the result of a very individual process. Therefore, while we all willingly get into our cars to go to work each morning, some will drive slow, some fast, some tailgate, others look in all directions before proceeding, and still others will even finish their morning dress while barreling down the road apparently oblivious to the consternation they elicit in their fellow drivers.

This presupposition of "utility" was further refined by Daniel's uncle Jacob, who was cited earlier, in which Jacob made the valuable realization that life does not exhibit the same inexorable characteristics of games of chance. As the Bernstein so aptly put it "Reality is a series of connected events, each dependent on another, radically different from games of chance in which the outcome of any single throw has zero influence on the outcome of the next throw." (Bernstein, 121) Jacob realized that probabilities are not fixed for the events of life and therefore risk cannot be managed completely *a priori*, that is before an event occurs, and that probabilities for life events can only be estimated from what happened after the fact or *a posteriori*. This understanding leads to a need for experimentation, or at least observation, with the potential for changing degrees of belief. Thus, not unexpectedly, we discover that life has a strong component of contingency leading naturally to uncertainty in which the probabilities are not known and are perhaps unknowable under some circumstances.

Despite these difficulties there are still a few worthwhile observations that grew out of this "classical" period of probability analysis and risk management that have proved themselves to be invaluable aids to this very day, in part because they are easily grasped and generally applicable to relatively large samples. The first was the observation by De Moivre in the early 1700s that large samples of independent elements would distribute themselves around a mean in a symmetrical pattern that has become known as a "normal" distribution or the "bell curve" due to its striking resemblance to the outlines of an ordinary bell. So many natural and man-made phenomena distribute themselves in this beautiful set, and the mathematics describing the pattern are so tractably elegant that there is a tendency to apply this distribution to situations that only approximate this behavior. The curve has found an impregnable application in the manufacturing world where customers have come to expect an unerring uniformity of performance and finish for products with little deviation from the "norm."

Closely aligned with these insights of the early 18th century was a most ingenious development by one Thomas Bayes whose essay describing his system was published posthumously by the Royal Society in 1764, though it languished for some twenty years after that without much notice. The advantage of Bayes formulation is the inference that can be made about a population based on samples from that population. The primary use of the Bayesian system is in using new information to revise probabilities that are based on old information. This was the first occurrence of measuring uncertainty, which constitutes unknown probabilities, essentially inferring unknown probabilities from empirical data gathered from real world events.

Another useful characteristic of normal distributions was described by Laplace in 1809 that is known as the "central limit theorem" that says the average of averages will reduce the dispersion around the overall average. It is interesting to note that the central limit theorem holds even for sample sets that do not exhibit a pure normal distribution, such that a large grouping of non-normal sample sets will resemble a normal distribution the more sets that are included in the calculation.

The underlying criteria for observations that distribute themselves in a "bell curve" is independence of both the elements and the observations, however, many processes in which observations and events are dependent in time in which one event is affected by a preceding event, such as stock prices, can eventually resemble a normal distribution if the chain of dependence can be disrupted often enough during the sample period. With respect to stock prices, information affecting stock valuations often occurs randomly, so over a large enough period of time, the price of a given stock will resemble a normal distribution.

Another characteristic that many systems exhibit over time is "regression to the mean," first described and quantified in some detail by Francis Galton who studied population distributions and published a paper on the topic in 1877 title "Typical Laws of Heredity." Galton observed that systems may tend to "stray" from the norm for some period of time, but there are usually forces at work that bring the trend back toward the overall average. In nature, this phenomenon explains why the human race is not producing ever taller, smaller, fatter, thinner or other characteristics in humans that would otherwise make the grotesque, common. In human affairs it explains why the stock market experiences "corrections" that eventually makes losers of winners and winners of losers.

The Victorian Hope – the End of Risk. There was a time not so long ago during the Victorian era when many thought that if sufficient measurements could be made of various phenomena then, in the aggregate, nearly all risk and uncertainty could be eliminated and controlled. Others had great expectations of taking the reins of human progression and directing them into favored paths. It is likely, in fact, that you are already familiar, in one form or another, with the work and objectives of Francis Galton. Some may even know that Galton was the grandson of one Erasmus Darwin whose more famous grandson is known to every educated person in the world as none other than Charles Darwin.

Galton built upon the work of predecessors such as Bernoulli, De Moivre and others. He was fascinated with the powers for categorizing random events that the normal distribution afforded. It was apparent to Galton that the message of the bell curve is that certain data belonged together and could be analyzed as a relatively homogenous unit. Conversely, the opposite was also significant, that is, the absence of the normal distribution would suggest "dissimilar systems."

Galton was onto something. Unlike his progenitors in the field of probability and risk analysis, he was not looking for the common thread that linked past, present and future, but those characteristics of systems that identified them as distinct from one another. He built upon the work of a Belgian scientist named Lambert Quetelet, who was twenty years older than Galton, an inveterate investigator of social conditions, and as obsessed with measurement as was Galton.

Quetelet was "an entrepreneur of science as well as a scientist." (Bernstein, 158) He was involved in founding several statistical associations including the Royal Statistical Society of London and the International Statistical Congress, and helped to establish a new astronomical observatory in Belgium. For our study his most significant work was the result of his interest in the French census of 1829. Quetelet was fascinated with the variations that existed within and between the various population groups within France, and was driven to know if the differences were random, in which case different samples taken from each group would look very much the same, or fundamentally systematic, which would result in the distributions of samples being drawn from diverse groups possessing intrinsic differences. His goal set Quetelet off on a measurement orgy in which "He examined birth and death rates by month and city, by temperature, and by time of day… He investigated mortality by age, by profession, by locality, by season, in prisons, and in hospitals. He considered … statistics on drunkenness, insanity, suicides, and crime." (Bernstein, 159)

From the mountainous data, he published the results of his examinations in *A Treatise on Man and the Development of His Faculties* in 1835. His work was more than just a dry tome of numbers and statistics, however. Perhaps unique in the annals of probability and statistics his worked actually captured the imagination and interest of the general populace due primarily to his clever invention of a popular protagonist that he called *l'homme moyen* or "the average man." For each group that Quetelet sought to describe, whether criminals, drunks, soldiers, dead people and others, he presented the "average man" (or woman) as the designated representative. While his work is epochal in social analysis and has served as a model for other such works, it was not without its detractors.

Quetelet saw bell curves everywhere he looked, and developed his observations into concepts of cause and effect that he captured in a book on the application of probability to the "moral and political sciences," which he published in 1836. However, some questioned whether Quetelet was "reading" more into the data than was justified. One of his harshest critics was Antoine-Augustin Cournot, a famous mathematician and economist, as well as an authority on probability. Cournot maintained that unless we observe the rules of probability "we cannot get a clear idea of the precision of measurements made in the sciences of observation … or of the conditions leading to the success of commercial enterprises." (Bernstein, 159) Cournot ridiculed the concept of the "average man," insisting that the totally average individual would be nothing less than a monstrosity, explaining nothing and arising from no cause.

Into this heady milieu of infatuation with the power of social statistics, Francis Galton sought to explain the superiority of the favored classes with the hope of realizing the Victorian dream of social positivism. His method was to classify people by "natural ability," that embodied "… those qualities of intellect and disposition, which urge and qualify a man to perform acts that lead to reputation… I mean a nature which, when left to itself, will, urged by an inherent stimulus, climb the path that leads to eminence, and has strength to reach the summit." (Bernstein, 163)

Galton gathered voluminous masses of data from 1866 through 1869 to prove that talent and eminence are hereditary attributes, and which he summarized in his most important work, *Hereditary Genius*. Galton wanted to prove that hereditary alone was the source of special talents, but he arrived at "the undeniable, but unexpected conclusion, that eminently gifted men are raised as much above mediocrity as idiots are depressed below it." (Bernstein, 163) Galton discovered that eminence does not last long, falling to little over a third for male offspring of men of "reputation," and to as little as 9% of their grandchildren, though Galton attempted to explain their precipitous decline to the habit of prominent patriarchs marrying rich, though apparently fatuous, heiresses.

Charles Darwin told his cousin, after reading *Hereditary Genius*, "I do not think I ever in my life read anything more interesting and original… a memorable work." (Bernstein, 164) Darwin encouraged Galton to continue his hereditary research, but Francis was already in hot pursuit of the now discredited field of eugenics. Despite the misuse of Galton's research, an egregious misapplication of probability and decision theory, during the 20th century by some dictators, most notably Hitler, and even prominent scientists and leaders in a few democratic countries, his studies resulted in an extraordinary discovery that influences most of the decisions, both small and large, that we make to this day.

Though developed using various lines of evidence, an experiment that Galton devised in 1875, which Darwin originally proposed, involved examining the hereditary characteristics of sweet peas. To make a long story short, the result of this experiment led Galton to propose a general principle that has become known as regression or reversion to the mean, which he describes as "Reversion is the tendency of the ideal mean filial type to depart from the parental type, reverting to what may be roughly and perhaps fairly described as the average ancestral type." (Bernstein, 167)

With such devotion to the data and persistence in understanding what the numbers revealed, the Victorian world nearly succeeded in achieving their objective of eliminating risk as a driving force in human affairs. But reality was not to be so easily cowed, as confirmed in the last century by two world wars, various market crashes, pandemics and other disasters which have disabused that notion and forever terminated the nearly utopian dreams of the Victorians. In the modern era, the slide from an assurance of a knowable and controllable future has encountered an even more powerful force that will forever entrench risk and uncertainty as elements that must be addressed in decision analysis. That force is the human psyche driven by our natures as limited, temporal, and perhaps fundamentally irrational creatures who will never know all that there is to know.

The Nature of Decisions and the Future

Irrationally consistent. During the "classical" phase of risk management, best defined by the Victorians, there was a pervasive conviction of the underlying rationality of human decision making. In the last century there has been a growing realization that humans do not consistently make decisions strictly on the basis of utility and what should rationally be in their own best interest. Several studies have revealed some interesting aspects of how we use available information and what motivations lie behind the decisions we make. In general, our decisions are not strictly rational, but they may well be consistent.

This realization is significant for Systems Engineering on several levels. Not only does human bias impact the decisions made by stakeholders, systems engineers are equally subject to the same irrational, subjective biases as anyone else. In fact, there may be an even greater "danger" of making biased decisions by the engineering community compared with other decision makers, because we like to think that our approach to problems and solutions is not only practical and rational, but thoroughly based "on the facts," a condition that could induce susceptibility to the "Victorian disease" of being "certain" about the unknowable future. As decision makers, and those who offer advice to decision makers, it is crucial for system engineers to retain an "open mind" and seek the expertise, opinions, knowledge, experience and wisdom of a diverse constituency.

One of the most useful insights into the human decision process was provided by Prospect Theory. The basic discovery is that people will reject a fair gamble in favor of a certain gain. On the surface this has the characteristics of being risk averse; however, further insight is gained when losses are also considered. Generally, the choices we make between negative outcomes are mirror images of our choices between positive outcomes, that is, when it comes to losses we are risk seekers. In other words people generally will accept a gamble and reject a certain loss, even if the potential loss is greater than what would otherwise be certain. When viewed in totality, the conclusion is that most people are "loss averse." It is not that people hate uncertainty as much as they hate to lose. One outcome of this characteristic is an often perverse tendency to cling to mistakes rather than "cutting our losses" and moving on.

Another great insight is that in general most people will compartmentalize what would otherwise be better addressed as a totality. We are great at looking at the parts of a situation and even divvying them up into separate mental accounts, but we have trouble "integrating" across all those compartments to see the bigger picture. The hazard of course is that we can sub-optimize particular conditions or accept unnecessary losses because of the inability to see how decisions on the sub-scale level will affect the overall situation.

We are also subject to numerous biases with little awareness of their presence. They include such things as how recently information has been introduced, thus discounting perfectly valid though older data; attaching greater likelihood to more vividly described phenomena; and crediting greater likelihood to a phenomenon that has been described with a greater number of elements. We decry the undue influence of "opinion" in important decisions, for good reason, because opinion likely has little relationship to what is real due to the subtle influence of biases that exist just below our level of awareness. Understanding the basis of opinion is important to countering its power.

Another common characteristic is an aversion to uncertainty. Studies have shown that in general people prefer to take risks on the basis of known rather than unknown probabilities. That is, information does make a difference in how we make decisions and people exhibit an aversion to ambiguity. However, there is an interesting twist in this characteristic that depends on the sense of competence one has in the domain being considered. That is, people will bet on vague, ambiguous perceptions in situations where they feel particularly competent. This would seem to invert the old saw into "wise men rush in where fools fear to tread..."

Another discovery in the modern era is that while the normal distribution would seem to describe many phenomena, there are conditions that can make slavish adherence to the principle most unwise. Some conditions that will cause havoc is a "norm" that is not at equilibrium or a trend that corrects on a cycle much longer than our decision window would allow. Analysis of the stock market has shown that while stock prices generally follow a normal distribution, certain extreme excursions will occasionally occur at the tails of the distribution that exceed the bounds of "normal" behavior. This characteristic has been described recently as "Black Swan" behavior, meaning a phenomenon that was thought not to be possible until it happens. (Taleb 2007)

Decisions, Risk and Systems Engineering

What is the bottom line? In the introduction to his book, *Against the Gods*, Peter Bernstein makes the rather hyperbolic assertion that over the centuries great thinkers have "converted risk-taking into one of the prime catalysts that drives modern Western society." (Bernstein, 1) However, have we fooled ourselves, at least in part, into thinking that we can control the uncontrollable, namely our inclination to do what is fundamentally not in our own best interest? When one considers that in today's world, simple acts and apparently unrelated events can unleash tremendously destructive forces such as 9/11, and the global financial "meltdown" of 2007/8. These two events are generally thought to be unrelated, but could the loosening of certain financial controls after the terrorist attacks in 2001 have contributed to the eventual ballooning and subsequent collapse of financial markets?

While risk management has helped produced aircraft, automobiles, spacecraft and nuclear weapons that have expanded our knowledge and comfort while contributing to the prevention of another world war, could not these same devices be used to produce devastating destruction, whether quickly through global nuclear war or slowly through destruction of the environment? How much have we actually advanced over civilizations of the past? While many of us exist in greater comfort and ease than the vast majority of humankind throughout history, numerous others, even now, survive on the edge of existence. Despite the vast increase in knowledge and capability, the world today is filled with far more contrasts and uncertainty than has ever existed before. Is the dichotomy we experience today a transitory condition or the harbinger of greater disruption to come? Will our understanding of risk management and decision analysis help resolve these questions or actually lead to even greater uncertainty?

This author suggests that resolving these issues of increasing and destructive contrasts, divisions and disparities will be a primary role of Systems Engineering in the future, if this discipline is to actually be a part of "the solution." However, to do so will likely require that, as a discipline, Systems Engineering and the practitioners thereof will need to consciously think more broadly than most of the immediate stakeholders of a project are willing to commit. This implies that the typical context diagram will not only include the immediate environs of the system, but perhaps at least the next level up both structurally and temporally, i.e. over the system's lifecycle. The implication is that over the system's lifetime, the system itself will be an influence in altering the very context in which the system exists and functions. Unfortunately, there are few tools available for this kind of understanding and precious little time or resources available in most projects to think very far beyond near term deployment. As a community of practice, however, INCOSE offers a unique opportunity to consider the implications of the practice and application of Systems Engineering in broad categories.

Of course, Systems Engineering can actually contribute to and consequently exacerbate "the problem." Just as Francis Galton's breakthrough work in heredity contributed indirectly to the eventual demise of his most favored Victorian world, and, through spiraling upheavals in the 20th century, replaced his world with our own that is ripe with promise, but having a core of uncertain composition that may be just as mushy and overripe as was his beloved Victorian age.

James Martin in his landmark best paper of the 2004 International Symposium on "The Seven Samurai of Systems Engineering," not only describes the complexity involved in developing a system that adequately addresses a problem, but rightly acknowledges the origination of a completely new problem that is directly traceable to the implementation of the solution. (Martin 2004) Given the increasing complexity of the modern world and having witnessed the potentially destructive results of concepts and ideas stretching back through the past century, there is little doubt that engineers and perhaps system engineers in particular, have a moral responsibility to consider the consequences of their actions. The beauty of facts and the purity of finely engineered systems do not completely absolve those who made them possible from responsibility in the way they are used whether "as designed" or through abuse, either intentional or unintentional. Sometimes the cure *is* worse than the disease.

Managing Risk – the Never Ending Story. When it comes to risk management and decision analysis, the story is hardly over. If there is any message from the history of the development of numbers, probability, and the basis on which people make decisions, that message says there is still far more to understand regarding the nature of risk and decisions then what we know today. If there is one certainty, it is that there will always be uncertainty and risk with the potential in some systems for truly catastrophic Black Swan events. Where there is substantial risk, no single answer is sufficient, but the advantage we have today is centuries of development in decision analysis along with real world trial and error. Where events are independent, straight probability based on historical data can be used, but where there are dependencies involving multiple diverse decisions from many sources that interact in complex, non-deterministic ways, more sophisticated approaches must be used, involving a mix of probability, Baysian analysis, bias analysis, and other techniques, such as modular design for ease of updating, while remaining alert for "sudden," unexpected, and out-of-bound Black Swan behaviors that can be the consequence of either natural or man-made conditions.

The latter situation, in particular, demands that where the consequence of failure is not acceptable that the system be designed with significant resilience of which there are several options. One approach is for the system to identify the upset, adapt and make appropriate changes at least as fast as the disruptive influence. Another option is for the system to isolate and neutralize the offending input and any "infected" subsystem. This option requires that the rest of the system can continue to function or at least retain operational status while the condition exists and the correction is implemented. An ancillary approach is for the system to simply operate at reduced efficiency, and either tolerate errors produced by the offending member, or detect and correct the misbehavior by other means. A final option, assuming other approaches have been exhausted or the system function is not critical, but a catastrophic failure is undesired, would involve the system shutting down in a controlled manner to achieve a "soft landing." Of course, the danger in all these options is that a malicious adversary, a failed sensor, a non-linear control behavior, or an out-of-bound driver could spoof the system into an undesired or unnecessary response. A dynamic system will almost always retain some unanticipated, emergent behavior, or interact with or alter its environment such that the system will require regular updates and refurbishment to remain useful. Ultimately, risk management is an ongoing process that may extend well beyond the system's original development into deployment, ongoing operations, upgrades and even system replacement.

In closing, it is fair to say that risk management is not strictly a "by the numbers" process. There is no algorithm or pure process that can be applied that will resolve all risk. It is not a weight balance, power load or even a dynamic control situation with clear inputs and obvious outputs. One cannot completely decompose risk as though it were a functional requirement. It often exhibits emergent properties with potentially complex interactions involving external forces and conditions over which the systems engineer will likely have little control and possibly even less knowledge. Perhaps most disconcerting is that system engineers and other decision makers can contribute unknowingly and unintentionally to system risk in significant ways, even while attempting to ameliorate risk. Pause for a moment, during the heat of a difficult project, think over the implications of risk, and consider the possibility that you may be part of the problem.

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