RISK DYNAMICS—AN ANALYSIS FOR THE RISK OF CHANGE

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ABSTRACT

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The concept of risk has evolved over the centuries of human history. People care about risk because much of our property and human lives are constantly at stake in the face of unforeseeable future. Unlike the fixed, known past, the future is always uncertain to us. In fact, such uncertainty is where risk arises. Thus, people assess risk by identifying sources of uncertainty and manage risk by trying to reduce those uncertainties. Indeed, existing risk analysis may be reduced to an endless anticipation of hazardous events, followed by a quantification of *how likely those events are to happen* and *what their consequences are*. Those approaches were originally developed for relatively well structured mechanical problems. However, our society inexorably marches towards greater complexity. On top of such natural progression, the advance of information and communication technology has made the rate of society's development faster than ever. Everything in society changes over time and the complexity of change brings us the uncertain future that perplexes our decision-making processes. Our current conceptual framework for risk analysis is now facing serious challenges due to the rapid pace of change in today's societies. *How can we analyze risk when systems are constantly changing?* To answer this question, this research will reexamine the concept of risk and investigate the uncertainty and complexity of change, to understand the very nature of risk in the ever-changing systems. In Newton's laws of motion and the ways of traditional Chinese medicine, we have found a new perspective of risk and a new way to analyze it.

For my parents, teachers and friends

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ABBREVIATIONS

CAD	Computer aided disaster
CDC	Centers for Disease Control and Prevention
HRO	High reliability organization
NRC	Nuclear Regulatory Commission
PRA	Probabilistic risk assessment
QRA	Quantitative risk assessment
RAM	Risk assessment and management, i.e. risk analysis
RCA	Root cause analysis
TCM	Traditional Chinese medicine

PROLOGUE—
RESEARCH GOALS AND OUTLINE

Change occurs all the time. Given enough time, everything in the world will change. Change is everywhere and we live with it everyday. Weather changes everyday and given enough time the earth's climate changes. Markets change everyday and given enough time the whole financial system changes. Some changes are evident; others are more subtle.

Take a city like San Francisco for example. We all notice the dynamic parts of the city: people commute to and from downtown San Francisco for work during the weekdays; traffic moves over and sometimes clogs the Bay Bridge day after day; events are held here and there around the city every weekend; tourists flock in and wander over the Golden Gate Bridge each season. Everything in the city is flowing. It seems chaotic, yet despite the constant, dynamic flows that comprise it, San Francisco as a whole remains stable, indeed a fixed entity that keeps gradually developing year after year. Holland (1998 p.1) introduces the basic elements of complex adaptive system with an example of New York City. However, what he emphasized was the persistent parts of the city. What we address here is the constantly changing parts of the city.

The city's development itself is a change. Change is *immanent* to the city: it is embedded into its very structure. People might ask, "Why does a beautiful city like San Francisco have to change?" The answer is—everything changes naturally. The material structure of the city itself changes, because things are naturally degrading and growing. Buildings become old, bridges corrode, living waste accumulates, but at the same time the residents want it to change, to be a better place to live, and they exert their efforts to renew the structures that make up San Francisco at the same time as they themselves are growing and decaying. This population itself is in constant change; people move in and out; old people die and new generations are born. Over the years, the city's culture changes accordingly and then what people think and want changes as well. Challenges from Nature never end and are constantly changing. Time and tides flow, temperature fluctuates, storms come and heavy rain pours. Vital supplies, such as water, gas, power, and food, have to be constantly adjusted for the city to survive the challenges.

San Francisco's constant changes also exist within a network of interconnected, constantly changing regional, national and global entities. San Francisco as a city does not exist and operate by itself. Since its power lines connect to the nation-wide grid, a power plant break-down hundreds of miles away may affect its power supply for downtown office buildings. Gasoline consumed in the city comes thousands of miles away from the Persian Gulf, thus the gas price fluctuates with political situations in the Middle East. Financially, the city is supported by the state government of California and has to compete for the deficient state budget with hundreds of other cities in the state. Economically, the city is interdependent with the rest of the world, thus, it suffers also when the world financial situation changed during the financial crisis. Such external changes from the greater environment in which San Francisco resides are usually beyond the city's control and have to be adapted to through internal adjustments. All those changes together define how San Francisco as whole develops.

Whether it's an ambient, constantly occurring change, an environmental adaptation, or a programmatic change to create a better future for the city, all changes involve uncertainty; thus, all changes entail risk—that is, to put it briefly, the chance of having an uncertain consequence. Taken as a whole, San Francisco can be thought of as an extremely complex engineered system. The risk problems challenging most complex engineered systems are no different for the city of San Francisco. To assure the achievement of system goals, change is necessary, and thus, risk is inevitable. We can manage risks only when we can recognize them and deliberate their potential consequences. However, regardless of all the risks we can control, there are always risks that remain beyond our knowledge—"unknown unknowns, the ones we don't know we don't know," as Donald Rumsfeld, the former U.S. Secretary of Defense famously said. Such risks appear in the form of surprises or accidents during our journey to the goals. Consider the magnitude 6.8 Great San Francisco Earthquake of 1868, for instance: it was one of the most significant catastrophes the city had ever undergone, certainly outside the category of repeated disturbances and never to be surpassed—that is, until a magnitude 7.8 earthquake in 1906 replaced it forever as the Great San Francisco Earthquake. People may argue that an earthquake is a known risk, but we never know exactly when and where it will happen. The greatest challenge in risk analysis is how to assess and manage these unknown situations. As Bookstaber (1999 p.18) states in his inspiring talk given to the Federal Reserve Bank of Atlanta Risk Management Conference, “It is more than a challenge; it is a paradox: How can we manage a risk we do not know exists?” Besides interactively responding to the unfolding catastrophic events, is it possible that we make correct decisions early in the normal operation and prevent problems from happening—to create a successful future, rather than a catastrophic one?

The problem of analyzing risk has become more challenging over the past decades as the world we live in and the systems we manage have become increasingly complex. As we have depicted, systems and their environments are constantly changing, which makes everything uncertain. Change fraught with uncertain always pose risk to our future. Given the constant uncertainty of change, the precise question we need to ask is *How can we assess and manage a risk for a changing system?*

Similar challenges appear in the biological setting, where Nature has surprises that are coped with by life forms of all kinds. A pandemic disease that spreads quickly and threatens the existence of certain species, a prolonged drought that destroys a once-abundant food supply, and an earthquake that strikes in a formerly stable geological area are Nature’s equivalent to unforeseeable changes for complex engineered systems. It is apparent that current risk analysis approaches are not applicable in such complex settings. This research is not trying to devalue the usefulness of current approaches; rather, we aim to provide a new perspective through reflections on the concept of risk and the increasingly complex world that we face.

Complex engineered systems pose a challenge to current risk analysis methods. The complex and dynamic nature of such systems make it difficult for us to assess and manage risks. In fact, risks fluctuate when systems adapt to changes in environment and conditions – risk is a reflection of how systems react to changes, e.g., hurricanes in New Orleans (September 2005), floods in Taiwan (August 2009), wildfires in Southern California (June-August 2009), landslides in China (August 2010) and the worldwide H1N1 pandemic (April 2009). This research project proposes a new perspective on thinking about and analyzing risk – *the risk of change* – for complex engineered systems while they are striving for adaptive changes to achieve goals in constantly changing environments. We follow a two-fold approach in this research: theoretical and empirical. The theoretical approach draws on various fields and concepts to develop a conceptual framework for analyzing the risk of change. The empirical approach uses examples of various kinds to explain and demonstrate the proposed methodology. Figure Pro-1 illustrates how those philosophies and theoretical foundations contribute to the development.

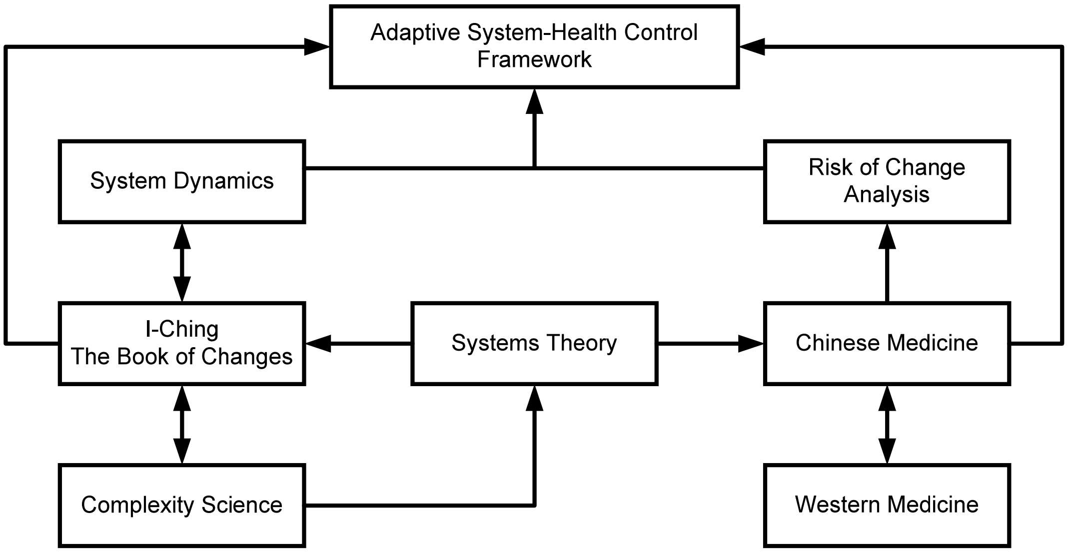

Figure Pro-1. Research Foundations

The remainder of this dissertation is divided along the lines implied by the title:

Part One: Beyond the Risk of Chance starts in **Chapter 1** with a review of the history of risk which explains how current approaches came to be. A brief discussion of the current approaches – *the risk of chance* – is given. The historical review ends with a discussion of the increasingly complex and dynamic nature of society. Intricate interdependence and relationships between various systems make the originally complicated engineered systems become even more complex. The way engineered systems are understood requires a paradigm shift. In **Chapter 2**, we examine the problems of the current risk concept and the way it is assessed and managed. Various philosophies and theoretical foundations applied in this study are reviewed in **Chapter 3**. The *I Ching* and *complexity science*, which respectively represent the Eastern and Western understandings of complex phenomena, are compared and used to derive the conclusions that the universe is constantly changing with simple, stable patterns. We then draw an analogy between risk analysis and medicine and compare the differences between Eastern and Western approaches to healing. We will draw on the concepts of health and disease in *traditional Chinese medicine* (TCM). Its emphasis of *holism* and *dynamic balance* are highlighted as the key for dealing with risks in *complex engineered systems*. In **Chapter 4**, we review the latest efforts scientists have devoted on this topic. Progress has been made in these studies; however, most of them follow the reductionist approach trying to measure uncertainty more accurately in order to regain control of increasing complex systems. And yet, none of them has found a cure in their quest. We critique their general approach to the problem and propose as an alternative and evolutionary view of systems seeing accidents as developing processes of functional degradation. Accordingly, we introduce a new perspective on risk – *the risk of change*.

Part II: Risk as a Potential of Change begins in **Chapter 5** with a descriptive metaphor for system change: the motion of a determinate physical object, in this case, a truck. *Newton's Three Laws of Motion* are applied to describe the potential for system changes. The risk of change is qualitatively defined as the momentum of change. This conceptualization casts risk and opportunity as two sides of the same coin: both are inevitable results of change. Driving *forces* that propel system changes are discussed. We believe that forces are patterns and exist in various forms ranging from the cultures of a nation to the habits of a person. The effects of forces may accumulate over time and eventually induce failures if no proper adjustments are made. Subsequently, we propose a way to quantify the risk of change in **Chapter 6**. *System Dynamics* is applied because its behavior model synthesizes rules and habits, i.e., forces, acting on the system. The concept of *stocks and flows* provides information to quantify the risk of change. The potential consequence of change is measured by *system inertia*, which is the amount of resistance to change. The *risk-of-change analysis* is introduced. *Resilience* is defined and discussed under the concept of the risk of change. **Chapter 7** suggests new strategies for dealing with complex risks. In fact, we believe the risk of change is not directly manageable since it is inevitable under change. What has to be managed is the change itself and those forces that drive the change. System constitution is crucial because it defines the potential of change to be risk or opportunity to the system. *System health* cycle and conditions are discussed. The two paradigms of risk, the risk of change and the risk of chance, and their risk analyses are compared. Characteristics and differences are highlighted. As a result, we propose to promote system health through adaptive control.

Part III: Managing the Risk of Change starts in **Chapter 8** with further investigation into critical theories in TCM. Dynamic balance in the holistic view is re-emphasized with a close look into theories of *yin yang* (the ancient Chinese understanding of how things work) and *wu xing* (the ancient Chinese recognition of how systems interact with each other). We recognize *yin yang* as a framework that TCM applies to reduce the complexity in the universe and *wu xing* as a *self-organizing* structure that governs the interrelationship between functions of inner organ systems and much more. Both theories contribute to the concept of maintaining a dynamic balance and correspond to the concept of *positive and negative feedbacks* in System Dynamics. We explore also TCM's model of *human body structure* with the emphasis on *constitution* and *vital substances*. In **Chapter 9**, we review TCM approaches to healing including *origins of disease* (etiology), *pattern differentiation* (pathology) for identifying *origins*, *locations*, *characters* and *trends* of diseases, as well as prevention and treatment principles. However, a full application of TCM theories to engineered systems is not possible at the current stage. Reasons for that are discussed. In **Chapter 10**, we propose for complex engineered systems a framework of *adaptive system-health control*, which are concluded from previous TCM discussions. A case study is presented to demonstrate the application of the proposed methodology.

Finally, we present our **Contributions** and **Conclusions** of the research and suggestions for **Future Research** in the *Epilogue* section.

RISK DYNAMICS <PART ONE>: BEYOND THE RISK OF CHANCE

Thesis: How things change is not always obvious to us especially in an increasingly dynamic and complex world. Constant change is an unchanging quality of complex engineered systems. The conventional concept of risk may not be applicable to this new situation. There is a need for reexamining the concept of risk and thus a new way of analyzing risk.

Chapter 1. Research Background

Risk analysis is a very old idea. The history of risk is interwoven with the remarkable story of how our ancestors fought against the will of gods. The history of any idea brings its own baggage that, whether we want it or not, often limits our current thinking about the concept. Risk is no exception to this limitation. Concepts of risk are a source of considerable confusion even among experts specialized in this subject. Kaplan (1997 p.408) mentioned in his talk given to a plenary session at the 1996 Annual Meeting of the Society for Risk Analysis that one of the first things the Society did when founded was to establish a committee to define the word risk. But the results of the committee's 4-year efforts had only added to the general confusion about risk, saying in its final report that it may simply be better not to define risk, which is what we intend to address in this research.

To judge the value of our current methods of dealing with risk and, if possible, to make any progress in the future, we need to first be aware of its past. We must know the story about why people in the past tried to tame risk, how they approached the task, and what modes of thinking and language emerged from their experience that brings the concept of risk to what it is now. The purpose the following first section is not to depict the history of risk over again since such information (Bernstein 1996; Covello and Mumpower 1985; Hacking 1975; Vick 2002) can be found elsewhere, but rather to bring out its meaning and content in the context of this research. Such a perspective will bring us to a deeper understanding of where we stand among the confusion of risk, and where we may be heading to make it clear.

1-1. Behind the Emergence of Risk Concept

1-1-1. Measures Taken for Risk before 13th Century

As civilization has developed, strategies for risk have had to cope with increasing lives and properties at stake. Risk is an inescapable component of the flowing process of life and living. In the most primitive lifestyle known to human beings, people hunted and gathered food that grows wild and drift from campsite to campsite for shelters to protect themselves. In the face of the varied natural hazards, their lives are the single most important property they have to protect. Gradually, people started growing crops and raising animals to supplement their food supply. As agriculture developed among ancient tribes, lands were occupied, tools were created, and houses were built. Things at risk, now, were not merely their lives, but also their properties. People needed to act cautiously for protection of both, guarding against extreme natural phenomena, wild animals and fluctuations of climate and soil condition. However, activities concerning moving to a new campsite, initiating a hunting season, or crop harvesting seemed to be full of uncertainty and difficulty due to limited knowledge of nature. To make decisions of such importance, our ancestors would resort to "signs from the gods" through divination of some sort to anticipate the likely outcomes of each alternative. Favorable signs were used to make decision for actions. In their paper about the history of risk assessment and risk management, Covello and Mumpower (1985) indicate that this practice found as early as 3200 B.C. may have been the original form of risk assessment and management (RAM). Unquestionably, the problem of risk and the needs for assessing and managing risk have been one of human beings' major concerns for a long time.

Bernstein (1996 p.1) concludes that "the mastery of risk" defines the boundary between modern times and the past. Until human beings discovered a way across that boundary, the future was merely a "joke of the gods," rendering humans virtually passive before nature.

1-1-2. Expanding Sources of Knowledge between the 13th and 17th Century

Much of the ancient Western forms of risk analysis were lost in the period between the fall of the Roman Empire and the Dark Ages. Around the year 1200, theological and philosophical developments occurred which would lead to the rediscovery of knowledge as we know it.

For any number of reasons, the idea of knowledge was a fundamentally different concept for a pre-1200 thinker. The essentially theocratic character of governance at the time meant that all facts were basically artifacts of the approval of authority. All events were caused by an omnipotent prime causal entity, God who revealed almighty truth through scripture and doctrine. (Vick 2002 p.21) This was a return to theological doctrines before the time of Aristotle. Nearly a millennium earlier, Aristotle argued that objects posed their own nature as "an entity unto itself," possessed of its own endogenous logic. Movement and change were seen to be intrinsic properties of an object based in nature; although situational factors could play a part in creating change and movement, ultimately the divinely given nature of the objects themselves were the basis of their movement. (Bodnar 2009) The new 13th century philosophy, however, differed in that it allowed for religious doctrine to emerge not only from demonstration from facts of nature, but also from doctrine as revealed by religious authority, which we see now as belief and opinion. (Vick 2002 p.21)

For Aquinas, between divine revelation (the facts of the existence and goodness of God, for instance) and church doctrine as revealed through scripture and exegesis (for example, the idea that God was split into three seemingly arbitrary and unrelated entities), there existed a huge knowledge gap – namely, some means of showing if empirically observed facts were indeed in accord with divinely revealed truth. It was fairly self-evident to Aquinas that God was good and that God existed; these were in the category of divine revelations, and simply taken on faith. In contrast, the idea that God approved or disapproved of a particular form of governance, or a social practice, required logical proof, based on an examination of signs from God.

This idea – that not all religious proclamations had the full force of the word of God Himself – was a revolutionary one in theology, and its impact on philosophy is complex. The main impact of this idea was to make articles of faith (like God's existence and goodness) into material suitable for inferential logic for arguments about what was right – in other words, as a form of theological assumption for arguments about reality, or in our parlance, ontological beliefs. For Aquinas, there was a need for the study and analysis of empirical facts as signs from God. This religious phenomenology marked the beginning of what we know as the concept of evidence – but this was not evidence at the service of the scientific or philosophical facts as we know them, but rather an epistemological concept of evidence and its relation to reality, a question like "What evidence do we have that this is God's will?" Standard risk management accounts, such as the slightly facile one that Vick presents (Vick 2002 p.31) miss the point – the main achievement of Aquinas' thought is not that it developed some new philosophical truth with regard to the consideration of scientific evidence, because philosophy did not exist at the time (it was a part of theology) nor did science. Indeed, Aquinas' achievements are primarily theological in nature – but it just so happens that his way of knowing God are of greater interest to us than his conclusions about God.

The simple concept of evidence, although it is easy for us to take for granted, forms a core building block of what we consider today to be risk management, for the concept of risk cannot exist without the concept of chance, and an understanding of chance requires an understanding of the nature of evidence. Philosopher Ian Hacking (Hacking 2006; Vick 2002 p.22) argues that the absence of the concept of evidence was the reason it took so long for the development of the mathematics of chance. Prior to a concept of evidence, probability was highly subjective, based on experiential and unquantifiable "seat of the pants" estimates. With the concept of evidence in place, the stage was set for the development of probability theory and the concept of risk.

1-1-3. Early Development of Risk in the 17th Century

The early development of the risk concept and its management as such was closely related to the emergence of probability theory around 17th century, when the Renaissance (around 1654) was in full flower, "…a time when much of the world was to be discovered and its resources exploited… a time of religious turmoil, nascent capitalism, and a vigorous approach to science and the future." (Bernstein 1996 p.3) The human fascination with games of chance at this time was a major driving force which led to the discovery of a probability theory. (Bernstein 1996; Hacking 1975; Vick 2002) Through early understandings of *relative-frequency probability*, concerned with characterizing variability in measured data or observed occurrences, as well as that of *subjective probability*, a scaled numerical measure of one's belief or confidence about its occurrence, a notion of risk analysis which we would recognize as mature developed. (Vick 2002 p.3)

In 1645, French mathematician Blaise Pascal and his lawyer and brilliant mathematician friend, Pierre de Fermat, together solved the puzzle that a Franciscan monk, Luca Paccioli posed, which asked how two players in a game of chance should divide their stakes should the game conclude prematurely. Pascal and Fermat's answer developed the combinatorial mathematics of probability by using all the possible combinations and permutations to calculate how outcomes of the game would occur. Plausible solutions to Paccioli's puzzle could include just walking away with stakes as they were (an unsatisfactory solution for estimating the "true value" of what would have occurred) or projecting a possible trend forward (so that a losing player, for instance, might keep losing). Fermat and Pascal proposed instead to tally up all the possible combinations of outcomes, crediting the players accordingly. We might see Fermat and Pascal's solution as a modified deterministic stance – that is, it does not state that there is only one pre-determined outcome, but rather a finite set of pre-determined outcomes. It was not long after Pascal and Fermat's discovery that people began exploring its application and two immediate ones took hold: the *aleatory*, concerned with games of chance or gambling, and the other *epistemic*, concerned with knowledge or understanding, a practical differentiation that still exists today. (Vick 2002 p.31-38)

Despite the advancements that science made in developing the number of possible outcomes, the deterministic view of the world underlay foundational Enlightenment developments in science, thus embedding determinism early in the development of the scientific study of probability. After all, probability for the Classical probabilists was above all a *way of knowing*, and the study of probability was the study of how rational men knew things – in other words, an essentially epistemic endeavor. The universe was knowable and effable "…just as Paracelsus had said a century earlier, there were no incurable diseases – just ignorant physicians… Insufficient knowledge was just a temporary state of affairs that would inevitably yield to scientific discoveries like Galileo's. All events were predictable in principle and none would be seen to occur by chance when the governing laws were found." (Vick 2002 p.32)

The emerging field of demographics was concerned from the very beginnings, with observations of the subjective experience of average men, most classically John Graunt's plague-ridden Londoners. Its great power lay in its ability to collect and aggregate meanings from the experiences of average men. However, such experiences were seen to be in the category of deterministic facts, in the sense that there could only be one average, one median, one mean, etc. Thus, measures were seen as facts discoverable through inductive processes by reasonable men. The opinions and thoughts of reasonable men and average men had merged – but only to the degree that average men were subjects of study, from whom reasonable men drew deterministic conclusions through inference. This type of fact itself was entirely new – as Vick would put it, it was a subjective belief – based on projection into infinity of an inductively obtained statistical rule. Thus, per Vick, no coin would ever flip perfectly 50-50 over a limited number of trials, or even an infinite number of trials, since the probability of the coin landing on its edge at least once approaches 1 given an infinite number of trials. Nonetheless, we accept that coin flips tend towards 50-50 as a matter of convenience. (Vick 2002 p.11-12) Similarly, even though no Londoner might conform precisely to the etiology and patterns of disease spread that Graunt found, this was simply an acceptable difficulty. The notion of what we might term the perfectly 50-50 coin was an acceptable abstraction for Classical probabilists.

Nearly three centuries later, a combination of intellectual developments laid the foundations for what we know today as a modern view of probability: a full development of Dedekind and Cantor's set theory as well as combinatorial mathematics (Fermat and Pascal's modified deterministic view expressing probability functions as a question of frequency). This came together in the work of the Russian mathematician Andrey Kolmogorov, who proposed the Chapman-Kolmogorov equation, setting forth an axiological view of probability based on set theory. (Vick 2002 p.20) For the first time, people had all the intellectual tools they needed to make policy decisions and manage risk in a quantifiable, rational mode. (Bernstein 1996 p.3)

1-1-4. Development of the Mathematics of Chance in the 18th Century

A centuries-long, gradually accelerating sequence of discoveries in mathematics of chance ensued through and after the emergence of probability thinking. In 1665, Leibniz's use of the numerical probability scale to reflect one's degree of certainty opened up the application of probability to single instances, as a quotient, instead of existing purely as a quality of an aggregate. (Vick 2002 p.34) In 1713, Jacob Bernoulli argued further that probability is a degree of certainty and differs from absolute certainty as the part differs from the whole, rendering evidence not only qualitative, but also quantitative. As Vick (2002 p.36) puts it: "While Leibniz had concerned himself with what kind of evidence it took to reach some degree of certainty, Bernoulli wanted to know how much."

In 1764, Bayes' notion of conditional probability established a new way of combining different sources of evidence, casting probability as more than an instantaneous snapshot, but also a chain of decisions and probabilities. The Bayesian notion of conditional probability combined Leibniz's notion of reconciling different forms of evidence with Bernoulli's quantitative, inductive methodology. (Vick 2002 p.38)

Modern methods of dealing with the unknown start with measurement, with odds and probabilities. Invariably, the numbers come first; without odds and a concept of probability, risk management is entirely a matter of "the gods and the fates… wholly a matter of gut." (Bernstein 1996 p.23) It is this mathematical, empirical foundation that is the greatest indebtedness of modern risk management to the Enlightenment era.

Hundreds of years later, we now live in a world of numbers and calculations. The quantitative methods of how people do science, engineering and risk analysis are greatly affected by early mathematical discoveries. Compared to conditions at the end of the Renaissance, the digital worldview has certainly improved our lives, but at the cost of also limiting our thinking when applied incautiously. A culture of numeracy, it seems, has its own dangers. Some researchers term it "CAD" for "computer-aided disaster," a twist on the familiar "CAD" as in "computer-aided design," a commonly used tool in engineering. (Bea 2005; Mellor 1994) Or, as Bernstein (1996 p.7) notes it:

> *The mathematically driven apparatus of modern risk management contains the seeds of a dehumanizing and self-destructive technology. Nobel laureate Kenneth Arrow has warned, "[O]ur knowledge of the way things work, in society or in nature, comes trailing clouds of vagueness. Vast ills have followed a belief in certainty." In the process of breaking free from the past we may have become slaves of a new religion, a creed that is just as implacable, confining, and arbitrary as the old. Our lives teem with numbers, but we sometimes forget that numbers are only tools. They have no soul; they may indeed become fetishes. Many of our most critical decisions are made by computers, contraptions that devour numbers like voracious monsters and insist on being nourished with ever-greater quantities of digits to crunch, digest, and spew back.*

1-1-5. Science and Development of Statistics in the 19th Century

Statistics has become an indispensable tool of science, and largely changed the focus of scientific thinking from the thoughts of a "reasonable man" to those of an "average man." (Vick 2002 p.39) The concept of the *reasonable* or *rational man* had driven a great deal of scientific speculation up until this time. The concept of the rational man was simply a rational hypothetical observer who could be counted on to adjudge the veracity or plausibility of an idea or claim. Thus, not only were philosophers and thinkers rational men, they also made ideas and wrote books for other rational men who could be counted on to make rational decisions. In contrast, the development of combinatorial mathematics and statistics developed the concept of what we might term the *average man* – an ontological construct simply referring in the aggregate to the masses of people whom statistics surveyed.

The mode of reasoning at play was essentially deterministic. Given a certain set of repeatable events with predictable frequencies, future events could be predicted with objective, clockwork certainty, absent any subjectivity, beliefs, or potentially questionable personal knowledge. Decision-makers could be truly rational men.

This concept of the rational man is a common assumption that runs from the late Renaissance throughout the Enlightenment Age in philosophy and politics; its modern development is the philosophy and decision calculus we know today as utilitarianism. First formulated by Pascal, then re-popularized by the philosopher Jeremy Bentham in the late 18th century, utilitarianism holds that humans are decision-makers that maximize utility, or, in the economic definition, decision-makers who maximize their relative satisfaction. Each person owes a duty to reasonable behaviors according to the theory of utility under the same or similar circumstances. (Bernstein 1996 p.189-191) Since utility theory is one of the most reductive and powerful means of comparing the relative goodness or badness of various decision outcomes, it is not surprising that it can be seen to underlie the vast majority of conventional risk analysis practices. However, an account that prioritizes the continued dynamic balance and well-being – the *health* – of the relevant system can provide a powerful alternative calculus for making decisions, as we will argue.

The Concept of the Average

The concept of the *average* (arithmetic mean), drawing from the *Gaussian distribution* set forth by Carl Gauss in the early 1800s, measures the central tendency of a data set on a histographical curve, the Gaussian distribution. However, as later statisticians have argued, not all distributions of measurement errors fall into Gaussian distributions. For instance, on the Gaussian account, a comparison of manufacturing defects across time in a certain product would, once the survey size was sufficiently large, fall into a normal curve. However, any number of individual factors that we recognize today (such as company health, manufacturing tolerances, local regulatory climate, composition of material inputs, rate of production, labor conditions, etc., etc.) might cause the curve to skew to a J or even U-shaped curve. Certainly such non-Gaussian distributions are common. (Taleb 2007) The idea that an average, a single number, might in some manner usefully convey a complex reality of multiple measurements and states can thus be seen to be at best an optimistic notion. Not to mention the notion of varience (σ^2) as another, perhaps more difficult to grasp concept, also attempt to reduce the data to a smaller set of indicaters; it has a very powerful impact on average man, who consider events in excess of 3 or 4σ as impossible.

This reductive, summary notion of the average was developed further in 1835 by Adolphe Quetelet who put forth the concept of the "average man," a notional entity whose statistical norms could be seen to govern humans and their behavior. (Vick 2002 p.43) The average man or *l'homme moyen* (literally "the man medium" or "the man mean") was the perfectly representative sample of a particular social group for whom policies could be formulated which would apply correctly to the average man's representative group. On Quetelet's account, an average criminal, for instance, could serve as the basis for policies governing an entire class of criminals. Similar to the concept of the Platonic ideal, the average man was a perfect representative of a particular type of social being. (Vick 2002 p.156)

Today, we recognize that this concept can be deceptive and incorrect; oftentimes, the concept of expected value and average mislead our judgment to the real situation, which may be rare event like "black swans" per Taleb, or simply a non-normal distribution. The average man as an ontological concept (in other words, as a real person somewhere in the world with a name and a face) has been shown to be internally inconsistent; the one thing that unites all people, after all, is our differences. (Taleb 2007 p.242) As a concept of measurement, the notion of an average man is even less helpful. If we really could define and locate "average men," this would be at best a temporary state. Human beings are in a state of constant flux, it must be remembered; the traits that make a person average on one day may change (the person may change) or the average itself may shift (a different person will be the "average man" on a different day). We argue that knowing the patterns of this change provides more useful information than knowing the identity of a single constituent element. An average is always an observed, empirical fact, and as such, averages are insensitive to rare unforeseen events with potentially huge consequences. Thus, risk analysis requires judgment and the consideration of single systems that statistics does not provide. As a useful concept for the formulation of risk analysis, the notion of the "average man" is at best inconsistent and unhelpful.

Statistical Inference

Statistical hypothesis testing is another important historical development in the Enlightenment period that determines a number of key assumptions underlying current risk management practice. All forms of statistical measures like certainty measures (p-levels), significance tests (like t-tests, ANOVAs) and even modern forms like meta-analyses essentially quantify certainty, thus eliminating belief and opinion from ontological questions. The question "Is this effect real?" no longer requires recourse to subjective opinion; to paraphrase the Apple slogan, "There's a test for that." This has the effect of granting a form of confirmatory approval to the objective, empirical investigations that science undertakes. (Vick 2002 p.44)

Statistics has had an important effect on the development and practice of science. The study of certain mass phenomena – for instance, biological problems like enzyme interactions in a solution – is impossible absent statistics. The study of such mass phenomena prevails in fields like physics, engineering, medicine (both the individual and especially the public health varieties) – indeed, virtually the only field which remains untouched by the statistical study of phenomena in the aggregate is perhaps philosophy, from which statistics emerged. Basic physical facts which we take for granted like radioactive half-life, the quantum wave-function collapse effect, even our own racial and personal identities, could not exist without assuming the validity of statistical measures. As the need has grown to make decisions for larger and larger masses of people encountering ever-faster rates of change, statistics has even grown to generate its own decision-making methods as increasingly rational modern policy-makers make decisions based on statistically-driven events models.

Statistics is, however, not without its intrinsic flaws. Statistical measures are often difficult to understand, even for decision-makers. Even 99.95% statistical certainty that something is true does not necessarily make it true. Let us consider, hypothetically, the odds of someone flying a commercial jetliner into a crowded building. This could have been seen to be vanishingly small prior to September 11, 2001, but later events proved, this statistically verifiable notion of relative frequency was invariant to impact, creating a false sense of safety. Low-probability, high-impact risks are quite real and must be engineered against. In addition, statistical measures can be seen to be ultimately just that – measures, and not the actual truth. Certainly there is a clear number of planes which have flown into buildings, and one might divide that number by years to obtain the odds that a plane-building crash will occur on any given day, and similarly obtain the odds for any particular building being hit by a plane (divide by the number of buildings under consideration). However, even were such a number obtainable – after all, the number of buildings and planes as well as their flight paths change every year – this would still be uninformative as to why a plane might hit a building and how, as engineers, we might prevent catastrophic impacts from occurring in such a scenario. And, in fact, were we to say “the odds of 9/11 happening were 1 in *x*,” where *x* is the number we derived, this would say little about the complex set of factors that brought it about; we would have a measure that would be perfectly valid statistically, but utterly meaningless practically. Statistical measures of certainty, even to a very fine degree of quantification, do not reduce the uncertainty of the unknown.

These flaws in statistics result in a pattern of flaws in the science that we take for granted in risk management. The most important statistically-derived flaw in the science that affects risk management is its invariance to synergetic and emergent effects. Suppose drugs A, B, C, D and E all have 95% efficacy at treating a certain disease. The combination of all five drugs does not necessarily have 95% efficacy, nor even any statistically derivable efficacy rate at all. For insurance purposes, the number of years added to a patient's life expectancy may not be the sum of all the drugs' efficacy to the patient's life expectancy added together. In fact, the compounded side effects could lead to an iatrogenically caused adverse drug event. The deterministic character of statistical measures means that misusage of statistics can easily lead to incorrect or problematic decision-making.

Taking for granted the validity of statistical inference is a core underwriting principle of modern science. However, ultimately statistical measures are not truth; measures are never certain, and randomness pertains even at the observational level. Further, despite so many of the constituent parts and inflow/outflow materials of these systems are constantly changing, statistical measures of engineered systems are invariant with time. Since it is impossible to adequately reduce the randomness associated with change, a more change-tolerant paradigm of risk seems justified; to do otherwise would be to admit the intrinsically flawed nature of the risk measures we suggest. It might be satisfying to offer a 99% safety rate with the full backing of statistically verified science, but in engineering's typically high stakes endeavors, a 1% failure rate may be so catastrophic that it invalidates the entire value of the system to begin with. Unknown unknowables will always elude expectation; the empirical view of past experience as "a sequence of events rather than a set of independent observations" may even blind us to high-impact unknowns. (Bernstein 1996 p.334-336) If we see the world as interconnected and correlated as a whole, using statistical data on past events to predict the future ones is never perfect. As we will suggest, past data is better used to understand the correlation in between system functionalities and the overall system behavior that emerges.

1-1-6. Modern Risk Thinking in the Deterministic Worldview 1900-1960 AD

In addition to developments in mathematics and statistics, modern risk analysis is heavily indebted to early developments in economics and finance. Under the assumptions of the deterministic worldview, human beings are deemed rational creatures as acting with the same rules found in nature; thus, a full understanding of the rules is a full understanding of human being and nature. This core notion of financial engineering finds is counterpart in the early development of risk analysis in the 1960s.

Among those early developments in economics and finance, the one most relevant to the development of risk thinking is the modern stock option, an outgrowth of the commodity future and arguably the first true "derivative" financial instrument. Researchers like Bachelier, Black and Scholes and Merton set forth formulae and finance strategies that defined a pricing scheme drawing on the expected behavior of investors with regard to time and securities exchange, in essence putting a price on the risk (of chance). (Bernstein 1996 p.311-312; Jenkins and Kennedy 2003 p.28-33) An option in essence anticipates the future price of a security, absent evidence or analysis of the operation of the underlying security, based sheerly on the past price performance of the security. As such, the price for an option on a publicly traded share of stock is a reductive, non-holistic measure of the risk involved, without regard to the system health (or lack thereof) of the underlying company. In contrast, an investment paradigm such as value investing would consider the health and expected profitability of the underlying company, yielding a different value less sensitive to volatility. The comparative efficacy of these two approaches today is fairly clear; a Black-Scholes formulation of an options price for Enron, for instance, would have been accurate as to its expected performance based on history – but, as everyone today knows, grossly wrong as to its eventual performance. A value-investing paradigm with a preference for high levels of operating cash and a prejudice against high credit balances would have correctly deemed Enron a poor investment.

Kenneth Arrow's Nobel Prize-winning conception of the "complete market" marks the beginning of the insurance and risk-sharing concepts. (Bernstein 1996 p.204) Both are important risk mitigation measures. Arrow argued that the more is insured, the better; the ideal world would be one in which everything was insured. Indeed, risk transferring is made possible by the concept of insurance. However, it is not wise to transfer all risks to the insurance company, as Saporita (2006 p.16) puts it, risk transferring "is intended to address risks beyond… control…, or those risks not willing to be accepted…" Even though insurance can cover all the monetary loss one may have, due to its practical limitation, there are things that cannot be recovered by insurance, such as human lives, memories, reputations…etc.

The deterministic worldview emphasizes that everything occurs with a cause and people make rational decisions. However, modern developments in psychology during the late 20th century cast considerable doubt on the idea that people are perfectly rational economic decision-makers. Our view of future events is shaped by past events which may not be an accurate guide. (Bernstein 1996 p.6) In addition, while the natural universe may be reducible to determinate and clear laws, the human world is very clearly not. Up until the modern era, the chief concern of most human beings was a struggle against nature (highly common primitive occupations like farming and mining are perfect examples) determined by very lawful, predictable natural conditions. Thus, it seemed natural (and to an extent still is) to consider human cognition as being similarly lawful and orderly, just like the laws of nature. The idea was that humanity would to progress towards a Laplacian idea of a "vast intelligence" capable of understanding all causes and effects, (Bernstein 1996 p.198) An orderly view of the social world, it was thought, could be achieved with Newtonian certainty allowing everything to be measured and calculated, given sufficient effort. Despite significant advances in physics, mathematics and cosmology, however, this basic mindset continued to persist well into the nuclear era of the 20th century.

1-2. Conventional Approaches to Risk Analysis

1-2-1. The Development of Risk Analysis since the 1960s

More sophisticated risk assessments were applied to and further developed by several government agencies in the United States, most notably by the Nuclear Regulatory Commission (NRC). Various probabilistic risk studies of reactor safety were carried out in the late 1960s and 1970s, but the most widely recognized and important one is the 1975 Reactor Safety Study, also referred to as the Rasmussen Report, or WASH-1400. (Vick 2002) The WASH-1400 introduced many of the methods and insights that are still used today. In a sense, it formed the basis of the modern practices of probabilistic risk assessment (PRA) or quantitative risk assessment (QRA). (Apostolakis 2000) It is considered the first full scale PRA project in the nuclear industry. (Kastenberg 2007c p.11) Henley and Kumamoto (1992 p.10-11) call it "epoch-making." Its epochal nature lies in its systematic approach in ranking and assessing the probability of a huge variety of nuclear accidents, and developing event trees, fault trees, and risk-consequence techniques laid the foundations for risk management as we practice it today.

Significantly for our purposes, the WASH-1400 report's methodology was *retrospective*. That is, much like its forebears in the development of the U.S. Space Program, the WASH-1400 report's approach to risk measurement worked with consequence, then worked backwards to identify causation, then assess probability and propensity for such causation. As such, it was firmly within a tradition of risk assessment "as a retrospective process… developed by the U.S. Space Program in the 1950's and 60's with the advent of Failure Modes and Effects Analysis (FMEA) in an attempt to both understand and correct missile and rocket launch failures." (Kastenberg 2007c p.5)

The role of the WASH-1400 report in the development PRA in nuclear safety provides important lessons with regard to risk assessment and the importance of framing its applications. (Apostolakis 2000; Kastenberg 2007c; Vick 2002) Initial concerns about nuclear applications produced "worst-case 'maximum credible' or 'probable maximum' event scenarios that were difficult for a reluctant public to understand" (Vick 2002). The results were, unsurprisingly, unspectacular. As Apostolakis observes, every safety technology has three phases of adoption: first skepticism, then usage of the safety technology "negatively" to critique existing systems, then finally "positively" to develop new systems. In Apostolakis' view, then, the Rasmussen Report can be seen as firmly within the first phase of skepticism; the nuclear industry was beginning to accept risk assessment as a practicable methodology. (Apostolakis 2004 p.515) What was missing was useful and practical meanings to probabilistic analysis. That arrived with NUREG1150 in 1990, which set the standard for all subsequent PRA, through usage of a full scope (Level III) PRA that included possible accident scenarios and their potential impact on the public. (Kastenberg 2007c p.16-17) In Apostolakis' view (2004 p.515), risk management could be said to have entered its second phase – it was being used to draw out the negative consequences and provided a critique of existing decisions. However, the "positive" third and final phase emerged with the 1995 Regulatory Guide 1.174, which for the first time "provided clear criteria for the review of 'risk-informed' changes to the licensing basis for a commercial nuclear power plant.” The 2002 Regulatory Guide 1.174 Revision 1 “lays out the approach for using PRA in risk-informed decisions on plant-specific changes to the licensing basis.” (Kastenberg 2007c p.16-17)

The notion of the fallibility of risk-management measures spurred the development of multiply redundant risk management systems. A philosophy of *Defense in Depth* informed nuclear risk management in particular. The defense in depth idea, borrowed from military strategy, positions redundant resources to be successively engaged as a problem worsens. If possible, accidents are prevented; if unpreventable, they are minimized; if they cannot be minimized, at least their effect is palliated as much as possible. In addition, multiple “fall-back” safety measures – for instance, a nuclear reactor with a passive secondary cooling system as well as an active primary cooling system – may be positioned with their relative importance and capacity load set by a number of deterministic factors. (Kastenberg 2007c p.10-11) As with most traditional risk management strategies, the notion of defense in depth assumes failure is caused by the attack, not by the system, thus revealing only particulars – not general patterns useful to a holistically oriented risk manager. As we will argue, *contra* traditional PRA/QRA, an accident is not a particular entity to be defined and studied in isolation, but rather must be understood contextually – that is, a full account of accidents should consider the severity of the attack *and* the state of the relevant system. A natural outgrowth of the development and elaboration of risk analysis in nuclear public policy is *Risk Informed Decision Making* (RIDM), which combines deterministic engineering insight with PRA.

Again, the purpose of this section is not to give a complete overview of the existing approaches to risk analysis, but to introduce the very basic concept of risk (of chance) and the resulting general approaches to managing risk.

1-2-2. The Risk of Chance—Qualitative Notion

Qualitatively, risk depends on what you do know and what you do not know. If science is the art of dealing with the unknown, risk analysis is the art of dealing with uncertainty. The Cambridge Advanced Learner’s Dictionary gives two definitions of risk:

a) The possibility [or chance] of something bad happening

b) Something bad that might happen

As evolving accross the history of risk, risk concerns the *possibility* of a hazardous *event* which implies something with *bad consequence*. Thus, this conventional sense of risk, as expressed in definition a), would be more accurately termed as the "risk of chance" in this research. Furthermore, as a part of its basis (indeed its very name – the discipline is not termed "opportunity" management but rather "risk" management), conventional risk analysis overlooks the possibility of good consequences, even to hazardous events. "Opportunity" is traditionally defined as separate from "risk." That is, it would be considered odd, though not entirely ungrammatical to say "the risk of success" or "the opportunity for failure." On its first face, this negative focus to the anticipation, assessment and management of chance events is somewhat odd. After all, risk analysis, as we have seen, emerges from a mathematical tradition attempting to cope with the idea that *anything* might happen. Indeed, as educated people, we can recognize that there are occasionally positive consequences to hazardous events, or even negative consequences to positive events; how one deal with the situation is the most important determinant of the resultant consequences.

By focusing on the negative side of chance – risk, and not opportunity – risk management as it is traditionally defined does not adequately represent the full range of possibilities open to complex or complicated systems. Remotely probable, high impact negative possibilities are well-documented and studied (catastrophic container failure, theft or misdirection of radioactive material, core meltdown, etc.) and even used as the basis for decisions which we would consider rational. However, remotely probable, high impact *positive* possibilities (improvement to the local environment, radically increased efficiency, or even successful research and development in safety management) are traditionally discounted. The probability of success ($\boldsymbol{P_s}$) are usually considered as a complement to the probability of failure ($\boldsymbol{P_f}$), denoted as $\boldsymbol{P_s} = 1 - \boldsymbol{P_f}$, for traditional risk management because it came from nuclear safety, concerned primarily with avoiding a negative consequence, i.e. not killing people, even at the expense of ignoring potential positive consequences. Indeed, as we will argue, it may not be possible to distinguish the two probabilities in real situations because, for every action we take, the result is always positive/negative (part of it is positive and part of it is negative), just as *yin* and *yang* are not seperatable from the "one" reality. Through a focus on the essential components of system health and resilience, it is possible to increase the potential for positive results by concentrating on *how the system operates to produce positive results*, rather than digging ever deeper into the realm of preventing the negative.

1-2-3. The Risk of Chance—Quantitative Definition

There have been notable and noteworthy attempts to quantitatively define risk. Kaplan and Garrick's set of triplets idea distills risk, as the name might suggest, into three simple concepts: (Kaplan 1997; Kaplan and Garrick 1981; Kastenberg 2007c)

a) What can go wrong?

b) How likely is it to happen?

c) What are the consequences?

Through a set of simple equations, a concept of risk, as defined by the probability of hazards with regard to safeguards, serves as the basis for an enumeration of various accident scenarios, and an estimation of the probabilities which can then be associated with their relative impact to obtain a single scale for weighing various outcomes. Though highly reductive, this approach is widely accepted to be incomplete. A high-probability, low-impact negative scenario, for instance, would have the same weight as a low-probability, high-impact negative scenario in this single-scale reckoning. (Kaplan and Garrick 1981 p.13-14)

It is evidently impossible to have a complete enumeration of various accident scenarios. Indeed, experience shows that it is the most unexpected scenarios which often cause the highest impact because we are not prepared for them. Further, traditional risk analysis' goal of assessing and managing system risk through imagining possible consequence is self-dooming, for as system complexity increases, consequence and scenarios must increase exponentially; thus, the more complex the system, the less likely its anticipation of future events will be useful. (Kaplan and Garrick 1981; McDaniel and Driebe 2005) Indeed, even if we do identify all important consequences, we still encounter fundamental difficulties in accurately measuring consequences; it may require too complex a family of *risk curves* to be describe the idea of risk in a complex situation. (Kaplan and Garrick 1981) A simpler, more internally consistent approach is warranted.

1-2-4. Conventional Risk Analysis Framework

Conventional risk analysis combines the disciplines of risk assessment and risk management (RAM). Risk analysis, as practiced today, asks the following questions: (Kastenberg 2007c p.3) *a) What are the risks imposed by human activities and natural phenomena on society and the environment?*

b) Are these risks acceptable?

c) What are the options for reducing these risks?

d) On what basis should we choose among these options?

e) How certain are we about our choice?

Among the 5 questions asked, risk assessment is concerned with Question a) and e)[1], and risk management is concerned with the questions b) to question d). The overall result is management of those "scientifically measured or estimated" impacts, whether positive, negative, or ameliorative, associated with "scientifically identified" dangers. (Short 1984 p.711) In beginning a risk analysis, this standard procedure results in the following steps (see Figure 1-1):

1. Decompose the system operation into primary steps, which are required in achieving the system goals; the failure is defined as not achieving the goals.
2. Anticipate all possible errors and hazards that may potentially fail the system.
3. Determine the consequence and probability of failure for each hazard (scenario).
4. Rank the risks and identify most risky scenarios for risk management options based on the availability of resources.
5. Implement the selected risk management options.
6. Record lessons learned and feedback.

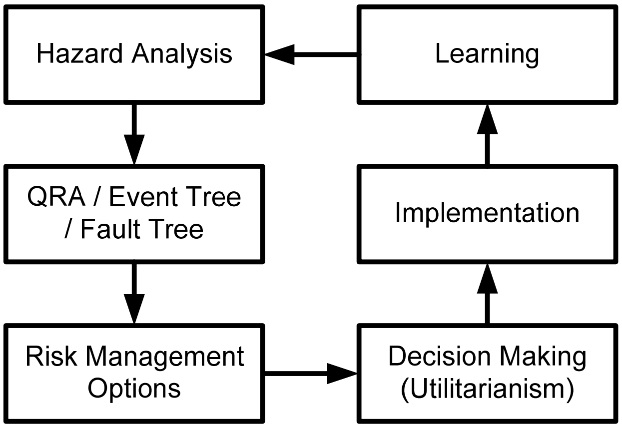

Figure 1-1. Conventional Risk Analysis Process

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[1] from personal communication with Professor Kastenberg, June 11, 2010

This conventional approach and its sub-approaches divide risks into separate, particular "diseases" of a system and analyzing their "pathology" by fault tree analysis (in which an undesired state of a system is analyzed using boolean logic to combine a series of lower-level events) and event tree analysis (which is based on binary logic, considering an event either has or has not happened, to identify a series of final consequences and their probabilities). By focusing on accidental events (mostly in a negative, harmful sense) as an entity by itself, traditional approaches are also insufficiently *holistic*. Without an understanding of the system's operation, its underlying condition (or its "constitution," as we will explore further) and state of health, it is impossible to develop a method for dealing with unforeseeable risks.

In the following sections, we will discuss and critique conventional risk analysis from the viewpoint of the dynamic approach which we will develop in Parts II and III of this work. It is noteworthy that the word "conventional" here means risk anaysis approaches based on the risk of "chance," as opposed to the risk of "change" which we will propose in this research.

1-2-5. The Focus of Conventional Approaches

The focus of conventional approaches to risk analysis today is based on failure-event/accident anticipation (Apostolakis 2000; Apostolakis 2004; Kastenberg 2006). This reduces risk assessment to a search for "causal links" verified by "objective" experimental processes and eventually integrated to a "set of triplets." As may be seen in the light of our foregoing arguments, this focus on failures and accidents means that conventional risk analysis can assist us only if a risky situation is anticipated and identified. No "real-time" value is present; this form of risk analysis will not tell you the implication of an error during a task only after the task has already failed. That is, a traditional account of risk is insufficiently *dynamic* without attention to constantly changing nature of risk.

Yet the struggle to arrive at a truly "objective" set of parameters for outcome probabilities, paradoxically, brings risk analysis full circle to an awareness of its limitations. As Bernstein (1996 p.197) puts it:

> *The essence of risk management lies in maximizing the areas where we have some control over the outcome while minimizing the areas where we have*

absolutely no control over the outcome and the linkage between effect and cause is hidden from us.

Despite these efforts to quantify risk and make analysis objective and regular, the result is still far from objective as a whole. Risk assessment depends heavily on experts making what are fundamentally subjective probability assessments of the expert's judgement as to "how likely is it that this will happen?" Risk assessments must include not only objective evidence but also subjective judgments, usually those of an qualified expert. (Vick 2002 p.51) Ideally, this approach, as it seems, requires modern experts to become the "rational men" of Classical probabilists.

1-2-6. The Benefits of the Risk of Chance

Despite our criticism of the conventional notion of the risk (of chance), this idea does nonetheless provide a useful foundation for thinking about risk. The idea of the risk of chance is that risk analysis should attempt to include all important chance events, or at least as many as possible.

Within a system with a narrow range of resultant values, a conventional risk-of-chance approach based on enumerating and measuring possibilities is more than sufficient. If there are only a few reasonably expected possible states for a system based on a smaller number of interacting parts, then an exhaustive fault-tree/event-tree analysis is not only feasible but useful. No complex paradigms or heuristics need be set forth; a set of simple, determinate rules will suffice. The operation of a small parking lot, for instance, will probably not require a complex risk-of-change analysis of the type we will propose; a simple risk-of-chance analysis without regard to the internal dynamics of a parking lot may suffice. In sum, a simple, well-formed problem requiring little adaptation to change is an ideal use for a risk-of-chance analysis.

Traditional risk-of-chance risk managers, since they accept that all events are to some extent unanticipated and unforeseeable, tend to make detailed particular backup plans and mechanisms, developing well-defined quality assurance (QA) / quality control (QC), emergency and crisis management plans, i.e., interactive RAM per Bea (2005). Thus, acceptance and awareness of the risk of chance makes risk managers better able to react to systems that vary rapidly within a narrow band of performance.

1-3. Shifting Paradigms of Systems

1-3-1. Society Evolves, Problems Emerge, Then Worldview Changes

> *Human history is often seen as an inexorable march towards greater complexity—in ideas, artifacts, social, political and economic systems, technology, and in the structure of life itself. While we do not have detailed knowledge of ancient times, it is reasonable to conclude that the average resident of New York City today faces a world of much greater complexity than the average denizen of Carthage or Tikal. A careful consideration of this change, however, suggests that most of it has occurred recently, and has been driven primarily by the emergence of technology as a force in human life. In the 4000 years separating the Indus Valley Civilization from 18th century Europe, human transportation evolved from the bullock cart to the hansom, and the methods of communication used by George Washington did not differ significantly from those used by Alexander or Rameses. The world has moved radically towards greater complexity in the last two centuries. (Braha et al. 2006 p.1-2)*

The advance of information technology in the past decades has made the rate of society's advancement faster than ever. Distance has been largely overcome and human-made barriers lowered or removed to facilitate the exchange of goods and ideas. Globalization makes this dynamic society even more complex; networks of interconnectedness and interdependence have grown. This increasing integration of society has enriched life but also created a world of massive, interconnected systems so complex that they seem "to have a life of their own. This is where complexity truly enters our lives." (Braha et al. 2006) Rasmussen, in his *Risk Management in a Dynamic Society: A Modelling Problem* (1997), goes further, stating that the location-less, inter-connected dynamic society of the present brings with it a dramatic challenge to conventional risk analysis: society may be too complex and move too fast for conventional risk analysis to adequately encompass. Rasmussen's (1997 p.186) account touches on a number of important themes we will discuss further, noted here:

> *A very fast pace of change of technology is found at the operative level of society within many domains, such as transport, shipping, manufacturing and process industry. This pace of change is much faster than the pace of change*

> *presently in management structures… An even longer lag in response to change is found in legislation and regulation. The different time lags found at the different levels thus present a problem, and the dynamic interaction among levels during a period of change becomes and important modeling issue. [Note mine: the rate of change]*
>
> *The scale of industrial installations is steadily increasing with a corresponding potential for large-scale accidents. Very low probabilities of accidents have to be demonstrated for acceptance of operation by society. [Note mine: system mass] Consequently, models should not only include normal or average performance, but also very rare conditions.*
>
> *The rapid development of information and communication technology leads to a high degree of integration and coupling of systems and the effects of a single decision can have dramatic effects that propagate rapidly and widely through the global society. This has been demonstrated by the effects of less successful computerized trading systems (e.g., the Wall Street turbulence in 1987 (Waldrop 1987)). It is thus becoming increasingly difficult to model systems in isolation and to make small-scale, local experiments to evaluate models. [Note mine: holism]*
>
> *Furthermore, companies today live in a very aggressive and competitive environment which will focus the incentives of decision makers on short term financial and survival criteria rather than long term criteria concerning welfare, safety, and environmental impact. [Note mine: goal setting / system constitution]*
>
> *These trends have a dramatic effect on the necessary approach to modeling system behavior in some very fundamental respects, and they raise the problems of modeling by structural decomposition versus functional abstraction.*

Our traditional conceptual framework for risk analysis is now facing serious challenges due to the rapid pace of change in today's societies. The problems created are deep, fundamental problems that cannot be solved on the superficial level on which they were created. We need a new level, a deeper level of thinking – a *paradigm shift* based on the principles that accurately describe the changing behavior of our society and the engineered systems that support it – to solve these deep concerns. As Albert Einstein observed, “The significant problems we face cannot be solved at the same level of thinking we were at when we created them.” (Covey 1989 p.42)

1-3-2. Kuhn’s Concept of Paradigm Shift

In his highly influential book, *The Structure of Scientific Revolutions*, Thomas Kuhn introduced the concept of *paradigm shift*. Kuhn shows how almost every significant breakthrough in the field of scientific endeavor involves a shift in the assumptions and patterns of thinking carried out by scientists. The process begins with a shared conceptual framework, or paradigm, developed within a certain scientific community focused on the problem solving achievements of its theories. As long as the prevailing paradigm retains its problem-solving capabilities, research in the field serves primarily to articulate and amplify it. During this phase, the paradigm determines what questions are asked, what quantities are measured, and what phenomena are observed, all of which are directed toward confirming, not challenging, accepted theory. Eventually, however, anomalies arise that the old paradigm cannot address. Attempts are made to modify prevailing theories to accommodate these disparities, but at some point there comes a pronounced failure in the paradigm’s problem-solving ability and it breaks down altogether within a short period of time. A new conceptual framework with different principles and theories emerges to change the entire view of the field and its fundamentals. This is not merely an extension of the old theories but an abrupt discontinuity. (Covey 1989 p.29; Vick 2002 p.65-68)

As the pace and complexity of societal change has accelerated, the conventional risk analysis paradigms have become less and less able to produce adequate, preventive solutions. It is apparent that existing paradigms of risk analysis have failed noticeably when dealing with complex situations. There is the need for a new understanding of systems in order to manage risk in them.

1-3-3. Shifting Understandings of Systems

Developments in modern physics provide us with the most important bases of our paradigm for how the world and systems operate (both natural systems, such as human body systems, and man-made systems, such as engineered systems). These system concepts depend heavily on the worldviews that generate them, or as Dr. Dossey (Sheikh and Sheikh 1989 p.396) puts it: "the very meanings of illness and health, the body, the will, therapies of all sorts and how to use them—all these issues depend on a worldview for their meanings." When we discuss the engineered system as an *entity unto itself*, the assumptions which we depend on to discuss these systems have a critical result on the practical result we produce. The most irreducible, basic sets of assumptions we use are physical ones.

Why bring in physics? From the dynamic perspective, the answer is obvious: if we are to resolve our deep concerns about risk analysis, we need to have a new level of thinking to understand the systems on a deeper level. Since all systems are made of *matter* and require *energy* (thus *forces*) for their activities, and physics is the study of *matter* and *energy* (thus *forces*) and their interrelationships, application of physical principles shows us the beginnings of a new understanding of complex engineered systems as dynamic, functional organisms.

The idea of the organization as a machine, or the organization as a living human system, transforms our understanding of systems in the same way that the theory of relativity remakes physics. (Lewis et al. 2008) Traditionally physical metaphors and physics have been used for reductionist purposes; they cast difficult questions in stark terms, but also ignore the effect of organization. As Kauffman (1980 p.1) puts it:

> *This [reductionist approach] sounds reasonable, but it leads to the illogical conclusion that there is no difference between a comfortable house and a pile of building materials, or between a frisky mouse and a test tube full of chemicals. The difference, of course, between the molecules in a mouse and those in a test tube full of chemicals is* ***organization*** *[Emphasis mine]. The molecules in a mouse are organized in a precise and complex way, while those in the test tube are just sloshed together. Most scientists realized that it was important to understand how the pieces fit together, at least in their own field, but they were still mostly concerned about the "parts" rather than about the "pattern (that brings the parts together).*

What is needed is a formal yet holistic understanding, one that deals as effectively with the epistemology of individual component risks as it does with the emergent dynamics of the system of risks as a whole. As with physics, an adequate formal yet holistic understanding of systems must recognize their *immanent dynamism*. Dynamic processes are the very substance of systems and organizations. As Scheid (2002 p.28) puts it:

> *(It) is not an aggregate of discrete morphological substances linked to each other anatomically by means of mechanical structure and physiologically by way of interactive functional systems. Rather, it is a complex unit of functions and a site of regular transformations. While these transformations have discernible patterns, the body itself is always becoming.*

What Scheid is discussing is, in fact, the notion of the body in Chinese medicine. This description, however, is also incredibly apt for dynamic complex engineered systems. This depiction of the dynamics of a complex system – the *body-as-system* notion from TCM – dramatically shifts the traditional Western understanding of the human body, from a classical-physics paradigm to something resembling a contemporary physics paradigm. The emphasis is no longer on static elements, atemporal measurements and the attempt to remove subjectivity from the decision-making process; rather, diagnosis in a TCM view focuses on the dynamics of change and flow throughout the system and its interaction with its environment.

This new systematization results in a set of powerful, reductive questions: *What is a system? What creates risks in systems? What are the signs and evidence that point to the cause of an accident?* These are, in fact, the re-figuration of questions from a theory of physicians: "What is a human body? What is it that provides the physician with complaints and with a history of an illness? What is it that the pathologist examines under the microscope?" (Sheikh and Sheikh 1989). In their chapter entitled *The Importance of Modern Physics for Modern Medicine* (Sheikh and Sheikh 1989 p.398-401), Dossey sets forth an argumentative position worth examining at length for correspondences that sets forth the perils and paradoxes of the system-as-body concept. In short, as we become more and more concerned with fixing a more and more accurate, lawful, even Newtonian physical representation of the system, the constituent parts of the system themselves disappear, for:

> *As long as we confine ourselves to the see-touch-feel world of the senses, the world of common, everyday ordinariness, we know what bodies are, and there is no need to raise the questions. But it is the business of modern physics to look beyond the world of the senses, to abandon the domain of common sense happenings; at this point human bodies are not what they seem.*
>
> *In contrast to what we see at the macroscopic level (which is describable by traditional physics), physical bodies at the level of the atom are mostly nothing but thin air. The amount of actual "material" inside an atom is roughly that of*

> *a baseball inside the Astrodome. This fact stands in stark contrast to the sensory experience of the doctor who experiences the body as a substantial concrete entity.*
>
> *But physicians see a body that is made up of "things" – organ systems such as the cardiovascular system; specific organs such as the liver; individual cells that comprise the organs; intracellular components such as the ribosomes and mitochondria; different molecules such as the DNA; and atoms and subatomic particles that comprise the molecules. Summing all these "things," the physician arrives at a definition of the body.*

For all the descriptive power of a microscopic, Newtonian view of human systems, however, consciousness is missing. Consciousness cannot be fixed as a certain physical object, even on the Newtonian account. A contemporary account must include emergent behaviors – that is to say, qualities such as "being alive" or "having awareness" which come about through the interaction of system parts – which inflect this understanding in the modern sense. The classical understanding that we have been critiquing, in fact, closely corresponds to the risk management concept of the complicated-system paradigm – a snapshot of risks that is by definition static in time and space. As Sheikh and Sheikh (1989 p.398-401) continue:

> *The paradox is that at the most elemental level the picture is very different. From the point of view of modern physics, the body is mostly nothing: it is almost total emptiness. There are no hard elemental particles, no separate bits that are assembled in ever-increasing complexity to finally add up to a body; there are only evanescent phenomena that cannot be pinned down at points in space and time as billiard balls might be.*

A more complete picture from the body/system perspective that we discuss corresponds to the Complex-System paradigm—it is dynamic in time and space. Yet despite physical principles, such as the Heisenberg Uncertainty Principle and wave/particle duality, the concept that all energy (and thus all matter) exhibits both wave-like and particle-like properties, there remain durable, fixed emergent properties in the universe like *qi* or patterns of energy flow. This idea is similar to the *simplicity principle* in the *I Ching*, or the notion that everything has a simple essential way that it follows. Despite the fact that we can acknowledge the physical substrate of our bodily systems may constantly be in flux at the most basic of levels, there are nonetheless simple patterns of flux which can be discerned.

Complex engineered systems can be seen in the same way as bodies—a combination of ever-changing patterns or habits which are constantly in flux, at different rates of changes inside a system. Arguably, it is not the matter that makes us up that our identities consist in; rather, it is the durable, invariant patterns of emergent behavior that make us recognizable as the same person after 5 years after all the matter in our bodies is replaced. As Dossey continues: (Sheikh and Sheikh 1989 p.398-401)

> *Thus bodies can be seen as chains, stretching out through time and space, by virtue of the sharing of actual constituent parts – a point of view that is obscured by the traditional view of the body as a concrete, enduring, unchanging object…*

We suggest something similar to Dossey's notion of "chains, stretching out through time and space" to explain the existence of a system: the continuity of the system resides in its existence across multiple time-states. This new perspective on systems explains why boundaries of large-scale complex engineered systems have become increasingly indefinite and vague – it is not merely that they have become spatially and organizationally more complex; rather, the patterns of change that make them up, and the environmental changes they undergo, have become radically more complex as civilization has advanced. Today, it is very likely that when seen in the traditional manner, the commonly encountered engineered system is of a scale so large as to dwarf human observer in comparison to the entire system, as if we were the floating atoms inside a gigantic human organism. The challenge is to find a view of a body and indeed of a system that attends closely to its qualities of interconnectedness and change, for as Sheikh and Sheikh (1989 p.398-401) concluded, that:

> *It might be that the most significant part of the legacy of modern physics to medicine will be the destruction of a rigidly local view of human beings. Locality – the idea that something is fixed at a particular point in time and space – fails at the level of the atom, and it fails also at the large-scale level of human bodies when they are viewed with pinpoint accuracy. A modern view of the body implies an unmistakable connectedness between all bodies, an intrinsic non-locality that is part of the life process. This quality cannot be found in the classical view of bodies or of living things: It is one of the most profound differences separating the medicine of the past and that of the future.*

What is required is a new view of systems that draws and re-configures the modern notions of "connectedness between all bodies" and "nonlocality" and casts them in useful terms that generate useful questions. As it turns out, this will correspond to the TCM view of the body which focuses on the connections and relationships between organ subsystems, as opposed to the Western view of the body that focuses on the physical parts of the body, as exemplified by the comparison in Figure 1-2a and 1-2b.

Figure 1-2a. Chinese Depiction of the Human Body
(Kuriyama 1999 p.10)

Figure 1-2b. Western Depiction of the Human Body
(Kuriyama 1999 p.11)

1-3-4. Systems Thinking

Systems thinking is a framework that is based on the belief that the component parts of a system can best be understood in the context of relationships with each other and with other systems, rather than in isolation. The only way to fully understand why a problem or element occurs and persists is to understand the part in relation to the whole. As Kauffman (1980 p.1) puts it:

> *One of the results of [reductionism] was the division of the sciences into many different specialties. Because the basic units of each subject are so different, it seemed that the ways these units were organized must also be unique, and that various specialties therefore had little in common with each other. The result was that the experts in each specialty developed their own specialized theories and their own specialized languages to describe them. Eventually, this meant that scientists in different fields could no longer understand each other and that the public couldn't understand any of them without years of study.*
>
> *Then, beginning in the 1920's a group of researchers began to make a serious study of the* ***patterns*** *[Emphasis mine] themselves, the ways in which all different kinds of "systems" were organized. And they made a startling discovery; no matter how different the ingredients of different systems looked, they were all put together according to the same general rules of organization! For the first time, there was a way of linking together all of the scattered fields of knowledge and showing what they had in common.*

This new approach to the understanding of systems is known as *General System Theory*. (Kauffman 1980 p.1) In its support, Bertalanffy (1968 p.32) argues that "there exist models, principles, and laws that apply to generalized systems or their subclasses, irrespective of their particular kind, the nature of their component elements, and the relations or "forces" between them. It seems legitimate to ask for a theory, not of systems of a more or less special kind, but of universal principles applying to systems in general." This theory makes possible the application of systems analysis for tackling significant, messy, real-world problems which do not fit neatly into various specialties, at a time when we face serious problems posed by the increasing dynamic society.

An understanding of how systems work has to begin, of course, with an idea of what a system is. Bertalanffy (1968 p.54) describes three different kinds of distinction in his concept of a system as:

> *a) according to the* ***number*** *of elements,*
>
> *b) according to the* ***species*** *of elements, and*
>
> *c) according to the* ***relations*** *of elements. [Emphasis mine]*

The number of elements implies a boundary of the object set, which may be physical or conceptual, and the species of elements can be expressed as quantitative or qualitative attributes of the elements. The *relations* of elements are a key distinguishing factor between patternless "piles," "heaps" or unstructured collection and true systems. A system is a collection of objects, with attributes, which interact with each other based on certain relationships to function as a whole. The illustration in Figure 1-3 shows this point.

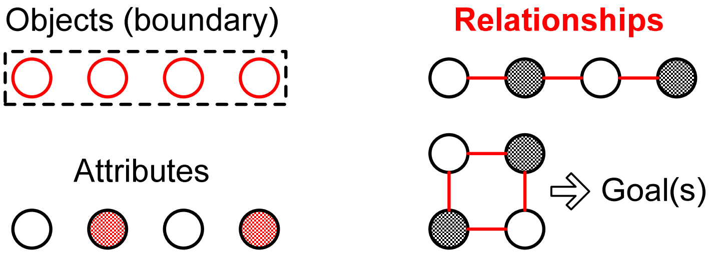

Figure 1-3. The System Concept
Adapted from (Bertalanffy 1968 p.54)

In addition the words "to function as a whole" imply a goal or goals for each system. The cooling system in a car, for example, may consist of a radiator, a fan, a water pump, a thermostat, a cooling jacket, and several hoses and clamps. Together they function as a whole to keep the engine from over heating, i.e., the goal, but separately they are useless. To do the job, all of the parts must be present and they must be arranged in the proper way. Moving one end of a hose just an inch is enough to put the whole cooling system (and the car) out of commission. (Kauffman 1980 p.1-2)

Kastenberg (2007c p.22) suggests that a general system is "goal seeking" and its goal is to search for equilibrium or balance (homeostasis) in a self-organizing or adaptive way. This is significant enough to quote, again, at length from Kauffman's (1980 p.2) words:

> *Another difference between "systems" and "heaps" is that "heaps" are not essentially changed by adding to the size of the heap or taking some parts away from it. Adding more milk to the milk already in a pail just gives you a larger amount of milk, but adding another cow to the one you already have does not give you a larger cow. In the same way, pouring half the milk into a second pail gives you two smaller amounts of milk, but dividing the cow in half does not give you two smaller cows. You may end up with a lot of hamburger, but the essential nature of "cow" – a living system capable, among other things, of turning grass into milk – would be lost. This is what we mean when we say that*

> *a system functions as a "whole." Its behavior depends on its entire structure and not just on adding up the behavior of its different pieces.*

The recurrence of "the whole is more than the sum of the parts" theme should be significant to us here. It leads, quite directly, to the fundamental idea of systems thinking, the idea that if "we know the total of parts contained in a system and the relations between them, the behavior of the system may be derived from the behavior of the parts." It is more than, as Bertalanffy (1968 p.55) puts it, "that constitutive characteristics are not explainable from the characteristics of isolated parts. The characteristics of the complex, therefore, compared to those of the elements, appear as 'new' or 'emergent.' If …we know the total of parts contained in a system and the relations between them, the behavior of the system may be derived from the behavior of the parts."

In other words, life – whether for a human body or for a system – is an emergent property, and as with any emergent property, it is inseparable from its immanent substance. The difference between a human being and human-being-sized can of protein soup is, as Kastenberg would put it (2007c p.22-23), a characteristic of a general system:

> *It is often said that for these complex general systems, "the whole is greater than the sum of the parts." This statement means that there is an emergent property that cannot be exhibited by the parts alone…living organisms can be dissociated into their component organs, tissues, cells, etc. Quantitatively, nothing is lost, but qualitatively, life is lost; the organism is no longer living.*

A system can be part of a larger system. If it is, we call it a "subsystem" of the larger system. And that larger system, of course, can be a subsystem of a still larger system. In fact, this pattern of systems being part of larger systems which are part of still larger systems, and so on, is something we will find wherever we look, in all parts of the human environment. (Kauffman 1980 p.2) The illustration in Figure 1-4 shows how such a hierarchy of systems would look if we started with one particular atom in one cell of our own brain and worked our way up from there as many levels as we could go. Each system on the list combines with other systems of about the same level to make up the next larger system.

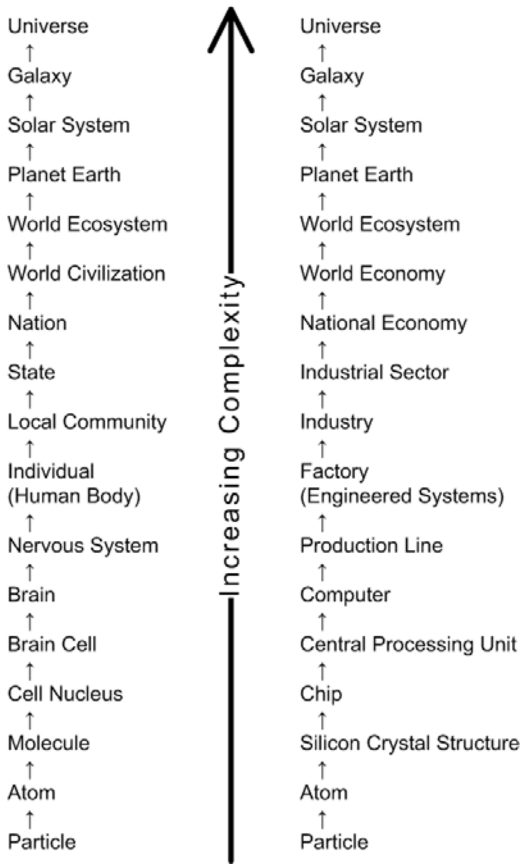

Figure 1-4. The Levels of Systems
(Kauffman 1980 p.2)

In summary, the concepts of systems thinking provide us with tools for better understanding problems of complex systems. However, these approaches require a shift in the way we think about the performance of a system. In particular, they require that we move away from looking at isolated events and their causes (usually assumed to be some other events), and start to see systems as a collection of interacting processes.

1-3-5. From a Complicated View to a Complex View of Systems

Although conventional risk analysis is a product of the old paradigm our societies and the engineered systems that support them have been dramatically changed. Historical or empirical data that usually provide some idea of the probability of an impact, or the impact's magnitude, are simply missing for some of the novel systems and problems that we face today. For Kastenberg (Kastenberg 2007c) the line is between the complicated systems paradigm of yesterday and the modern complex systems paradigm, developed in the light of the modern physics worldview. On Kastenberg's account (2007c p.20), the complicated system paradigm is:

1. *Reductionism/Atomistic*: understood by studying the behavior of their component parts,
2. *Deterministic*: deduced from cause and effect (a search for causal links or chains), and
3. *Objectivistic*: determined independent of the observer, that is, only deduced from "objective" empirical observations.

Thus, a factory, in the complicated systems view, is simply composed of machines, computers, pipelines, the raw materials it consumes, the people that work at the factory. In contrast, the complex systems view is:

1. *Holistic/Emergent:* the system has properties that are exhibited only by the whole and hence cannot be described in terms of its parts,
2. *Chaotic:* small changes in input often lead to large changes in output and/or there may be many possible outputs for a given input, and
3. *Subjectivist:* some aspects of the system may only be described subjectively. The system is simultaneously a whole and a part of a large whole.

For the complex systems view, the human behavior of the machine operators, the process of the factory's manufacture, and the programming of the machines are more of interest. The material aspects of the factory are, by their nature, different than the workers, machine and raw materials that make up the factory itself, for the business of the factory is the conversion of that raw material and worker labor into a finished commodity. We may even go a step deeper and see the human being as a process of social reproduction and commodity production, making each human being also another sub-process in the grand process that is the factory.

As Kastenberg (2007c p.20-21) goes on to note, the developments of the epoch which he calls the post-industrial, or information age in our view, have made the complex systems view superior to the complicated systems view for dealing with the distinctive problems of modernity, for, as he notes:

> *It should be made crystal clear that the impacts of human activities on both society and the environment (from developing nuclear power plants to deploying nuclear weapons) have always been complex. In the past, however,*

> *the only undesirable consequences of an Industrial Age technology, such as a nuclear power plant, that were considered in a PRA were geographically local (public health effects out to one mile or 25 miles) or they were observable in "real" time (the unfolding events at Three-Mile Island). This gave the impression that the current risk paradigm is accurate because locality and observability were two characteristics of the impact. This lens has changed in modern times and yet our practices are still based on the same paradigm. That is, a core melt accident has "global" impacts (a severe accident at one plant affects all plants) and manifests very quickly (e.g., loss of public confidence worldwide). In the case of disposal of radioactive waste, the undesirable consequences are almost imperceptible (e.g. the migration of high-level radioactive waste takes place over geological timescales or millennia). Moreover, these impacts may be temporally persistent and/or irreversible (e.g. the degradation of public welfare due to nuclear proliferation).*

A perfect example of the contrast between Complicated and Complex systems is the personal computer (a Complicated System) and the Internet (a Complex System). A computer is a very complicated system with millions of electronic components inside. The internet would be even more complicated in this sense. What distinguishes the two systems is that, although a computer is complicated, we can still understand how the system works by understanding each part of it. We type in what we want to say, print the page, and we know exactly what we will get. Everyone who repeats this process will get the same thing that other people get. That is a complicated system.

A complex system like the Internet is not merely millions of computers being connected together. There is something more than simply adding up all the computers. Understanding each computer would not help us understand the meaningful patterns that emerge as a whole, like the daily flow of e-commerce, the endless arms race between virus writers and security researchers, the constantly fluctuating content of search engines and the constantly updated domain name server system that runs the Internet. It is an aspect of the Internet as a complex system that small causes can produce big effects, for example, if someone puts a piece of virus code onto the internet, somewhere in the world might suffer serious financial crisis, as has happened several times in the past decade. This is what we call the behavior of a complex system. In a sense, the complicated systems paradigm focuses more on the individual constituent objects within a system, while the complex systems paradigm focuses more on the relationships between objects, as well as the emergent properties of the complex system that the objects inhabit.

1-3-6. Systems as a Collection of Dynamic Functional Processes

To help us understand the distinctive problems of modern risks and their management, Bea proposes a framework for engineered system. As Bea defines it (2005 p.33), engineered systems consist of seven essential elements, namely: *operators*, *organizations*, *environments*, *hardware*, *procedures*, *structure*, and the *interfaces* between each of the aforementioned elements. Bea's definition of the engineered systems suggests the importance of the interfaces (relationships) between each of the system components.

On our account, an *engineered system* is one where there is a *goal* for the system to function as a whole. Further, the system is, by definition, in involved with, and intervened in, by humans, and finally, the system is *constantly changing*; thus, the system state is *time-variant*. Per our definition, engineered systems share several key characteristics that are essentially those of complex systems, namely:

1. System elements are highly integrated,
2. Small causes can have system-wide effects,
3. Cause and effect are not obvious and direct,
4. System behaviors may be counterintuitive,
5. The whole system is constantly changing.

The system state's variance with time is an important determinant of its formal nature. Even as the constituent members of the system are constantly changing, there exist, as Holland (1998 p.7-8) puts it:

> *...patterns of interaction that persist despite a continual turnover in the constituents of the patterns... Persistent patterns at one level of observation can be building blocks for persistent patterns at still more complex levels... At each level of observation the persistent combinations of the previous level constrain what emerges at the next level. This kind of interlocking hierarchy is one of the central features of the scientific endeavor.*

What is seen again and again is the recurrent idea that *the interaction of recurrent patterns within a system is more important than its constituent elements*. This recognition of the system as a collection of changes is the most significant insight of the systems paradigm of engineered systems. It is the idea that a system can be understood as a collection of interdependent and interrelated, abstracted "functions or patterns." Even a machine, although tangible, is essentially created to perform a fixed function or pattern as a system. It is as true of physical engineered entities like buildings, computers and tables as it is of more notional engineered entities like projects, networks and even companies, for as Chesbrough states, "[a] system, e.g., a firm, can be seen as a collection of processes and capabilities" (Chesbrough 2009 Open Innovation class slides).

This idea – that systems are *composed of processes* – has important paradigmatic implications. After all, as Bronowski puts it (Sheikh and Sheikh 1989), "relativity is the understanding of the world not as events, but as relations." Relations – for Bronowski and indeed Sheikh and Sheikh solely the relation of an observer to the observed – can be understood as a kind of *pattern* or *habit*, a recurrent process or transformation that, in operation, comprises a system.

This idea is more than a particularity of a certain system. Rather, it has implications that stretch further, and indeed encompass the system as a whole. After all, engineered systems are viewed in this research as interrelated components that are kept in a state of dynamic equilibrium by feedback loops of information and control. A system is not treated as a static design, but as a dynamic process that is continually adapting to achieve its ends and to react to changes in itself and its environment. The original design must not only enforce appropriate constraints on behavior to ensure safe operation, but must continue to operate safely as changes and adaptations occur over time. Thus, formally speaking, an engineered system is not only composed of processes, the system is also, as a whole, a constantly changing process, much like a life cycle, and this reality should be reflected in a truly contemporary risk analysis paradigm. On our account, you cannot consider an engineered system's "life cycle" without saying "life" – that is to say, considering the engineered system as a living organism, with its own health, constitution (a notion we will explore further shortly), functional organs and interrelationships in-between.

Chapter 2. Criticisms of Conventional Risk Analysis

Risk analysis combines risk assessment and risk management. Both are driven by scientific and technical considerations based on sciences and applied mathematics. In somewhat oversimplified terms, scientifically measured or estimated risks associated with scientifically identified hazards are to be managed. This conventional risk analysis works well when the system under consideration has historical or actuarial data on failure rates and empirical data on public health and environmental impact. However, in an increasingly dynamic society, where systems have no fixed and well-defined boundaries, and their elements are interrelated and interdependent, the application of the conventional approaches appears to have many problems and constraints that need to be addressed. We discuss some of the important issues in the following sections.

2-1. Risk Assessment

2-1-1. Anticipating All Events Is Not Possible

It is not possible to anticipate every event, especially those events that occur rarely. Although we can prevent accidents by adequately learning from past experience and anticipating possible accidents using state-of-the-art technology, there are always unknown and unknowable events in the system that we can never predict happening. To go the other direction and include expert opinion or subjective beliefs through structured exercises such as fault-tree generation develops even more novelty, for "[fault-]tree generation is an art, not a science… Different sets of assumptions and models yield different sets of scenarios and source terms." (Kumamoto and Henley 1996 p.19)

It may simply be the case that we *cannot predict accidents* for these new and novel systems. The Chinese translation of the word *accident* is "*yi wai*," which in Chinese literally means *outside-of-expectation*. Indeed, there are statistical and theoretical constructs – specifically, Taleb's (2005) notion of a "black swan" event – that posit that "rare events exist precisely because they are unexpected." As Taleb (2005 p.109) puts it:

> *Rare events are always unexpected, otherwise they would not occur. The typical case is as follows. You invest in a hedge fund that enjoys stable returns and no volatility, until one day, you receive a letter starting with "An unforeseen and unexpected event, deemed a rare occurrence…" But rare events exist precisely because they are unexpected. They are generally caused by panics, themselves the results of liquidations (investors rushing to the door simultaneously by dumping anything they can put their hands on as fast as possible). If the fund manager or trader expected it, he and his like-minded peers would not have invested in it, and the rare event would not have taken place.*

Things are always obvious after the fact, and all conclusions are in the end "after the fact," or *ex post facto*. As Hollnagel et al. (2006 p.1) put it: "Efforts to improve the safety of systems have often – some might say always – been dominated by hindsight." Because we have only the past as a basis, Hollnagel et al. (2006 p.2) contend, this "colours our anticipation and preparation for what could go wrong and thereby holds back the requisite imagination that is so essential for safety."

Prediction in novel systems where previous experience is lacking intertwines the subjective and the statistical, for where the statistical fails, the subjective returns, in the form of human judgment, expert input and statistically based opinions. Yet in these new analyses, there is always something that is not quantifiable, and these factors are often omitted, as Liang notes (2006 p.51,117). Or, as Taleb puts it (2005 p.98), "Whenever there is asymmetry in outcomes, the average survival has nothing to do with median survival." On Taleb's (2005 p.56) account, the task of the risk manager is not to see events of the past as retroactively sensible, but rather as natural consequences of the factors which brought them about. As he puts it:

> *While we know that history flows forward, it is difficult to realize that we envision it backward… A mistake is not something to be determined after the fact, but in the light of the information until that point. A more vicious effect of such hind sight bias is that those who are very good at predicting the past will think of themselves as good at predicting the future, and feel confident about their ability to do so.*

In the end, the epistemological difficulties posed by the innately statistical (and thus flawed) and innately *ex post facto* (and thus outdated) nature of our understanding of risk are overcome not through just attempting to anticipate it more accurately, but rather through the search for actual, practical solutions. As the famed American computer scientist Alan C. Kay (1971) said, the best most practical idea is not to try to anticipate or predict the future. As he puts it, "The best way to predict the future is to invent it… it's easier to invent the future than to predict it." In other words, the future depends on how we want it to be and what we do to make it happen. We can be proactive about the future we want to achieve, instead of being reactive to accidents and events that stand in our way to the future. We argue that a more *proactive* paradigm is the way forward for the constantly changing conditions of risk today. A modern risk management paradigm should seek participation in the operation of the system, rather than the status quo *reactive* paradigm that attempts to prevent accidents and anticipate through developing accident theories. A core element of our critique is Vick's (2002 p.58-60) argument that the development of retrospective, fault-tree/event-tree based conventional risk management, in "affirming the consequent," reifies the theories it attempts to test, an artifact of the hypothesis-testing approach. The answers which our account develops, and more importantly the questions it raises, are different than Vick's, however. We are interested in the interrelationships of essential dynamics and changes in processes. Thus, we conclude our discussion of risk anticipation with the process of developing new technologies in new markets presented by Chesbrough, (2003 p.12) which perhaps best exemplifies our argument with regard to process:

> *When commercializing a new technology requires the resolution of both technical and market uncertainty, you cannot anticipate the best path forward from the very beginning. You simply don't know all the possibilities in advance. Not only is the future unknown, it is unknowable. No amount of planning and research can reveal the facts, because they simply don't exist yet. Instead, you must make an initial product to learn what some customers like and dislike about it. Then you must adapt your plans in response to the feedback as you go along, and make adjustments as more information becomes available…*
>
> *In summary, then, the best way to develop new technologies in new markets is to follow a few important guidelines: First, seek to explore a variety of possibilities, for which you should seek rapid feedback at as low a cost as practicable. Second, search for tests that are highly faithful to the eventual market, so that early success with the test is highly correlated with later market success. Finally, instead of detailed, thorough, and careful planning, you*

> *should instigate some initial probes and then react quickly to the new information that these probes reveal.*

2-1-2. Risk Is Not Time-Independent

As discussed in Chapter 1, the conventional definition of risk is usually simplified as a combination of probability and consequence of all imaginable events or accidents, i.e., the expected loss. Conceptually, this definition should enable easy ranking of risks and thus simplify decision-making. But in practicality, its usage is limited since the result derived through statistical inferences is largely based on the past samples of (at best) similar systems whose conditions in most cases are not identical to those of the system in question, and events also may occur which are completely outside expectation. And as the old argument goes, “all analogies break down at a certain point.”

It may be argued that statistical inference already includes time information, for the foundation of statistical inference is that knowledge can always increase with incremental information. (Taleb 2005 p.127) With Bayes’ theorem, evidence in different forms could be reconciled and used to update probabilities in a consistent and logical way to reflect a change in the state of knowledge. (Vick 2002 p.38) Thus, the more data and information we have about the system the more precise prediction about the future we will get. However, this event-based statistical inference would fail in two conditions: rare events would occur in asymmetric, “long-tail,” or unpredictable distributions, as well as definitionally unknowable events, and “Rare events are always unexpected, otherwise they would not occur.” (Taleb 2005 p.109)

In dynamic systems – systems that are constantly changing – we can never predict the precise future state of a system. Events that happened in the past may provide information as to the system state at that time, but as the system changes over time, that past information would be almost useless for predicting the future state of the system. Data from past experience is only effective in certain current events that have happened in the past, but many of them may never happen again and unknown new events may suddenly occur when systems gradually change over time. Based on Cracraft’s thoughts in the book, *Understanding Change* (Wimmer and Kössler 2006 p.270), we believe that all events are embedded in systems that are changing over time. Cracraft states it well:

> *Although many scientists may not think of themselves primarily as “historians” - they may be studying problems that can be assumed to be atemporal, or they*

> *may use "explanatory" equations that are time-independent (such as much of traditional physics and chemistry) – nevertheless the systems they study are the result of previous evolutionary change and, to some degree, however imperceptible, are still changing.*

Understanding risk requires an appreciation of how and why systems and their surrounding environments change over time. Instead of investigating single events that may never repeat again in the same form in such dynamic systems, what we need to learn from history are the patterns of their changing behaviors.

Time matters in risk analysis because functional problems associated with general degradation or aging, such as corrosion and weathering, do not usually exist in the form of an accident. Such problems may appear to be minor for the first sight, but their chronic (cumulative) effects, however, can be significant in the long run, either as independent factors (like lowered value, compromised system integrity, etc.) or as causatives or enablers for serious catastrophes (e.g. catastrophic structural failures, business-endangering flaws, serious system crashes). Thus, the current definition of risk fails to communicate the threat of such chronic (cumulative) effects which are often clarified only after accidents happen. Without a proper consideration of time (and accordingly the system state change), those chronic (cumulative) effects on risk cannot be quantified.

2-1-3. Searching for Causes Never Ends

Root cause analysis (RCA) is a class of problem-solving methods aimed at identifying the root causes of accidents or events in the field of risk analysis. The practice of RCA is predicated on the belief that accidents are best prevented by attempting to correct or eliminate root causes, as opposed to merely addressing the immediately obvious symptoms. By directing corrective measures at root causes, it is hoped that the likelihood of accident recurrence will be minimized. However, there are problems in this searching for causes. Chief amongst them is the innately human difficulty in discriminating causation from correlation. As Krausz discusses in his book (2000 p.50-54), *The Limits of Science*, the actual processes that create a particular form of causation are inextricable from their original contexts of ongoing processes and active factors.

Numerous problems plague RCA. Random chance cannot be separated from causation "unless we are pure determinists." (Krausz 2000) Further, each causative factor is itself the basis for another RCA and thus innately probabilistic. Since RCA is based on a notion of conditional independence between each level of causes, it is assumed that the occurrence of each event is independent from the rest. Thus, RCA performs well in systems that are highly reliable and well-defined, so a wide spread of failures does not exist. This, however, is not true in systems that are complex in nature.

Finally, the search for causation is an infinitely regressive process. The problem is that there is always a cause for the event and another event that causes the cause. The analysis goes on and on and never gets an end—any root cause we might identify, by the very rules of the exercise, will itself have meaningful root causes which we must attend to. For Krausz (2000 p.50-51), this is not so fatal a flaw as to invalidate RCA altogether; rather:

> *...such lack of certainty does not destroy the causal inferences drawn on the basis of statistical data. But it does mean that alternative outcomes are feasible, and that regularities we uncover such as that in most cases infections can be cured with antibiotics will be probabilistic.*

Thus, even for Krausz, at best RCA offers probabilistic answers. Instead of resolving the basic epistemological questions of statistical validity, this approach simply displaces the uncertainty onto the outcomes. Further, although promising as a complicated system risk management strategy, RCA fails to adequately incorporate the feedback-loop driven, dynamic nature of managing the risks of complex systems into its methodology, for as we have discussed, the causative factors underlying an accident or disorder may change as time goes on—what causes disorder in the system at one time may have a helpful effect at another time. In addition, attention to purely causative factors may not satisfactorily describe the importance of emergent behaviors in the operation of a complex system.

2-2. Risk Management

2-2-1. Risk Is Not Properly Communicated

Too often, the conventional risk of chance definition (risk = probability × consequence) does not raise appropriate awareness of risk, especially in complex situations. Risk of chance is likelihood and consequence, not a simple multiplication with safety as the additive inverse of risk. Risk is a normative notion, changing with situations and expectations, and must be assessed accordingly. (Epstein 2006 p.9)

Probability is used to communicate uncertainty when we analyze risks. Aside from the limitations of acquiring accurate probabilities for risk assessment that we have discussed in 1-2-4, the notion of probability itself creates a false sense of risk. As Taleb (2005 p.183) points out, we humans are essentially probability-blind. He explains that "our brain can properly handle one and only one state at once. It is difficult for our brain to imagine a state with 75% chance of happening." A 25% chance of getting influenza is a description for a target population that around 25% of them may be sick. However for individuals, one is either sick or not. There is not a state of "25% sick or 75% healthy." Besides, a low chance of having a fatal disease may relax our vigilance on the part of prevention, but there exists a chance that someone may develop that particular disease, even the chance is low; a high death rate of a certain disease may discourage our resolution to fight for our survival, but that does not mean no one can survive. Information of such kind deceives our perception to the changing conditions that we are actually facing and misleads us into making inappropriate decisions. (Taleb 2005 p.182-183)

> *Consider a bet you make with a colleague for the amount of $1000, which, in your opinion, is exactly fair. Tomorrow night you will have zero or $2,000 in your pocket, each with a 50% probability. In purely mathematical terms, the fair value of a bet is the linear combination of the states, here called the mathematical expectation, i.e., the probabilities of each payoff multiplied by the dollar values at stake (50% multiplied by 0 and 50% multiplied by $2,000 = $1,000). Can you imagine (that is visualize, not compute mathematically) the value being $1,000? We can conjure up one and only one state at a given time, i.e., either 0 or $2,000. Left to our own devices, we are likely to bet in an irrational way, as one of the states would dominate the picture—the fear of ending with nothing or the excitement of an extra $1,000.*

In the case of earthquakes, one that happens once every one hundred years usually deludes people into believing that it will not strike them at least one hundred years from the last time it occurred. But in fact, the earthquake is possible to occur at any second from now. It might not happen the past one hundred years, but may happen two or three times in the next ten years. The probability of its happening once every one hundred years is statistically sampled over a long span of history and across a large area. It does not tell you for certain whether the earthquake is happening or not at this point in time and space of where you are. Nor will it tell you how *bad* the earthquake is – is there a certain number of Richter Scale points which occur in a century? Would such a measure even be meaningful? The problem, as Taleb points out, is that our existing conceptual systems simply cannot conceive of a probabilistic impact as a concrete entity.

Nowhere is this innate conceptual difficulty clearer than in high-profile public catastrophes. The risk assessments associated with swine flu are instructive in this regard. In April, the Centers for Disease Control and Prevention (CDC) announced the detection of swine flu (H1N1) cases in the United States[2]. When the 2009 H1N1 virus became widespread, massive confusion and panic ensued. In June, the World Health Organization raised the alert to its highest level, stating that the H1N1 virus had spread to enough countries to be considered a global pandemic. Since the pandemic began, 50 million in the United States alone have been infected. CDC estimates indicate that worldwide, approximately 200,000 hospitalizations and 10,000 deaths occur yearly from H1N1. A vaccine created this year, which public health authorities say is the best way to protect against H1N1, was made available to the public this fall. Many countries urge their citizens to take the vaccine and aim to vaccinate the people in large scale to prevent further spread of the epidemic. However, a small percentage of vaccinations may result in potentially fatal complications. As the number of vaccinations rise, the probability of at least one fatal-complication occurring rises as well.

Let us consider the risk of H1N1 from different angles. From a government standpoint, since it is believed that statistically the number of deaths caused by the vaccine is far less then that may be caused by an outbreak of H1N1, most governments try to get as many people as possible to take the vaccine. Seen from a different perspective, however, the vaccination in such a large number, in fact, is a tacitly approved doctrine of acceptable harm: kill people or damage their lives (at a lower percentage) by vaccine (since no vaccine is perfectly safe) in order to protect a larger percentage of deaths from influenza. It would appear, at least on the surface, to be a matter of simple mathematics; count the number of dead from one approach, count the number of dead from another approach, and simply choose the approach that kills less people.

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[2] Source: Centers for Disease Control and Prevention http://www.cdc.gov/h1n1flu/

CNN Health http://www.cnn.com/2009/HEALTH/12/30/top.health.stories/index.html?iref=allsearch

The individual viewpoint sees things quite differently – and, from the individual's viewpoint, rightly so. It doesn't matter how frequently the vaccine is effective in preventing flu infection if its side effects are too costly to bear. (Taleb 2005 p.10) In fact, hindsight – not from the *ex post facto* perspective of risk managers, but rather from a more organic perspective integrating the situations of individuals within the system – shows that, in fact, for individuals, the anti-vaccination approach may have been correct after all. An approach that, for instance, focused on healthy living, strengthening immunity and quitting smoking while rejecting a vaccine would reduce a number of factors which make an individual more likely to catch H1N1. From the perspective of such a healthy person, in fact, it might legitimately be argued that a risk of adverse reaction to vaccine – whether biological, social, or even religious, as has occurred – is so significant as to outweigh a probabilistic prevention of a probabilistic harm, especially when the panic eased after health authorities determined that the H1N1 virus appeared to be no more dangerous than the regular flu virus. Evidence showed many of the seriously ill patients had underlying medical conditions.

The failure of traditional risk management to predict proper individual responses to the H1N1 pandemic are emergent properties of the process, demonstrating the necessity of a dynamic approach. Here, we have an adverse effect – improper advice – that is integrated deeply into the system of management, at a system-wide level, in fact. Its effect is not obvious and direct, and in fact counterintuitive – for who would think to ignore such an urgently phrased public health message? And, as the whole system is constantly changing (the characteristics of the H1N1 virus, as well as the public health response, are constantly evolving), new assessments of the danger of H1N1 that showed that it was not more dangerous than regular flu demonstrate that even a relatively well-understood problem may suddenly appear radically different after the passage of time.

For H1N1, what actually ends up being the correct individual response is that for an individual, in fact it is *not wise* to take the vaccine if he/she is healthy and does not expose himself/herself frequently in crowded places or places where one acquires infectious diseases easily, such as hospitals, since, it is actually riskier for that healthy person to take the vaccine than to take the chance of getting the flu.

What the H1N1 scenario shows is that real decision-making situations are complex and ambiguous. Accurately estimating the probability of outcomes in the case of complex engineered system is difficult and often impossible, and more importantly, many managers understand this. Thus, it therefore makes sense for them to place less faith in probabilistic impact estimates and focus on outcomes instead. So, for example, where the Nuclear Regulatory Council traditionally asked in risk assessments: *What can go wrong?* And *what are the consequences?* Today NRC risk managers ask *how likely is it that something will go wrong?* And, more importantly, *what performance is needed?*[3] One way of increasing decision makers' confidence in quantitative estimates is to document assumptions, methods, and data sources and present these together with numerical estimates. (Marais 2005 p.167)

Even if the chance of an accident is properly quantified, the associated consequence is difficult to estimate because accident scenarios and system boundaries are usually difficult to define clearly, and outcomes always engender new outcomes. What is seen as undesirable, and how undesirable it is relative to other options, depends heavily on individual value systems. (Marais 2005 p.36-37) With H1N1, from the perspective of a doctor tasked with following the Hippocratic Oath, "First, do no harm," one might legitimately reject the risks associated with the vaccine simply on the basis of the medical profession's deeply embedded value systems and attendant decision culture. Similarly, from the perspective of a worried parent, no cost might seem too great in obtaining a dose of vaccine, given a child attending a public school with hundreds if not thousands of other potentially infected children in close contact, even after factoring in (or discounting) the risk of adverse event from vaccine.

Seen from the traditional, non-dynamic approach, the H1N1 pandemic is a bewildering array of differing judgments and value systems. Since the crisis is occurring in a historically new context, with little empirical or historical data to support probability or impact assessments, a broad field of unknown risks with unknown, potentially irreversible, potentially unnoticeable impacts confronts the decision-maker. (Covello and Mumpower 1985 p.116) Again, the necessity of a more dynamic, responsive approach to risk management becomes apparent.

2-2-2. Motivation for Making Improvements Is Not Included

By definition, hazards are threats to people's lives and what they value and risks are measures of hazards. (Kaplan and Garrick 1981; Modarres 2006) Quantitatively, but not more precisely, risk is the expected value of possible loss of the adverse effect of a hazard.

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[3] http://www.nrc.gov/about-nrc/regulatory/risk-informed.html

Since the focus is mainly on the negative potential of risk – the failures, – risk management strategy traditionally aims at only rescuing the system. Such paradigms exclude the possibility of promoting the system to a higher health state.

A truly realistic risk management paradigm must also include the risk of the positive. As Short (1984 p.711) puts it, the need is for a more value-agnostic concept of risk, for:

> *The concept of risk need not, of course, be so closed or negative in connotation. A more neutral definition simply specifies that risk is the probability of some future event. Indeed there is a substantial literature concerning positive aspects of uncertainty and risk in people's lives. While risk- and cost-benefit analyses focus on both positive and negative potential outcomes, benefits tend to receive short shrift in these analyses as do positive aspects of risks. Scientific and social-policy analyses of risk are typically concerned with negative potentials, and they focus on a very limited range of things people value: their health, but not usually their mental health; their lives, but not usually their lifestyles; communities, or institutions, or the quality of their lives, their economic well-being in aggregate, but not in individual or distributional terms; the physical environment, but neither the social values associated with it nor ecological scarcity.*

To accept the *positive*, in addition to the merely *ameliorative*, possibilities to be gained from risk management hints at the beginnings of our new paradigm. Extending fully on Short's ideas, current risk-management approaches focus on eliminating the causes of failures, considered as singular, unitary events, and forget that there are certain conditions , manifesting as durable patterns with changing constituent parts, that are necessary for the failures to occur. If it is possible to control the conditions at a "healthy" level, we can prevent failures from happening, without having to anticipate the causes.

The risk management strategies of businesses, in fact, already incorporate this concept. Corporate risk managers accept the infinitely regressive nature of causal fault identification, and instead of endlessly questing for blameworthy original causes, focus instead on practical, structural solutions based on the internal resources they have available. As Kirkwood (1998 p.2-3) puts it:

> *Many people try to explain business performance by showing how one set of events causes another or, when they study a problem in depth, by showing how a particular set of events is part of a longer term pattern of behavior. The difficulty with this "events cause events" orientation is that it doesn't lead to*

very powerful ways to alter the undesirable performance. This is because you can always find yet another event that caused the one that you thought was the cause. For example, if a new product is not selling (the event that is a problem), then you may conclude that this is because the sales force is not pushing it (the event that is the cause of the problem). However, you can then ask why the sales force is not pushing it (another problem!). You might then conclude that this is because they are overworked (the cause of your new problem). But you can then look for the cause of this condition. You can continue this process almost forever, and thus it is difficult to determine what to do to improve performance.

If you shift from this event orientation to focusing on the internal system structure, you improve your possibility of improving business performance. This is because system structure is often the underlying source of the difficulty. Unless you correct system structure deficiencies, it is likely that the problem will resurface, or be replaced by an even more difficult problem.

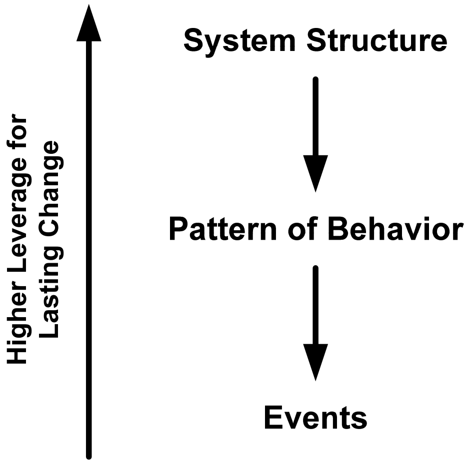

Figure 2-1. Seeking for High Leverage
(Kirkwood 1998 p.2)

Structure shapes function – in this context, business *behavior* – and this produces a chain of *events* that constitute the business, as shown in Figure 2-1. And, as with the Nuclear Regulatory Commission's approach, the focus is on *the performance required of the system in order to prevent accidents*. The internal structure of the system and its interactions may be a greater causative factor in accidents than any external factor; thus, when managers look to what variables they can manipulate to produce the desired outcomes out of the systems they manage, shaping the constitutive effect of system structure is a natural first place to look.

On Kirkwood's account, it is the conditions, seen as patterns of interaction inside and outside the system which are persistent in a system that are the most practical areas of inquiry. However, as Krausz and Taleb note, for separate reasons, these are often omitted in the search for causality. For Krausz (2000 p.44), the difficulty is the human tendency to read *conditions* as *causes*, or as he puts it:

> *[The] distinction between cause and condition is arbitrary but not entirely capricious. There are relatively stable conditions, in addition to those that change—it is the latter that are usually singled out as causes: Thus in the case of a forest fire, it is the spark that ignites the fire and the wind that fans it, that are said to be the causes of the conflagration, rather than the state of the climate or the composition of the wood.*

For Taleb, the difficulty is evaluating the probabilistic badness or goodness of a condition, even if we accurately identify the pattern that is causing the problem that Kirkwood is attempting to solve. These risks may in fact be effectively "transferred" by purchasing an insurance policy. Ultimately, however, since the focus is on events and accidents, such an approach detracts from a proper concern about system health and resilience – or what we will later term *system constitution*. In reality, system constitutions vary. A fire accident occurring in a chemical plant, for instance, is different from that in a house. Instead of the accident, the system itself should be the focus. This limitation of view to events-before-systems often promotes a too-little-too-late style of problem solving which only recognizes problems *after* something bad has happened. This ignores true catastrophes, for, as Liang (2006 p.108.119) puts it, "... there is usually no significant "event" before some catastrophic disease happens." A truly preventive risk management solution should detect and allow for undeveloped or latent problems, and focus on maintaining a stable level of overall system operation.

2-2-3. Solving the Wrong Problem Creates Backfires

Since the future is inherently unpredictable, any change to the current system will inevitably induce further disturbance in the future. Knowledge of this fact can, in fact, override typical risk-aversion and increase risky behavior by managers; seemingly safe control measures may in fact increase the overall amount of risk in the system. (Bernstein 1996 p.335) Knowledge of the ongoing patterns of change and a focus on maximizing the limited resources and rationality that decision makers have requires a new system of risk: the risk of change. Knowledge of only the risk of chance, as we will show, may lead to solutions for the wrong problems. As Bernstein (1996 p.336-337) puts it:

> *Nothing is more soothing or more persuasive than the computer screen, with its imposing arrays of numbers, glowing colors, and elegantly structured graphs. As we stare at the passing show, we become so absorbed that we tend to forget that the computer only answers questions; it does not ask them.*

When the incorrect bases for judgment are used, incorrect risk decisions result. A focus on sheerly quantitative bases for technical judgment, due to their basis in statistics, can be seen as questionable. The typical questions – "Is it safe within safety criteria? How safe is safe enough?" are insufficient. Systems may exhibit seemingly healthy operation, but often mask problems of functional deterioration; indicators exceed safety criteria only when it is too late. Periods of healthy operation may be the best time for avoiding bad situations.

Notions of "acceptable" risk may be inadequate. (Kaplan and Garrick 1981 p.23-24) The attempt to optimize system health based on a single numerical measure may not be adequate, even if the single numerical measure is a core one, such as the acceptable risk. For instance, if a system breaks down at a health criterion of 100, is it safe when the indicator is 90, 97, or 99? The answer of this question is never easy and depends heavily on the system uncertainties. Long before the indicator reaches the safety criterion, the system has been under functional change, and such period maybe the prime time for turning the bad situation. (Liang 2006 p.41) Since criteria are set for average systems through samples and experiments, the bases for decisions that affect the system may not be replicable in practice. (Liang 2006 p.65-66,118) Following only the conventional methods of increasing safety factor, building redundancy (the duplication of critical components of a system with the intention of increasing reliability of the system) into the system may be a waste of resource if we have the ability to manage the risk interactively, over the course of the system's operation. In addition, safety levels may change over time; a practice that was considered safe once may not be considered safe in the future. High blood pressure is an example; although high blood pressure by itself may form a symptom of an underlying condition (for instance, hypertension), it is also an adaptive mechanism – altitude changes, for instance, can produce blood pressure adaptations which are perfectly natural. Since systems are in a constant, natural state of fluctuation and change, an attempt to fix their safety levels to just one state may in fact produce its own complications.

Chapter 3. Philosophy and Theoretical Foundations

Throughout human history, philosophies and theories have been proposed to explain how the world works. An important reason for the search of such understanding is to prevent undesirable events from happening and to keep our world working properly as we expect. This desire has facilitated the early development of risk analysis which is, as Chapter 1 illustrates, essentially is a systematic way of understanding a system. As the world marches toward greater complexity, conventional paradigms of risk analysis fail to reveal malevolent events that may potentially jeopardize the health of our systems.

Western approaches of understanding how systems work use the discipline of complexity science to reveal the nature and dimensions of systemic risk. In Chinese civilization, the primary source of understanding how systems work is the *I Ching*, or *Book of Changes*, which elucidates the patterns of change that make up systems, and their changes. Unlike its Western counterparts, the Chinese school of thought reads system as composed of patterns of change. Thus, the background assumptions underlying risk are radically different in the two traditions. For the Western tradition, systemic risk is to be adjudged through a study or collection of particulars to be managed for better or worse with statistical tools and generalizations. For the Eastern school of thought with regard to systems, the notion of systemic risk requires the idea of patterns in a homeostatic system, quite literally a body. Essentially, medicine is a form of risk analysis for human body systems, and just as somatic and physical metaphors indirectly underlie Western systemic risk analyses, allegories of the body and the patterns of its “energy” flow directly undergird the Eastern school of systems thinking. As we discussed earlier in Section 1-3-3, human body systems are complex. And although risk analysis as such may be missing in the Eastern intellectual tradition, a careful study of medicine as risk analysis for the body may provide great insights into analyzing (including assessing and managing) risks for complex engineered systems.

Before we can begin to examine in depth the metaphysical and cosmological constructs that will drive our change-oriented model, we will take a moment to compare and contrast the distinct approaches to healing practiced by the conventional Western medical field and that of Chinese traditional medicine. As we will show, conventional risk analysis draws on the same philosophical assumptions and ideas as western medicine that lead it to systemic difficulties and inaccuracies which can benefit from learning the Chinese approach to healing.

3-1. Eastern and Western Paradigms of the Universe

3-1-1. Complexity Science—the Western Paradigm

A few years ago an issue of the journal *Science* was devoted to complexity science (Science 1999). In a key article, *Simple Lessons from Complexity*, Goldenfeld and Kadanoff (1999 p.87) describe our world as both complex and chaotic. They are convinced that "(a) complex world is interesting because it is highly structured. A chaotic world is interesting because we do not know what is coming next. But the world contains regularities as well. For example, climate is very complex, but winter follows summer in a predictable pattern." The paradox of *predictable patterns* but *chaotic substance* is resolved with a simple lesson then drawn from the argument: "Nature can produce complex structures even in simple situations, and can obey simple laws even in complex situations."

The idea of *predictability* co-existing with *chaos* in this uneasy manner is apt for complex engineered systems. Just as with climatic systems, complex engineered systems are *dynamic*. As a body of interrelated and interdependent subsystems, a complex engineered system is not fixed; it is always changing and evolving. No matter how slow the changing may appear to be, the system state may not stay the same forever. For instance, an automobile, despite being composed of well-understood constituent parts, can display a shockingly wide array of complex, nearly irresoluble malfunctions, as many owners of mid-20th century British automobiles can testify.

The paradox of apparent chaos emerging from predictability is dealt with by Holland in his book *Emergence: From Chaos to Order*. In Holland's view (1998 p.3-4), complex engineered systems can be creations of a relatively simple set of basic rules. This is not chaos, for:

> *Recognizable features exist, as in a pointillist painting. In addition, the systems are animated—dynamic; they change over time. Though the laws are invariant, the things they govern change. The varying patterns of the pieces in a board game, or the trajectories of baseballs, planets, and galaxies under Newton's laws, show the way. The rules or laws generate the complexity, and the ever-changing flux of patterns that follows leads to perpetual novelty and emergence. Indeed, in most cases we will not understand these complex systems until we understand the emergent phenomena that attend them.*

For Holland, even though our understanding may be highly uncertain, the apparent chaos is not, in fact, chaotic, but rather emergent phenomena that, upon proper inspection, resolve into clear and logical patterns. Holland's words about complexity match closely what the Chinese classic *I Ching* has to say about the changing universe we all reside in, in three regards:

1. A small number of rules or laws can generate systems of surprising complexity.
2. No single constituent remains in place, but the system persists.
3. Uncertainty is fundamental to the system's changing nature and is not simply the result of lack of information.

We concur with Bernstein's account of chaos theory and other sophisticated innovations on computer simulation, but with different results. (Bernstein 1996 p.332-334) Bernstein argues that scenario simulations at best tell you the projection of the system if current pattern of behaviors persist. The result of the simulation is never a perfect truth. As we will argue, simulation is best used to judge current system–health condition, rather than future outcomes.

3-1-2. I Ching (The Book of Changes)—the Eastern Paradigm

The *I Ching* is a Chinese classic that aims at reflecting the universe in miniature. The Chinese word "易 *I* (*yi*)" implies meanings of "to change" or "to exchange one thing with another" when used as a verb. The word "經 *Ching* (*jing*)" in this phrase means "classics," "treatise" or the "scriptures" that derived from its original meaning of "regularity" or "persistency." Together, the phrase *I Ching* implies that the text describes some ultimate or essential way of change, which will be invariant to the flow of time in a changing universe. Thus, in some English versions, it is translated as "The Book of Changes" (Wilhelm and Wilhelm 1995). Similar to science's stated aim of improving knowledge of causes, the *I Ching*'s explanations include both a description of our lives and the world that surrounds us, as well as the way that life and the world change, and the way the various elements in our lives and in our world affect each other.

The name *I Ching* is carefully chosen. An understanding of the etymology of the title is revealing of its core concepts and assumptions. The linguistic context of the word "易 *I* (*yi*)" demonstrates the variability and power of the concept of *I* (*yi*). The word is often used in three different phrases: "簡易 (*jian yi*)" (ease and simplicity), "變易 (*bian yi*)" (change and variability), and "不易 (*bu yi*)" (persistency and invariability). (Ritsema et al. 2005; Wilhelm and Wilhelm 1995) In fact, the three phrases conclude the insights offered in *I Ching* into the nature of reality that may apply in various given situations and provide our guides to the system underlying the category of change.

a) *Jian yi* / simplicity: The situations depicted in *I Ching* emphasize the normal, quotidian, everyday aspect of life: What happens to everybody every day, and what is simple and easy to understand. (Wilhelm and Wilhelm 1995 p.25) For the *I Ching*, the fundamental laws underlying everything in the universe are utterly plain and simple, no matter how abstruse or complex some things may appear to be.

b) *Bian yi* / variability: This concept expresses the constantly changing nature of the universe. For the *I Ching*, it is only human beings' abstract thinking that singles events out of their dynamic continuity and isolates them as static elements of a flowing phenomenon. (Wilhelm and Wilhelm 1995 p.25-26) The *I Ching* advises that comprehending this limitation on our perception of single events demonstrates the importance of cultivating one's flexibility in order to have the ability to deal with an unknown future full of diverse, context-dependent situations. As Wilhelm and his father (1995 p.26) state, "(w)ithin this category everything is indeed in a state of transformation. In each moment the future becomes present and the present past."

Change, in the *I Ching*, is inflected heavily by the notion of time. Change is perpetually self-renewing (change produces more change) and pervasive (everything is changing). Thus, it is in the context of a background of constant change that life is to be understood. Interruption of the natural flow of change – life change, environmental change, physical change – produces not a Cartesian opposite (death), but rather an impropriety, or perversion.

In the change-oriented *I Ching* understanding, change is a normative concept. As Wilhelm and Wilhelm (1995 p.26-27) put it, "(t)he opposite of change in Chinese thought is growth of what ought to decrease, the downfall of what ought to rule. Change, then, is not simply movement as such, for its opposite is also movement. The state of absolute immobility is such an abstraction that the Chinese, or at least the Chinese of the period which produced [*I Ching*], could not conceive it. Change is natural movement, [or rather] development that can only reverse itself by going against nature." The rational conventional risk manager attempts, more or less successfully, to attain an ideal, optimal system state – but the *I Ching*'s critique is that that system state is, by definition, *static*. Growth and development of the system as a process, not a snapshot based on yet more *ex post facto* assessment snapshots, is the *I Ching* risk manager's goal.

This recognition of the normative dimensions of managed change is a key message of the *I Ching*. The idea that everything is constantly changing is a fairly apparent, if arguable, philosophical concept. The simple, trivial recognition that things change is not the primary message of *I Ching*, which is far from a simple, trivial work. Rather, what it tries to show us is a preparatory, or even *propaedeutic* message: "to know that this movement and development takes place in typical forms and that these are governed by the law of change, from which there is no escape, this is the knowledge that has fostered in early Chinese philosophy." (Wilhelm and Wilhelm 1995 p.27) Development and growth are not teleological, for a teleological end state is a static entity by definition cut off from change. Rather, development and growth are guides, or maps for what is recognized to be the constantly changing terrain of everyday life. The aim for managing change is not to achieve an arbitrary, static end state, but rather "to keep within the flow of change." (Wilhelm and Wilhelm 1995 p.27)

c) *Bu yi* / invariability: Wilhelm and Wilhelm (1995 p.29) argue that this sense of the word "*I* (*yi*)" is used as the opposite of the word "danger." We believe that what Wilhelm argues as danger is in fact "uncertainty," from which fortune can arise just as easily as misfortune. Although everything in the universe seems to be changing, among the changing tides there are persistent, central principles or rules, which do not vary with space and time and are static and fixed only in their relationship. This extended "net of relationships" gives change its stability and constancy. For example, though we cannot predict what type of adult a child will grow into (*bian yi*, or the idea of no teleological end state, applies), there is nonetheless some aspect of Holland's "simple set of rules" underlying the complexity of growing and developing, insofar as we do know that the child will grow into some form of adult, and assisting this becoming is part of the essence of what it means to be a child, and thus carries a normative dimension (the "right type" of change). As Wilhelm and Wilhelm (1995 p.30) explain, "[c]hange is not something that is carried out abruptly and irrationally. It has its fixed course in which the trends of events develop. Just as we confidently count on the sun rising tomorrow and on spring following winter, so we can be sure that the process of becoming is not chaotic but pursues fixed courses."

In the view of the *I Ching*, change can be influenced, but "such an influence is only possible by going with the direction of change, not against it." (Wilhelm and Wilhelm 1995 p.31) That is, change must be consonant, or concordant, with the prevailing system's flow of change. Identification of the flow of change, and its direction, will yield the proper direction for change. Indeed, by locating key moments of change – what Wilhelm and Wilhelm (1995 p.31-32) term "the moment of germination" for the "seed" of a complex system – it is possible in fact to create a series of programmatic changes from a strategically timed small change.

As the Bible would put it, there is a time for all things. Sheikh and Sheikh (1989 p.71) suggest the coincidental similarity between *Ecclesiastes* and *I Ching*:

To everything there is a season,
and a time to every purpose under the Heavens: …
A time to plant, and a time to pluck up that which is planted; …
A time to weep, and a time to laugh;
a time to mourn, and a time to dance; …
a time to embrace, and a time to refrain from embracing; …
a time to keep, and a time to cast away:
a time to keep silence, and a time to speak. (Ecclesiastes, 3:1-7)

In sum, *I Ching* provides a simplified model of how the universe operates. Through this model, it helps people understand the way that things change and suggests principles and patterns of behavior which persist over time in order to maintain a balance in our lives.

The *I Ching* is far from a simple work, and an in-depth exegesis of its metaphors for change is beyond the scope of this work. Thus, to the extent necessary, we will introduce key *I Ching* concepts with their appropriate doctrines in a distributed fashion, as necessary to develop the notion of a dynamic risk management system. The gist of what *I Ching* says, for our purposes, can be thought of as consisting of:

1. Human beings originate from the prevailing way, or current of change, existent within nature, known as the *Tao*. People should act and behave according to the *Tao*.
2. Human beings and everything in existence may be considered to share the same origin. The gift of higher intelligence obligates people to strive to maintain harmony among all things.
3. All things are constantly changing in the universe. People should adapt to changes with an understanding of their patterns in order to stay on the right track.
4. Age, time and life status (what we might call "the behaviors that befit people of one age or another") are of crucial importance to people's lives. People should live their lives accordingly.
5. Human relationships with other humans, other species and the environment at large are complex and irreducible to basic, static laws. People should manage them carefully according to *Tao*.

3-2. Eastern and Western Approaches to Healing

3-2-1. Medicine as a Form of Risk Analysis

The terminology and conceptual vocabulary used by Chinese traditional medicine are powerful in terms of their ability to describe and explain patterns of systemic change and risk. This "toolkit" of ideas is contained not only within the base text of the *I Ching*, but also importantly is encoded in the way that the *I Ching* was written. We will base this reading on Leung et al.'s (2003 p.308) *A Comprehensive Guide to Chinese Medicine* for its comprehensive history of Chinese medical tradition. As Leung records, the development of medicine as a collection of empirically based, deterministic illness-cure correspondences required two basic methods, or ways, of medicine: "1) to find an efficient cure for a given illness; and 2) to recognize this illness each time in order to treat it with the appropriate cure." We can recognize something much like the NRC's revised risk management goals – that of 1) assessing risks and 2) identifying the proper regulatory response to manage that risk.

To a large extent, the current practice of risk analysis is shaped by, and contingent upon, the practice of modern medicine: they share the same philosophical foundations; they have interlinked histories, and one cannot exist without the other. Notions of medicine – ideas like syndromes, symptom-effect dichotomies, system health, and indeed the causal basis of etiology itself – are used interchangeably in the discourse of risk management just as they are in medicine because they are core conceptual underpinnings of any discipline that must manage constantly changing systems. Medicine was developed to assess and manage problems caused by diseases – or in the terminology of risk management, *accidents* – that may threaten our body systems, or the system of our body as a whole. So it should come as no surprise that the concepts and vocabulary physicians use in diagnosing and treating diseases are similar to what risk managers do in assessing and managing accidents that cause damage to an engineered system. The difficult and rewarding part of the task is not merely identifying the correlation – this is trivial – but rather making the correlation *elucidate something about risk management*.

Since medical understandings are historically and logically prior to those of engineering, the language of engineering is in no small part the language of medicine, as the simplified comparison between the two shown in Table 3-1. This is why we say that just as human beings do, man-made systems get sick and hurt. To explore more fully what this analogy means, and its implications for practice, we must first briefly review the history of medicine and the comparison between Eastern and Western approaches to healing, in order to yield insights into diagnostic and prognostic patterns that in turn will shed light on the great puzzle that we are trying to solve in this research – risk analysis for complex engineered systems.

Table 3-1. Medicine vs. Risk Analysis

	Medicine	**Risk Analysis**
Target System	Human body	Engineered system
Threat	Disease	Accident
Problem Detection	Diagnosis	Risk assessment
Problem Solving	Treatment	Risk management

3-2-2. The Success and Limitation of Modern Medicine

All ancient forms of cures, both Eastern and Western, are essentially "a philosophical speculation based on clinical observation. Philosophy and physics interact intimately with medicine. Thus, in primitive forms of both Chinese traditional medicine and that of the Western world at large, "[c]auses of illnesses, abnormal processes and effects of treatments were all explained by metaphysical expressions and philosophies. What happens inside the human body – its structure, functions, situation when it becomes dysfunctional or reverts to normal – therefore remains obscure." (Leung et al. 2003 p.309) Early Western accounts of bodily function through the operation of humours, for instance, or early Chinese organ-metaphors are clear examples of both philosophical concepts based within the medical.

From an early date, traditional Western medicine was heavily influenced by a struggle between the logical and the divine. As the early Greek physician Galen stated in the title of his work, "The best physician is also a philosopher." Early physicians struggled to develop objective, theoretical underpinnings for their practice, with the belief that an atomistic, mechanical model would lead to "a genuine understanding and control of the Universe." (Leung et al. 2003 p.309) For these early physicians concerned with establishing basic questions like the function of human organs, the structure of the circulatory system and the care of common illnesses, the primary difficulty was establishing the application of basic logical rules that we take for granted. And since medicine was still heavily mixed with philosophy and religion, during the early days of Western medicine it was not unusual, for "heretic" physicians utilizing empirical study to be driven out of town or executed publicly for quackery. It was, as Leung notes, a time when the Western physician enjoyed the type of status that the Chinese physician does today, namely, a low one.

Through scientific objectivity and the gradual accretion of hard-won anatomical and medical facts, medicine as we know it in the Western world developed a *deductive* understanding of medicine as particular objective facts, within a framework of a theoretical objective medical understanding. This has led to a simultaneous decrease in the importance physicians place on *inductive* clinical observation. As Leung et al. (2003 p.309-310) put it, "Western medicine has thus conquered the world as a "scientific medicine," because it is based on physical objectivity. Using experimental methodology, Western medicine explains objectively the causes of pathological changes in the organs, tissues and molecules. It gives objective justifications for a treatment. Diagnosis and treatment are now based on the objective reality of material changes, no longer on vague and variable clinical behaviors. Although clinical observations are not totally ignored today, Western medicine relies more and more on laboratory investigations."

It is a commonly repeated argument against Chinese traditional medicine that it lacks *objective bases* for its diagnoses and prognoses. In reality, this charge is more apt when leveled at Western medicine, for, as Leung et al. (2003 p.309-310) state, in the historical perspective, "…its supremacy today relies essentially on the cultural dominance of a rationalist mentality, which considers physical objectivity as the unique parameter of truth. Although nowadays Western medicine has become the mainstream medicine all over the world, in light of our anthropological studies, it is Western medicine and not Chinese medicine which should be considered as strange, since its experimental methodology is very different from all other medical systems. The application of scientific methods in medical practice is, in fact, an isolated case in medical history." The issue is not that Chinese traditional medicine lacks objective bases – rather, it does not concern itself primarily with objectivity, and such objectivity as it has it draws on from inductive reasoning based on accumulated clinical observations, not deductively derived medical axioms based on experimental study. As inductive clinical observation is the common basis of all medical systems, per Leung's anthropological survey, we may state that the anomalous tradition, logically speaking, is in reality the Western one. So too may it be said that the traditional paradigm of risk management draws excessively on abstract, experimentally-proven models divorced from any real experience. It is part of the goal of this paper to offer an alternative, practical, experience-based model grounded in the constantly changing world of the observably real.

To be fair, through hypotheses, experiments and theories, Western medical tradition has considerably advanced the art of diagnosis. The tradition of particular, generally-applied knowledge, advanced since the early anatomical studies of Galen and Hippocrates applied their observations to form early theories of the human body, supplies a highly detailed phenomenology and ontology of the body. (Leung et al. 2003 p.2-3) However, despite the mighty power of science, there are still failures and disappointment. As any risk manager would tell you, knowing the risks is only half of the equation – it remains to be decided *what to do about those risks*. It is here, in the areas of preventive, holistic, bio-dynamic therapies that TCM excels, demonstrating a sophisticated, mature methodology of types of change and "energy" flows that may lack a basis in deductively defensible theory but has a strong foundation through literally eons of clinical observation.

A science of theoretically based particulars such as that advanced by the students and descendants of Galen and Hippocrates that form the basis of the success of modern Western medicine has its own drawbacks, for deduction has its own functional limitations. The corpus of experimentally-tested Western medicine excels at straightforward issues: infections, deficiencies, and tumors are a few examples. (Leung et al. 2003 p.6) However, when confronted with novel or unknown symptoms, the idea that every symptom must have a deductively derivable objective material basis becomes a handicap; as Leung (2003 p.6) puts it, “effective cure is beyond reach and even controlling symptoms can become haphazard.”

Just as early risk analysis reduced particular risks to specific organizational components, the growth of the modern medical specialist has today reduced illnesses suffered by a person to an illness suffered by an identifiable body component. Thus, it is not a person who has jaundice, but rather her liver that has jaundice; the treatment to be prescribed is then assigned to a narrowly constrained liver specialist. Even so-called “general” ailments like broken bones, severe wounds and aging have their own specializations (osteology, trauma medicine and gerontology, respectively). The result is an atomization, or mechanization, of the human body as medicine considers it, at the expense of a holistic, dynamic diagnosis and treatment cognizant of the inter- and intra-relationships of the patient’s organs, and indeed of the patient herself/himself. “Different organs are commonly taken care of by different individual healers or team of healers, who communicate and cooperate with different degrees of enthusiasm and dedication. Holistic care involves caring for the whole human individual as a compact, integrated biological entity. Instead, it has given way to a narrowly focused, specifically targeted, technology-based, well-planned spearhead of treatment. The greatly advocated holistic care is lost, unaware to the healers.” (Leung et al. 2003 p.3)

The result of the deductive bias and inductive inadequacy of the traditional rational tradition, as shown by (and indeed shaped by) medicine, is a startlingly wide array of seemingly insoluble problems. Conditions such as allergies or viral infection often involve unknown agents via uncertain pathways or ultra-microorganisms (such as bovine spongiform encephalopathy, or mad cow disease), causing a multitude of involvements. All those make handling and treatment very difficult. As a result, most treatments for chronic ailments like allergies stay at a level of symptomatic control; there is no commonly accepted Western "cure" for an allergy, because it is simply not seen as a curable ill. So too with most viral infections; from viruses as simple as common cold and influenza to those as fatal as AIDS, modern medicine still does not have reliable treatment methods. Other groups of diseases that modern scientific medicine have failed to provide effective solutions for include autoimmune system problems, chronic painful conditions and cancers. In all cases, endemic, systemic issues that are not traceable to a specific bodily component are implicated. In medicine as with the management of risk in engineered systems, constant development of more holistic, integrative, effective theories is needed.

3-2-3. East and West: Similarities and Differences

For all the value differentiations which we assign to it today, Eastern and Western systems of healing exhibited a high degree of similarity in their early stage of development. In the *Nei-Ching*, an ancient Chinese medicine classic, the scholar Ch'i Po said, "The most important requirement of the art of healing is that no mistakes or neglect occur." A similar statement can be found in Hippocrates's dictum of "*primum non nocere*" or "first do no harm." At the most basic level, these fathers of the Eastern and Western medical systems respectively set forth a basic rational *ends-means* orientation where the desired end is lessened harm, and all means that the doctor uses are aimed at bringing that cause about. Further, in both systems, the emphasis is on perception as the fundamental tool of the physician. Both speak to the internal and external causative factors of disease. Despite their differing bases in tradition and philosophy, both Chinese and Western medicines consider internally and externally caused ailments as treatable subject matter for their professions.

If we are to locate a divergence in the developments of the Eastern and Western traditions, the clearest point is the Enlightenment, and the Cartesian notion of the mind-body dichotomy. Advancements in measurement and observation, like the inventions of the stethoscope, microscope, and thermometer, all developed through hypothetical deduction, constituted not only leaps forward in medicine but also important changes to the field of empirical science at large. Through careful observation, hypothesis-testing, and theorization, modern medicine draws conclusions based on particular objective results – but at the expense of measures such as stethoscopy, self-reports and introspection which "are gradually discarded due to the difficulty of obtaining objective data." (Sheikh and Sheikh 1989 p.66) In contrast, the Chinese tradition has continued with relatively unchanged theoretical bases since its inception: it is still inductive, it is still based on clinical observations, and it still draws on the accumulated medical records of "millions of practitioners throughout thousands of years. The format of recording is a result of direct observation." (Tsuei 1978 p.552)

The notions of *atomicity* in the Western tradition and *qi* in the Eastern tradition demonstrate another important divergence in the two traditions. The oft-derogated notion of *qi*, or energy flow, could not exist in the experimentally-based, theory-driven science of Western medicine. Energy as *qi* is by definition immaterial and unobservable; it is a phenomenological entity, but not an ontological one. It does not exist in dead beings, for "*qi* (is) the current in a circuit that makes all body functions operate. The current can be felt when the circuit is on, but it cease(s) to exist as soon as the circuit is broken." (Tang 2004 p.54-55) Western anatomy, based as it is on thousands of years of cadaver study, or at best vivisection, simply does not have the observational building blocks to form such a notion. Thus, the reductionism intrinsic to the Western rational method – the search for gradually more and more unquestionable and concrete atoms of existence – results in an ignorance of the total *dynamic balance* of *qi* or energy flows that characterizes healthy systems. As systems theorists might put it, *qi* is an emergent property in complex systems, and as such it is a concept which we argue that risk management strategies for dynamic complex systems should account for.

Dynamic balance is a concept we will draw on extensively. By dynamic balance, we mean a constant state of adjustment to maintain a controlled system within operating or safety constraints, generally accepted to be health in human and engineered systems. Hollnagel's (2006 p.16) definition of dynamic stability is useful to us, surprisingly, in this context, when he states: "[c]omplex systems must, however, be dynamically stable, or constrained, in the sense that the adjustments do not get out of hand but at all times remain under control." While human homeostatic thermal regulation might aim for, for instance, exactly 98.6 degrees, both Eastern and Western systems correctly place the emphasis on the concept on the process of maintenance, not at the desired temperature, since internal temperature is always balanced with external conditions.

The treatment of the balance between internal and external environmental causation marks another key difference to the Chinese medical tradition that is of particular importance to risk management. The disease is the focus of traditional Western care as we know it. As Tsuei argues, even when developed into teams, those teams of specialized physicians are still treating the individual disease. The critique from the Chinese medical viewpoint would argue that this ignores the foundamental problem of the individual patient, which is that of the individual’s adjustment and health within the context of his or her environment: (Tsuei 1978 p.552)

> *The Eastern idea of health and disease is looked upon as the two sides of a coin. In other words, every individual person is in a state of balance between external insults and internal defensive mechanisms. If the insults are greater than one’s defenses, one is ill; if not, one maintains good health. Since the individual person is considered merely a microcosm existing in a macrocosm, there are changes every minute, with constant readjustments. The duty of a physician is to strengthen the internal defensive power and power of adaptation of each individual person and enable him to fight the environmental insults, or to adapt to external changes so that he can live in peaceful balance within himself and with his environment, thereby maintaining good health. The responsibility of a physician is, in fact, to promote health and treat diseases when they occur.*

So too with systems – the idea, in fact, that a system is “merely a microcosm existing within a macrocosm” in fact is almost a verbatim axiom of systems theory. We argue that that in standard professional practice, the practice of managing the risks associated with, for example, the structural integrity of a building, is inseparable from a consideration of the environment of changes and flows that the building takes place in. Isolating these risks from their environment is as impractical as treating a case of bronchitis without inquiring as to what kind of air the patient is breathing and how closely they live to a factory or industrial pollution source. In contrast to a prevailing mindset that aims at diagnosing only the *structural*, a proper diagnostic mindset for systems and personal health must also consider the *functional* aspects of how the system/person adapts to their environment.

Despite its apparent illogicality, this type of basic logical flaw – ignorance of functional internal/external environmental interaction – informs a surprising amount of medical and systems theory. Chinese medical theory accepts that “(a) disease may have an external cause, but all diseases have an internal cause and involve to some degree an illness of the spirit. Thus, the patient has a primary responsibility, and the health care practitioner can only assist him or her in becoming well. The basic energy is treated; all else flows from it…” (Sheikh and Sheikh 1989 p.66) In contrast, the specialized team of physicians driving traditional medical decisions considers a collection of individual symptoms with external causes; no attention is paid to internal etiological patterns that the patient may be in control of, relieving the patient of responsibility for their ills. " A pill exists or must be found for every ill…"(Sheikh and Sheikh 1989 p.66) In contrast, *preventive care* has always been the focus of the Chinese medical tradition. Ultimately, in order for any cure to be lasting, it has to also be preventive of future recurrences. The implications for risk management should be obvious: as risk managers, it is incumbent upon us to treat not only the external, immediate dimensions of risk, but also to set in place internal, preventive measures that diminish or eliminate those risks.

It is important in setting in place these internal preventive measures that the sensitivity to the emergent qualities of the system – in other words, the very life of the system – be preserved. A straightforwardly Western view of the balance between internal and external systems results in ultimately self-defeating preventive care. Tsuei (1978 p.552) has a concise summary of this argument:

> *The Western approach to health care involves, among other things, changing the environment in which we live. For example, if the weather is not ideal for the body, a shelter is built with temperature control; if the atmosphere and humidity are not comfortable, other controls are added. Antibiotics are developed to counteract bacteria harmful to the body. Sterilization techniques are practiced to shelter from the bacteria. In therapy, the same principles apply. Artificial limbs and organs are used to replace diseased or injured body parts. Synthetic hormones and vitamins are used for impaired bodily functions. These achievements mark the victory of science and wisdom of mankind. However, in spite of the fact that human life is being prolonged, and the handicapped and retarded are functioning, the majority of people may be free from serious disease but not from discomfort or pain, either physical or mental. In other words, people are still suffering and unhappy.*

The measure of success for a risk management intervention must include not only curing the disease, but also *restoring and promoting balance* with the environment. Simply curing the initial ailment is insufficient. Any acceptable, standard definition of health – a good example is the World Health Organization's definition – must include *the ability to function*. In its definition (WHO 2001), health is:

> *… a state of complete physical, mental and social well-being and not merely the absence of disease, or infirmity.*

What divides healthy and unhealthy states is the quality of the emergent property – life – that pertains to living systems. As Liang (2006 p.25,104) would put it, "[f]ocusing solely on curing diseases is never enough to keep us healthy and happy." A strategy aimed at maximizing health system functioning requires focus on strengthening adaptability from within, enabling the patient or system to deal with greater stress levels – giving that system or patient greater resilience, a term we will examine shortly.

The differences between Western and Chinese medicines are summarized in the following Table 3-2.

Table 3-2. Differences between Western and Chinese Medicines

	Western Medicine	**Chinese Medicine**
Philosophical Foundation	Reductionism	Holism
Reasoning	Deduction	Induction
Human Body Model	Structural model	Functional model
Concept of Health	Lack of disease	Total dynamic balance
Diagnostics	Causality oriented	Pattern oriented
Treatment Target	Diseases	Persons
Treatment Strategy	To cure diseases	To restore balance

3-3. Traditional Chinese Medicine (TCM)

TCM emerged in ancient China at a time when it was impossible for Chinese people to learn the physiology of the human body and the pathology of diseases that we now understand with the help of modern equipment and technology. Thus, early medical traditions had to see a human body as an organic whole and observe its external life activities and disease manifestations in order to understand its internal biological functions. With this specific approach – that of establishing a complete medical system based mainly on practical experience – the Chinese tradition introduced philosophical theories and concepts to the medical understanding like *qi*, the concept of energy flows which we have mentioned and will be discussed further in Chapter 8, *yin yang*, and *wu* *xing*, two terms which we will introduce in depth also in Chapter 8 to help organize the accumulated empirical data and form TCM's unique theoretical framework. (Lu and Lui 1998 p.1,5)

Since most people are more familiar with the modern Western approach in medicine, we will devote this section to discuss further these fundamentals of TCM.

3-3-1. The Philosophy of Holism

Underpinning the theoretical system of TCM is the concept of *holism*. This philosophy has its root in *I Ching*, where human being is seen as a small universe (microcosm) of the greater surrounding universe (macrocosm). (— 1994; Leung et al. 2003; Lu and Lui 1998; Tsuei 1978; Zhou 2004) This can be seen as a primitive version of Systems Theory, the interdisciplinary field about the nature of complex systems that resulted from Bertalanffy's General System Theory of the 1920's. (Bertalanffy 1968; Kauffman 1980) In sum, the concept of holism consists of two integral aspects:

a) the human body as an organic whole, and

b) the unity of human and heaven (i.e. universe or environment)

The term "heaven" deserves an explanatory note at this point. As used in the source literature which we are drawing on, "heaven" means the way the world should operate. Core to the concept of holism is, as Leung et al. (2003 p.49) describes it, the view of the body as "an organic entity composed of different organs and tissues, each having their own distinct functions but existing in a mutually interdependent relationship with each other. The body's organs, tissues and other parts are connected into this organic whole by the meridian system, a system of channels of the body in which the body's vital substances, including *qi* (commonly described as a form of vital energy in the West) and blood, circulate." In a holistic view of the risk management of a system, just as with the body, the channels of energy flow, or meridian system, literally maps flows to locations, tying together the material and immaterial. This concept of holism is illustrated in Figure 3-1.

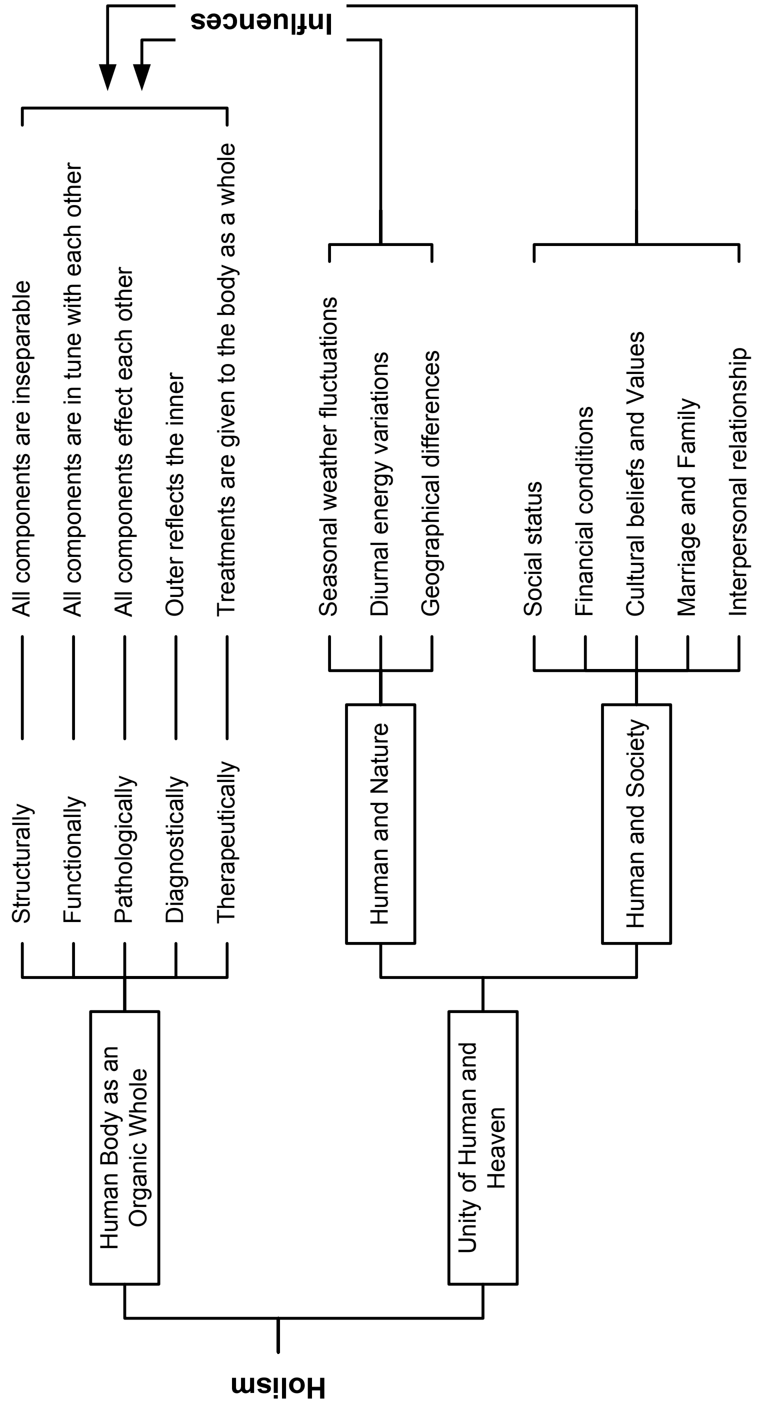

Figure 3-1. Concept of Holism
Adapted from (Zhou 2004 p.6)

As stated in *Nei-Ching*, the Yellow Emperor's Canon of Medicine, "Man is nothing but a creature living between the heaven and the earth." (Tsuei 1978 p.553) This can be taken to mean that, as Leung (2003 p.49,51) puts it, "[t]he philosophy of holism extends to the intimate relationship between humans and nature. [People] do not live in a vacuum, instead, they live within the natural and increasingly unnatural environment, and environmental change can have a significant impact on the body either directly or indirectly. The body can either adapt or a pathological response can occur (maladaption). Different seasons tend to be associated with different types of factors that cause disease."

Therefore, the *Nei-Ching* suggests that what is to be sought for people and for engineered systems is a harmonious, balanced relationship with the environment: "a man of wisdom will live his life in accord with the four seasons and in line with cold and hot climates keeping peace with the environment; he will live a harmonious life of joy and anger in a peaceful manner keeping peace within oneself; he will maintain a balance between *yin* and *yang*, between robustness and tenderness. Consequently, a man of wisdom will not be susceptible to attack from vicious energies and he will live a long life." (Tsuei 1978 p.553)

If a disease does happen, "treatment takes into account many environment factors including geography, climate and season… [Moreover, it is usually] tailor-made for the individual, and takes into account the individual's constitution, age, gender, syndrome, primary complaint and accompanying signs and symptoms, season of occurrence of the disease and geographic location." (Leung et al. 2003 p.49,51)

3-3-2. The Essence of Health and Disease

Health

It is important to clarify the definition of heath since a clear concept of health leads to an accurate perception of disease and accidents in human beings and complex systems. This allows for appropriate diagnoses and treatments to be developed accordingly. A core aspect of an empirically based Eastern view is the concept of holism. For this, we turn to Tang's *Getting Close to Chinese Medicine* (2004 p.24) for its explanation of this medical concept:

> *The human body is an organic whole that consists of various tissues and organs. Those tissues and organs, respectively, are formed by cells with distinct*

> *functions and properties. Through neurons, hormones and various other chemical messengers, our cells, tissues and organs interact and connect with one another and form a complex unity. Any change in organs, cells or even chemical composition at molecule level will influence and are closely related to the body as a whole. Therefore, it is not wise to isolate parts of our body trying to understand our health and disease; the body has to be studied as a whole. We all heard and joked about the story of "the blind men and an elephant." If we investigate our internal organs separately, we may not reach complete understanding of health and disease and are likely to make the same mistake that those blind men have made.*

The philosophy of holism is faithfully reflected in the way Chinese healers define health and disease. That is, for the Chinese tradition, a state of health per the WHO is a situation of balance: "when every thing coexists in perfect harmony, a person is in excellent health. Since the physiological process is in continual change and balance, as are the environmental conditions, this delicate change and balance between the microcosm (the human) and macrocosm (the environment) is constantly being readjusted in every respect. Once the balance is disturbed, illness sets in." (— 1994; Leung et al. 2003; Tang 2004; Tsuei 1978 p.553; Zhou 2004)

A subjective component is also core to the concept of health. For instance, Tang's (2004 p.23) account of the traditional Chinese notion of health holds that it should conform to two conditions: 1) each and every component of the body operates well and in harmony with the rest, as a result the dynamic balance is maintained internally; 2) subjectively, the person has to feel well.

An expansion of the concept of health is required before we can apply it directly to complex engineered systems. What should be retained from the TCM concept is that it must include a holistic picture of the dynamic balance between internal and external systems of change that constitute the complex engineered system.

Disease

In risk management in medicine as in engineered systems, an overdependence on objective test data can result in flawed decisions. For medicine, modern equipment and medical instruments are capable of revealing conditions of certain organs and chemical compositions in our body, at best locally. However, it is not possible to identify the functional relationships between parts and the whole through them. Besides, scientific experiments inevitably simplify the reality. In Krausz's (2000 p.48) view, "a scientific experiment poses a paradox since it selects out special sequences, and thus in a sense destroys the natural links that objects and events have in reality, by decomposing nature into events and particles." For instance, with a gastroscope, we can see the surface conditions of our stomach to confirm whether or not there are ulcers, tumors, or symptoms such as bleeding, inflammation or reflux. But it cannot help us observe the entire function of the stomach nor does it aid in understanding the connection between the stomach and our body as a whole. No modern doctor, Eastern or Western, would treat only the bacteria, knowing full well that left unaddressed, the causative factors of stomach disorder will bring the patient back again with the same symptoms. That is, taken by itself, the presence of *Helicobacter pylori* (*H. pylori*) might, for instance, necessitate the prescription of an antacid; but the testing results inform us merely of the existence of superficial phenomena. If we diagnose disease or judge our health based on those observed results, we are very likely to treat a wrong problem. What we see through a gastroscope is merely a snapshot of the condition of a stomach in the process of interaction under various factors: time of day, state of nutrition, gender, occupation, lifestyle and diet just to name a few. It tells us neither the source of such phenomena nor their causes, which must be derived through the diagnostic arts.

Suppose a patient presents with a stomachache. Through gastroscopy, a doctor discovers a *H. pylori* infection increasing inside the stomach. What this result actually tells us is that under the effects of various pathogenic factors, there is an excess propagation of *H. pylori* inside our stomach. It does not tell us several key pieces of information: Why the number of *H. pylori* is increasing? What the relationship is between *H. pylori* propagation and our inflammatory stomach and the balance of our body? If we mistake the gastroscopy result as the disease itself and try to use antibiotics as a cure, it is not possible for us to resolve the root problem that causes discomfort, and usually the relief will not last very long before the same problem happens again. (Tang 2004 p.24) There may be, for instance, an immune-system weakening illness, a severe smoking habit, or any number of other factors which are known to produce gastrointestinal discomfort which would escape untreated absent a holistic analysis of the patient's health situation. This is why today most doctors do not simply prescribe antacids or antibiotics without also advising patients as to stress-reducing life changes.

Symptoms of fault may in fact demonstrate the system attempting to regain its equilibrium. Physician and evolutionary biologist, Nesse, and ecologist, Williams, in their book *Why We Get Sick: The New Science of Darwinian Medicine* (Nesse and Williams 1994 p.19-23(8-11)), argue that in the human body, symptoms such as coughs, vomiting and fevers, although negative symptoms in and of themselves, may in fact be valuable defense mechanisms, and not defects (as a straightforwardly symptom-based understanding might analyze them as.) Consider the cough exemplified in the book:

> *Defenses are not actually explanations of disease, but because they are so often confused with other manifestations of disease we list them here. A fair-skinned person with severe pneumonia may take on a dusky hue and have a deep cough. These two signs of pneumonia represent entirely different categories, one a manifestation of a defect, the other a defense. The skin is blue because hemoglobin is darker in color when it lacks oxygen. This manifestation of pneumonia is like a clank in a car's transmission. It isn't a preprogrammed response to the problem; it is just a happenstance result with no particular utility. A cough, on the other hand, is a defense. It results from a complex mechanism designed specifically to expel foreign material in the respiratory tract. When we cough, a coordinated pattern of movements involving the diaphragm, chest muscles, and voice box propels mucus and foreign matter up the trachea and into the back of the throat, where it can be expelled or swallowed to the stomach, where acid destroys most bacteria. Cough is not a happenstance response to a bodily defect; it is a coordinated defense shaped by natural selection and activated when specialized sensors detect cues that indicate the presence of a specific threat. It is, like the light on a car's dashboard that turns on automatically when the gas tank is nearly empty, not a problem itself but a protective response to a problem.*
>
> *This distinction between defenses and defects is not merely of academic interest. For someone who is sick it can be crucial. Correcting a defect is almost always a good thing. If you can do something to make the clanking in the transmission stop or the pneumonia patient's skin turn warm pink, it is almost always beneficial. But eliminating a defense by blocking it can be catastrophic. Cut the wire to the light that indicates a low fuel supply, and you are more likely to run out of gas. Block your cough excessively, and you may die of pneumonia.*

In rational Western medicine, as in risk management, the results of tests and examinations are usually the sole basis of diagnosis. Oftentimes, the identification of an unusual index number or a visible change of a certain organ, no matter whether the observed facts affect or damage your physiological condition, indicates "a disease" and a treatment will be needed. The objective of treatment usually aims to bring the index back to a normal, standard value. Illness without an abnormal test result is not (and cannot be) treated as a disease and is usually attributed to psychological factors. Such cases do not occur if we focus the diagnosis of disease on the internal balance of a body instead of on those isolated incidents of abnormal test results. (Tang 2004 p.34)

A human body is a complete and complex system. The system operates well when each of its component part is in a harmony and balanced state. In other words, even for people who are diverse in terms of their age, sex and constitution, as long as harmony between the organs, tissues, vital substances, structures, mind and emotions exists, a person is healthy; otherwise, the person is ill. TCM's concept of holism proposes a distinct concept of health and disease from that of Western medicine. Test results as obtained in Western medicine, when abnormal, have to be considered along with the dynamic balance of the body in order to reach an accurate diagnosis. If the abnormal test results show that the balance of the body has been disrupted and symptoms of illness have emerged, then a disease can be confirmed. However, if the abnormal results appear under certain physiological conditions and the internal balance of the body is not broken, then it is not a disease. (Tang 2004 p.34) A test revealing high internal temperatures may indicate fever, or it may indicate normality – the person tested may live in a cold climate, have a faster metabolism, be undergoing a menstrual cycle-determined rise in body temperature, or may simply be at the edge of the range of known human temperature variations. A single measure, in medicine and in risk management, is never enough. The context must be considered, and the diagnosis and treatment must be adequately holistic in focus to succeed.

3-3-3. Pattern Differentiation and Treatment Determination

Diagnosis

Given the remarkable success of modern medicine, many wonder how TCM can reach accurate diagnoses without advanced biochemical technology, medical imaging equipment, or any of the scientific theories in Western medicine, such as anatomy, physiology, pathology, pharmacology. With mere visual observations, a few questions for a patient, and pulse taking, can a Chinese physician diagnose the patient's disease and give a proper treatment? The secret lies in the type of measures conducted. Rather than single measures that show the state of a human body, TCM practitioners are more interested in summary measures that demonstrate the human body's overall balance or lack thereof. The lesson for risk management is that single measures are valuable when they are *summary* in nature – that is, indicating the dynamic state of system – and not when they are static, reductive measures. The strength of this approach can be seen in the TCM view of diagnosis.

During the process of exploring the secret of life and diseases, ancient Chinese physicians developed their own concepts of holism and dynamic balance, in which the human body is seen as an organic whole with all tissues and organs operating in harmony and balance. Neither the strength of any single organ nor the level of any functional measurement can represent the condition of a whole body. A disease occurs when there is a disturbance of the internal harmony within the body. With the criteria of holism and dynamic balance, Chinese physicians determine where and how seriously a disease deteriorates the balance of the unified whole, through observation of various symptoms, and eventually arriving at an adequate understanding of its nature, i.e., the diagnosis. Based on such understanding, the TCM practitioner restores dynamic balance through various treatment methods with the intention to cure the disease. In practice, the process is called *bianzheng lunzhi*, meaning *pattern differentiation* and *treatment determination*. (Scheid 2002 p.202)

Essentially, diseases are deemed as developing processes that change the balance of our bodies. At each time-slice many observations, including interrogation, palpation, hearing and smelling in Chinese medicine, combine into patterns, as Kaptchuk put it, "the process of weaving together the elements and recognizing a pattern in myriad signs," which contribute to inferring each identified process (the diseases). With such understanding, the physicians then suggest treatments for the patients of their particular conditions. The understanding of the disease is an inference about a change in pattern over time; in effect, the disease itself, seen as a developing process, is more than those identified patterns that are conceptually linked across time intervals, if properly observed. Although we may not see the changing process (the disease) directly, we can still operate on the basis of patterns. Individual, micro-scale pathogenic details need not be of concern.

As Cracraft puts it in his article, *Reconstructing Change in Historical Systems* (Wimmer and Kössler 2006 p.278), the investigation of disease in TCM is focused on the imbalance of the body caused by diverse pathogenic factors. The micro-conditions that change after the imbalance need not receive much attention because those changes are merely a result of the broken balance; they are not the nature or key of the disease and should the root causes be solved, these symptoms should disappear or become irrelevant. The understanding of diseases in TCM evolves around the concept of holism and dynamic balance. (Tang 2004 p.16-17)

But why is it possible that we can determine the broken links and balance deterioration of the body's internal function through simply observing the external symptoms? Take an experienced gardener for example, why is it possible that he can judge a plant's nutrition and disease conditions by its appearance? That is because a plant is also an organic whole; there exists a direct and close relationship between its outward appearance and its inner balance. When a certain link of the plant's interior balance deteriorates, the appearance of the plant's branches and leaves change accordingly. Different changes imply different types of *balance deterioration*. Thus, it is completely feasible to determine the conditions of an inner malfunction by observing the external changes of the plant. The same situation applies to the human body; symptoms appeared during illness are in fact the result of a broken balance. Through research and study, we can summarize the connection between those external symptoms and internal balance conditions. Then, it is possible to determine the broken link and degree of balance deterioration of the body's internal function. Besides, human beings are able to think and express themselves; subjective illness can be expressed through languages. These subjective feelings provide more pieces of information about the disease for us to diagnose and treat it more comprehensively and accurately. (Tang 2004 p.17)

The results of laboratory tests and medical examinations are in fact a reflection of our visceral condition and/or the composition of body fluids or substances at the time of examination, i.e., the consequence of what diseases have done to our body. If the results are to hold as the nature of the diseases, then we are mistaking the symptom for the disease. For instance, taking a pot of boiling water on the stove, with a water temperature we can measure with a thermometer. If the boil of water is a problem to be solved, we have to ask what makes the water boil – the high water temperature or the fire under the pot? Let us revisit the gastritis example again. The illness of our stomach, the stomachache, resembles the boiling water that is a problem needs to be solved. The hyperemia, festering and ulcers are similar to the water temperature that can be observed on the surface our stomach through gastroscopy. Is the result the nature of our gastritis? Of course not - it is merely a result that our function-disordered stomach produces under the effects of various factors. If we use the result as a basis of treatment for our stomachache, it resembles adding cold water to the pot hoping that the water will not boil. Indeed, the water will cool down and stop boiling, but only temporarily. The stove under the pot is still burning; eventually, the water will heat up and go back to boiling. (Tang 2004 p.18) Only addressing the environmental force at work – the application of heat to the pot, the life patterns and flows that cause gastrointestinal disorders – allows solving these problems at their root level. Dynamic diagnoses that attempt to discern how the relevant system interacts with its environment can reveal such root level causative factors.

Treatment

Since the 19th century French microbiologist, Louis Pasteur, proposed the "germ theory of disease," Western medicine has come to believe that a vast variety of diseases (of course, such thought has been altered as medical science advances) are caused by bacteria or viruses; thus, one core objective of treatment is to stop and eliminate them. (Liang 2006 p.84) However, our body is a living organism and is provided with abilities of immunizing and adapting to defend ourselves from adverse effects caused by various environmental changes. Thus, we normally live with microorganisms – for instance, *Escheria coli bacteria* in our intestines – and when our ability to immunize and adapt decreases they become a pathogenic factor and make us sick. Even diseases which may strike healthy human beings – for instance, *Ebola*, methicillin-resistant *Staphylococcus aureus*, and *Salmonella* – only infect human beings when maladaptive behaviors are undertaken like disrupting a jungle ecosystem, rubbing up against dirty surfaces and eating undercooked pork respectively.

So what is wrong with an *ex post facto* conventional treatment aimed at eliminating bacteria and viruses after we are attacked? A useful analogy can be made here. Imagine that you were struck by someone and where you were hit is swelling and hurts. To heal yourself, would you treat the wound or go fight the person who hurt you? Of course, you would treat yourself. For infectious diseases, such as influenza or gastritis, the reasoning would be the same. In such cases, bacteria, viruses or other microorganisms are similar to the person who attacks you. The fever, i.e., body temperature disorder, caused by virus resembles the wound that needs to be healed. Thus, the motive of treatment should be to restore the balance of body temperature instead of fighting off the virus. From TCM's point of view, many cases of fever come from internal "heat" that accumulates inside the body. In addition, when the body is stimulated by cold, it causes the sweat glands to contract; as a result, the body's internal homeostatic cooling function is not able to remove the heat produced, thus resulting in fever. None of the antibiotics or the treatment of virus infection are capable of improving the adjustment function of body temperature and is effective to such kind of fever. (Tang 2004 p.12) This approach does not deny the importance of causative factors like bacterial infection. Rather, it proposes a new way of looking at the situation, prioritizing adjustment of bodily systems' homeostatic balance. A viral infection would not, for instance, necessitate *only* some type of TCM "cooling cure;" rather, in addition to conventional anti-viral medications, a TCM cure would also incorporate homeostasis-adjusting measures to aid the patient system to regain its dynamic equilibrium.

To consider the TCM approach to treatment further, the aforementioned gastritis is another perfect example. Through gastroscopy, the observed symptoms, such as inflammation, ulcers, and *H. pylori*, imply that under the attack of *H. pylori*, the stomach has become inflamed and ulcerated, causing the stomachache. However, if we view the stomach taking into the perspective the whole body as a system, and view the disease according to the laws of nature we have identified, and then review the gastritis from the standpoint of holism, it is clear that those inflammation, ulcers, and bacteria may come from a damaged dynamic environment inside and outside our stomach. (Tang 2004 p.24-25,314)

The same diagnostic logic that TCM applies to understand complex natural systems – those of the human body – transfers well to environmental systems. Consider eutrophication of water bodies, such as lakes or slow-moving streams. Through a test of water quality, we may find that the water body receives excess nutrients that stimulate excessive plant growth, usually algae. "This enhanced plant growth, often called an algal bloom, reduces dissolved oxygen in the water when dead plant material decomposes and can cause other organisms to die.[4]" In consequence, people may hold that the algal bloom is the root cause and try to weed out the algae using certain anti-algal chemicals, which may not be the optimal solution. Such a solution would overlook the fact that the slow-

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[4] Source: USGS 2010 http://toxics.usgs.gov/definitions/eutrophication.html

moving or non-circulating water and man-made pollution with nutrients have created a perfect environment for algae to grow and break the ecological balance of the water; thus, the algal blooms emerge. If we do not change the environmental suitability for algal growth, such as stopping man-made pollution and bringing in flowing water to restore the ecological balance of the water, and instead, eliminate algae by using chemicals, the algae will grow again and the same problem repeats.

Thus, under systems-oriented TCM methodology, curing gastritis requires that we examine the patterns that cause damage to the stomach environment – stagnating food, malformations of *qi* and *blood* flow, an overall level of malnutrition, declining stomach function, as well as living patterns as reported by the patient. These are the keys to a cure. After restoring the dynamic balance of the stomach, the causative bacteria will lose their suitable habitat. Antibiotics to kill them may not be required, since they will die naturally. Nor should we have to suppress gastric acid in the long run; ulcers are not likely to persist in a health body environment. The differences in treatment emerge from the perspective of holism and dynamic balance.

Disease, Symptom and Pattern

Chinese medicine understands illness as a process in which the same disease can express itself through different patterns. Thus, the same treatment might be described in the course of different disease, while the same disease might require different treatments according to the pattern present. (Scheid 2002 p.202) We turn to Scheid's analysis of the temporal metaphysics of TCM for a majority of this understanding. The knowledge required to differentiate types of pattern and symptom represent a conceptual understanding highly useful for risk management. Scheid (2002 p.201) sets forth, at length, the extended TCM notion of pattern in disease:

> ***Diseases*** *are disorders of structure or function of the human organism resulting from a loss of equilibrium between internal and external environments. Diseases have specific causes that produce regularly patterned pathologies by way of describable pathomechanisms. These pathologies and pathomechanisms express themselves externally in symptoms and signs.*
>
> ***Symptoms*** *and* ***signs*** *are the external manifestations of both diseases and patterns. They are experienced subjectively by the patient or determined diagnostically by the physician.*

> ***Patterns*** *describe typically occurring combinations of symptoms and signs. They reflect the temporal development of a disease through various stages (and thus the transformation of the disease itself) including deflections of the normal development of a disease by medical treatment and other factors such as constitution, climate, diet, and so on. [Emphasis mine]*

That is to say, *symptoms* and *signs* organize themselves into *patterns* discernible by the trained physician, connoting disequilibrium in internal systems balance or *disease*. As Scheid continues, "Chinese medicine's concern for patterns makes for a medical practice organized around the unfolding of process rather than the manipulation of bounded structures." The TCM physician and risk manager treats systems, both human and engineered, through simultaneous treatment of distinct diseases as well as through consideration of how these diseases express themselves in different patterns; that is to say, it considers "illness as a process in which the same disease can express itself through different patterns" (Scheid 2002 p.202)

Understanding the open-endedness of *pattern* and *disease* establishes a crucial contrast between the TCM and modern Western systems. Pattern and disease may be said to be open-ended linked concepts in TCM; a pattern is both the expression of a disease across time as well as the expression of internal balance-regaining homeostatic forces which may be aided by the TCM practitioner. Multiple patterns may be incorporated into a single disease concept, and vice-versa. Crucially, pattern includes potential improvements from treatment as well as potential deterioration from the course of the disease. In contrast, modern Western medicine treats the interaction of pattern and disease as a closed one, centering on the treatment of specific diseases considered as entities unto themselves. For the modern physician, a pattern expresses four core aspects of the development of the disease as distinct entity: "causation, location, pathomechanism, and character. Each of these reflects the nature of disease not in some abstract generalized form but in its concrete and specific manifestation" (Scheid 2002 p.201) For the traditional view of human systems, disease resides not in *pattern* but instead in *substance*.

To accept imbalance pattern as a disease across time with multiple potential expressions in substance unfixes the concept of disease from a determinate set of symptoms, suggesting the importance of considering a multiplicity of treatments as well as "pattern differentiation" as managers of risk for human and engineered systems. Pattern encompasses not only internal structure – the aspects of practical management that fields like traditional corporate systems management already recognizes – but also, critically, deals directly with how patient systems interact with their environments. In addition, the notion of treating the homeostatic balance of the patient system, rather than isolated problem scenarios with fixed solutions, represents the basis of a potential paradigm shift in risk analysis which we will explore more fully in our discussion of the application of TCM's systems analysis to the problems of risk analysis. Indeed, exploring further the complex way of diagnosis and treatment presented to us by TCM and understanding its implications on risk management will be the primary focus of Part III.

Chapter 4. The Need for a New Approach to Risk Analysis

As characterized in the Chinese classics, *I Ching*, and in relevant research of complexity science, our world is complex and dynamic. As Calvano and John (2004) argue in the beginning of their seminal paper, *Systems Engineering in an Age of Complexity*, two phenomena have driven the surge of this systemic nature in recent years: complexity and rapidity of change. "First, we face an unprecedented level of integration and are immersed in a "complex" web of interacting technologies and processes, dominated by the developments in information and communications technologies. Second, rapid change has become the norm with new technologies, practices, and organizations being introduced continuously into this highly integrated web." In the face of such increasing complexity, the set of a triplets methodology that Kaplan and Garrick proposed in 1981 (Kaplan and Garrick 1981) does not seem to bring us further in the search of the missing uncertainty nor help us identify risks that we do not even know that exist.

A myriad of researchers have devoted themselves to the field of risk analysis in the search for an adequately dynamic, change-oriented risk management system; in other words, in the search for a cure for the ill of the unknown. Many of these attempts provide illuminating insights into how accidents happen and how we can better proact, interact and react to them. (Apostolakis 2004; Bea 2000; Bea 2008; Elms and Brown 2006; Hollnagel et al. 2006; Kaplan and Garrick 1981; Kastenberg et al. 2003; Kastenberg et al. 2004; Leveson 2004; Loosemore 2000; Loosemore 2006; Mitroff and Featheringham 1974; Rasmussen 1997) Most of their studies, however, focus on dealing with *negative potential* of the risk in trying to measure uncertainties more accurately. We may regard this negative-potential centered approach as a rather pessimistic status quo.

The core critique of this status quo approach presented by TCM's understanding of system dynamics may be summed up as follows:

- Insufficient account of system dynamism – The status quo view is insufficiently dynamic, failing to account for a prevailing background of rapidly accelerating background change brought on by modernity. Differences in diagnosis treatment emerge when we understand and treat diseases from the perspective of holism and dynamic balance.

- Ignorance of background change – Harmony with background change is ignored in status quo accounts of risk. This produces blindness to problems caused by intrinsically discordant strategies. To return to our example, removing the application of heat to the pot solves the “problem” of the water boiling. Only by solving, the life patterns and flows that cause diseases and disorders can these problems be solved at their root level.
- Use of time-invariant “snapshot” data – Status quo accounts of risk are grounded on static test snapshots, not processes of change. In fact, processes of constant change and flow – for a flow is a constant change – constitute the system itself.
- Ignorance of emergent properties of internal and external systems and interactions between them – Particularizing, specifying and “pigeonholing” accidents and diseases ignores the basic fact that the life of a system, whether human or engineered, is an emergent property that is irreducible to substance. Such analysis literally “breaks apart” a living system, rendering it insufficient from the holistic viewpoint.
- Closed concept of patterns – The status quo view creates a “closed linkage” that conflates pattern with the substance of accident (or disease), instead of properly considering pattern as an open-ended concept incorporating existing system-internal and external/environmental forces, as well as the particularities of the disease or accident.
- No positivity – Not many of these status quo systems look into the complex and dynamic nature of engineered systems and try to look at the problem from the perspective of the positive potential of improving system health of the risk where we have great change.

In this chapter, we will discuss what has been focused on in this field and its current progress, and we will point out the problems of such approaches. Finally, we will introduce a new perspective on risk: the risk of change, and conclude with a consideration of the need for a new approach to risk analysis.

4-1. In Search of the Missing Uncertainty

Risk arises from uncertainty. As generally accepted by status quo studies, describing and measuring uncertainty would be a reasonable first step to decrease risk. This approach, however, has limited efficacy for complex systems where constituent processes are not well-defined and have vague boundaries. Research efforts have shed light on various aspects, but none of them have proposed a complete solution for analyzing risks in complex settings. What is missing in current approaches is a consideration of time and change, miscasting the accident as an event rather than a developing process.

4-1-1. Risk Arises from Uncertainty

When the number of potential outcomes to a situation numbers only one (formally, when $n = 1$ where n is the number of potential outcomes), there is no risk. Deterministic certainty is by definition incompatible with risk. Thus, if we accept that, as Benjamin Franklin said, "In this world nothing can be said to be certain, except death and taxes," then there is simply not a risk-based question whether or not you or I will die one day; nor that we will be taxed; everyone dies, everyone is taxed. Since taxes may be more or less severe, we may nonetheless quantify tax risk, according to accepted risk assessment methods, by how severe the impacts may be. There are multiple levels of *how much* you or I might be taxed, and to that extent, the amount is uncertain. For the amount of tax, we might say that $n >= 2$. However, since *the fact that we will be taxed* is certain, then on Franklin's account, "the risk of being taxed" is certain, for n=1. As Vick states, "(n)o risk exists if the future outcome is uniquely known (i.e., n = 1) and hence guaranteed. We will all die some day. The probability is equal to 1, so there would be no fatal risk if a sufficiently long time frame is assumed… In this context, a situation with two opposite outcomes with equal likelihoods may be the most risky one. In less formal usage, however, a situation is called more risky when severities (or levels) of negative outcomes or their likelihoods become larger; an extreme case would be the certain occurrence of a negative outcome."

A core concept of risk management is accepting that very little inside or outside the system is deterministic. If everything in the system was deterministic, then there would be no risk. In reality, there are uncertainties a-plenty that lie between our understanding and the reality of how systems work. "Numerical statements of probability are used to quantify at least some of these uncertainties according to a grab bag of procedures lumped under the heading of probabilistic methods. In various ways, they are intended to enhance the treatment of uncertainty by evaluating it systematically." (Vick 2002 p.105) In other words, we use the probability and consequence of an uncertain event to quantify its uncertainty, obtaining from that "risk."

Ultimately, however, the contemporary account of risk analysis must have recourse to patterns identified through inductive observation. "We can assemble big pieces of information and little pieces, but we can never get all the pieces together. We never know for sure how good our sample is. That uncertainty is what makes arriving at judgments so difficult and acting on them so risky… When information is lacking, we have to fall back on inductive reasoning and try to guess the odds." (Bernstein 1996 p.202) Since it seems inevitable that we resort to inductive reasoning and guesswork when faced with difficulty, and further that such difficulty is increasing with the complexity of the times, we will argue that inductive observation may be most effectively used as a basis from the very beginning, and not simply as a last resort.

4-1-2. Origins of Uncertainty

Similar to the term *risk*, *uncertainty* has meanings both vague and specific. In everyday conversation, uncertainty is a synonym for doubt. However, it is also used in more technical settings to express the degree to which one is unsure about the observations or results. In addition to the vagueness around the word itself, multiple sources of uncertainty exist and many have distinct characteristics that require distinct treatment in modeling and analysis. We will briefly set forth and critique the primary schools of thought in the status quo with regard to these topics.

Krupnick et al. (2006 p.9-24) give a detailed account of the typology of uncertainty that agrees with the principal distinction between variability (aleatory uncertainty) and lack of knowledge (epistemic uncertainty). These break down into three further broad categories, leaving them with four primary types of uncertainty:

- Variability – when an empirical quantity that can be measured as a single point value actually exists in a population of values, varying across space, time, or across individuals.

- Parameter uncertainty – the lack of knowledge about an empirical quantity stemming from limitations of the human ability to know, such as measurement, disagreement among measurements, or extrapolation errors.
- Model uncertainty – model uncertainty results from limitations in the ability to create causal or predictive models of real-world systems on the basis of the data. It is also due to a lack of knowledge about system behavior or to choices that determine model behavior. This is in contrast to parameter uncertainty which results from the practical limitations of data. The fact that we do not know how complex systems are going to change can be attributed to this uncertainty. In other words, we simply do not and may never have a perfect model for the world, which has important implications for conventional accounts that favor perfectly deterministic cause/fault-tree diagnoses.
- Decision uncertainty – this arises whenever there is ambiguity or controversy about how to quantify or compare social objectives. While variability, parameter uncertainty and model uncertainty are issues for risk assessors, decision uncertainty is a concern chief for risk managers. Formal decision-making processes may simply be reduced to a quantification of alternatives, followed by a utility ranking in order to make a decision by choosing an alternative that presents the maximum expected utility. In this process, uncertainties are represented through probabilities and probability distributions. The decision maker's attitude to risk is represented by utility functions and their attitude to trade-offs between conflicting objectives can be made using multi-attribute value functions or multi-attribute utility functions (if there is risk involved). However, in complex situations, alternative solutions or actions may be difficult to develop and quantifying those alternatives is yet another daunting task if not impossible. For complex situations, which we argue comprise the vast majority of engineered systems, we need an innovative approach to decision-making sensitive to the variability and complex particularities and commonalities of these systems' intrinsic dynamism.

Similar to Krupnick et al. (2006 p.10), Sociologist and scientist, Brian Wynne (1992 p.114-117) lists four types of uncertainty:

1. Risk – on Wynne's account, *risk* exists when the system and probabilities of outcomes are well known. It can be confidently calculated when the behavior of the system at risk is well-known, and the chances of different outcomes can be

defined and quantified by a structured analysis of mechanisms and probabilities. Interestingly for our purposes, this statement also implies the limitation of applying current risk assessment methods to complex engineered systems. The epistemic boundary for Wynne's notion of risk is limited to a "closed" set of possible correlations.

2. Uncertainty – when probabilities of outcomes are not known, *uncertainty* may be said to exist. Although uncertainty here is considered in the current risk assessment through incorporating subjective measures of probability, the results are often controversial. The subjective account here is not of the stakeholders or system managers themselves, but rather from "experts" or "reasonable man" surrogates who are themselves subject to intrinsic limitations.
3. Ignorance – for Wynne, *ignorance* is the limited ability to know systems. Ignorance is an epistemological difficulty that must be accepted as a certainty; there are simply things that are both unknown and unknowable to us.
4. Indeterminacy – *Indeterminacy* arises from complexity and unpredictable system behavior. "Conventional risk assessment methods tend to treat all uncertainties as if they were due to incomplete definition of an essentially determinate cause-effect system. In other words, they suggest that the route to better control of risks is more intense scientific knowledge of that system, to narrow the supposed uncertainties and gain more precise definition of it." (Wynne 1992 p.116) However, on Wynne's account, when causal chains or networks are open, the complexity of the system itself may prevent us from arriving at a detailed system definition. However, we argue for the necessity of an innovative approach to the understanding of complex systems that understands systems from a holistic viewpoint—one allowing for an open interaction between the concepts of pattern and accident/disease. Understanding patterns of system behaviors in system's constant change over time is the key to this new approach.

Kastenberg's account of uncertainty (Kastenberg 2007b p.21) holds the same viewpoints as Wynne and suggests that in addition to the aleatory and epistemic uncertainty inherent in complicated systems, complex systems is also characterized by indeterminacy.

Elms and Brown (2006 p.3-4) suggests that "[a] third aspect of uncertainty relates to the unknown and unexpected, to those things that neither random variability nor limitations of model quality will cover. [They call it] ‘ontological uncertainty,’ as it arises from the reality of what actually exists. But, that are not the expected norm; in other words, with surprise (surprisal uncertainty).” Elms (Elms 2004 p.119) believes that most surprises arise from human factors.

McDaniel and Driebe (2005 p.3,7) study “surprise” in complex systems. In contrast to Elms, they hold that some surprise in complex systems is due to lack of information or bounded rationality, i.e., information processing capacity (Simon 1991; Sterman 2000; Sterman et al. 2007). For McDaniel and Driebe, most of the surprise is the result of the fundamental nature of the system in question. Their belief echoes Heisenberg’s Uncertainty Principle. “What is crucial to Heisenberg’s insight is that this unknowability is essential. It is inherent and built in; it does not enter as a consequence of the clumsiness of the experimenter or the experimental apparatus. The problem is here to stay as part of nature” (Sheikh and Sheikh 1989 p.406) They further suggest that if the surprise happened because of the lack of sufficient information or speed, our response is to request better computers and more data collection; if bounded rationality is assumed to be causing the surprise, our solution will be asking for more care while pointing our fingers in search of who is to blame. (McDaniel and Driebe 2005 p.8) We agree with McDaniel and Driebe that it can lead us to a search for new approaches to solutions if the surprise is assumed to be arising from the dynamic nature of complex systems, but we suspect that over time bounded rationality can create systemic failure that cannot be easily solved without a holistic view of the system (we will discuss more about this view of bounded rationality in Section 4-2). To be noted is the way that they describe “surprise,” however, which seems to be a mixture of uncertainty and accident that are discussed in our research.

Table 4-1. Types of Uncertainties

E1	aleatoric uncertainty	known unknowables	variance governed by chance
E2	epistemic uncertainty	unknown knowables	knowledge governed by chance
E3	ontological uncertainty	unknown unknowables	governed by change
	(not applicable)	(known knowables are not uncertainties)	

4-1-3. Current Research Efforts on Risk Analysis

A major aspect of risk analysis is the management of uncertainty. Most literature in this field has focused on identifying areas of uncertainty that have not been analyzed before. Such studies anticipate accidents and seek for new types of failure modes specific to a certain industry or system in question. Proceeding such studies, preventive measures are suggested according to those accidents and failure modes that are identified in the studies (for instance, (Aven 2003; Ayyub 2003; Covello and Mumpower 1985; Modarres 2006; Saporita 2006; Smith et al. 2006)).

As discussed in Section 1-3-1, conventional risk analysis approaches are not applicable in the modern setting of a dynamic society and increasingly complex systems. Wynne (1992 p.113) states the problem aptly when he argues that:

> *Risk assessment as a scientifically disciplined way of analyzing risk and safety problems was originally developed for relatively very well structured mechanical problems, such as chemical or nuclear plants, aircraft and aerospace technologies. In such systems, the technical process and parameters are well defined, and the reliability of separate components is testable or amenable to actuarial in-service analysis. Indeed, so controlled are the parameters of such systems that risk analysis did not develop after design and manufacture, to try to understand the built-in risks; it was an integral part of design, influencing criteria and choices in normative fashion, right through the whole process. It should be noted that these systems have often shown themselves to be less well defined than analysts and designers thought, exhibiting surprising properties – such as exploding – which indicate that the system was less determined by controlling forces than the analysts recognized… For these last mentioned kinds of problem the limitations of available knowledge are potentially more serious because the system in question, not being a technological artifact, cannot be designed, manipulated and reduced to within the boundaries of existing analytical knowledge.*

Many critical research efforts recognized and have been devoted to address these problems of complexity:

a) In 1957, Allyn W. Kimball (p.134), a statistician with the Oak Ridge National Laboratory, proposed a different kind of error to stand beside “the first and second types of error in the theory of testing hypotheses." Kimball defined this new "*error of the third kind*" as being "the error committed by giving the right answer to the wrong problem."

In 1974, Ian Mitroff and Tom Featheringham (1974 p.383; 1976) extended Kimball's category, arguing that "one of the most important determinants of a problem's solution is how that problem has been represented or formulated in the first place." They defined type III errors as either "the error... of having solved the wrong problem... when one should have solved the right problem" or "the error... [of] choosing the wrong problem representation... when one should have... chosen the right problem representation."

b) Bea (2005 p.203) proposes a third approach – interactive or real-time approaches – to assessing and managing the risks associated with human and organizational factors in systems, due to the fact that there are many more incidents and near-misses in such systems than there are accidents and failures. "This indicates that people and their organizations are interacting with their systems to make sense of their developments and return them to safe states." Note that this approach casts accidents as developing processes, instead of isolated events, that unfold over time. This is consonant with the time-sensitive TCM concept of disease we set forth in Section 3-3-3. Bea (Bea 2008 p.203-204) suggests the following on managing the unpredictable.

> *The third approach developed is termed "interactive." This is interactive or real-time RAM as the potentials for compromises in quality and reliability of a system unfolds. This is assessment and management of the "unknowable" component of future threats to the quality and reliability of systems. This is management based on OODA (Observe, Orient, Decide, and Act) "loops" (recursive trials), migrating decision making, divide and conquer deployment, and requisite variety in problem identification and solving. This is engineering and management of the "unexpected." The engineering and management abilities and processes required to adequately address the unknowable and unexpected are very different form those needed for the traditional strategic engineering and management processes.*

c) Hollnagel argues that although there has been significant development in the understanding of how accidents occur, there has been no comparable development in the understanding of what safety is and of how it may be endangered. (Hollnagel et al. 2006) This critique shifts the focus from purely negative aspects of risk to positive aspects, a possibility that we incorporate into the concept of the risk of change in Part II of this work. We will argue that such a notion requires a shift to a more dynamic, holistically focused risk management strategy

Hollnagel (2006) further proposes the view that an accident is an *emergent property* of a system. According to Holland (1998), a phenomenon is perceived as *emergent* unless it is recognizable and recurring. Such qualification, in our belief, implies that we should not treat accidents as surprises. On the contrary, to prevent accidents from happening, complex engineered system must, as Hollnagel (2006 p.16) suggests, "be dynamically stable, or constrained in the sense that the adjustments do not get out of hand but at all times remain under control." Hollnagel et al. (2006 p.22) incorporates this idea and puts forth his concepts about *Resilience Engineering* arguing that:

> *Resilience… concerns the ability to recognize and adapt to handle unanticipated perturbations that call into question the model of competence, and demand a shift of processes, strategies and coordination. When evidence of holes in the organization's model builds up, the risk is what Ian Mitroff called many years ago, the error of the third kind, or solving the wrong problem. This is a kind of under-adaptation failure where people persist in applying textbook plans and activities in the face of evidence of changing circumstances that demand a qualitative shift in assessment, priorities, or response strategy.*

This idea extends Bea's interactive approaches from a focus on crisis management to a day-to-day management of the system operation, which echoes the philosophy of holism in Section 3-3-1.

d) A structural safety approach is taken by Elms (2004 p.124-125) where it is argued that what is required is a fundamental change in viewpoint from a narrower technical focus to a broader systemic approach. To move forward, he suggests we address the following issues:

- Managing for the unknown,
- Rational and consistent ways of dealing with epistemic uncertainty,
- Rational methods of analysis for complex demands,
- Improved methods of dealing with whole-system,
- Refinement of methodological issues,
- Greater integration with the social context,
- Improved codes.

At the end of his paper, Elms (2004 p.124) points out that "time-dependent variables and dynamic effects" are one of the many issues that has to be considered in the field of safety:

> *Essentially, probabilistic methods of analysis are ideally suited to handling and taking into account aleatoric uncertainty. They can also to some extent deal with epistemic uncertainty, particularly if effort is put into understanding the uncertainty. However, a second and entirely different type of approach is needed for dealing with ontological uncertainty. (Elms 2004 p.119)*
>
> *The threats to a structure arising from ontological uncertainty cannot be dealt with by a probabilistic analysis. Instead, the strategy must either be to reduce the likelihood of unexpected threats, or to ensure as far as possible that if a threat should become reality, then it would not result in complete failure of the structure.(Elms 2004 p.122)*

e) Loosemore presents the notion that risk can travel in two directions. Outcomes may be better (the upside of risk) or worse than expected (the downside of risk) (Loosemore 2006). Risk management should be as much about maximizing opportunities for gain as it is about minimizing the risks of failure. As Loosmore (2006 p.12-13) puts it, "[I]n most instances, opportunities to improve performance beyond original expectations are often neglected or come as a by-product of the risk management process. However, if one is alert to opportunities at the outset of the risk management process, then many unexpected insights can be gained to improve performance. New opportunities may be identified in the course of managing risk and as a consequence of how risk is managed." We will argue that the dynamic systems focus we propose incorporates the potential for upside risks in a coherent, holistic system.

f) Rasmussen (1997 p.186-191) suggests a new paradigm of modeling by functional abstraction rather than modeling by structural decomposition. Rasmussen's concept matches our discussion in Section 1-3-3 that a system is understood as an interacting collection of patterns rather than a fixed composition of matters.

g) Kastenberg's (2002; 2006; 2007b; 2007c; Kastenberg et al. 2004) hypothesis on risk further confirms Rasmussen's idea. He suggests that "any evaluation of the impact of human activity on the ecology of life must shift from being based on a consideration of the individual elements of a system to being based on a consideration of the emergent properties of that system." In fact, he proposes that emergent property degradation is the appropriate measure of risk for the whole of a nonlinear system, in the same way that a summative measure of risk is currently used for assessing a linear system." However, we suspect that there exists one single measure that is capable of describing a complex risk: the risk of change.

4-2. Uncertainty and Complexity of Change

The true source of uncertainty lies in the complexity of change that is still unknown to us. In fact, much of the research in conventional risk analysis was built on the assumption that uncertainty of situations is the result of a lack of information. This has led to an emphasis on uncertainty reduction through ever-increasing information seeking and processing, including better measurement and observational instruments. Pending uncertainty reduction through better information, efforts are devoted to uncertainty management and hierarchies of controls. A central goal has been the avoidance of surprises. (McDaniels and Driebe 2005 p.3) In fact, it is not a question of measuring uncertainty accurately or anticipating accidents prudently; those approaches do not take into account the fact that systems evolve and change over time because of their complex nature. Wimmer and Kössler (2006 p.285) believe that "change involves risk since it contains uncertainty." We believe change in complex situations is a major source of uncertainty. The complexity of change, however, has prevented us from measuring uncertainty accurately. Decisions made without complete information create defects in systems over time. Even those wise decisions once made the systems successful would later become what Chesbrough (2006) has called the "dominant logic," hindering systems' development when their environment changes. Change is the key to the perplexing puzzle of risk analysis. The way we perceive systems and their risks has to be changed with a holistic perspective incorporating change.

4-2-1. Nature of Changes

What *I Ching* and *complexity science* have taught us is that the universe is constantly changing with certain unchangeable principles. Such change often manifests in the form of events or accidents to which systems change in order to react. Changes and causation are also wildly unfixed in the real world. The whole previous state of the world may have seemingly caused one single event to happen and one single event may be changing the state of the world that we are currently aware of. Change involves risks. Thus, managing risks by reacting to events makes sense for most of us.

Imagine our experiential world as a television screen that feeds us information about changes inside the television set. The "live" computation which it uses to show information may be unknown to us. This television shows us events and accidents as images and stories that are vividly shown on the screen. If suddenly a fire accident occurs on the screen, it would be absurd to react to the accident since we know it is merely one of the myriad images that are created by the constraints of shape established by a regulated electron beam hitting a fluorescent screen in early television sets. We argue that events and accidents, be it misfortune or fortune, are all such images resulting from certain unchangeable principles of change on which we should focus our attention. Acting on myriad possibilities of events or accidents is simply an impossible task.

There is no doubt that human will is one among the many causes that make our dynamic world tick. (Krausz 2000 p.54-57) Indeed, the conscious human will is what sets goals for engineered systems and initiate changes of systems in order to adapt changes that are outside of systems' control and are in no way related to human will. (Wimmer and Kössler 2006 p.286) In addition to effecting change, human will plays an important role possibly also in preventing projected change that leads to a disaster. As Hollnagel et al. (2006 p.41) put it:

> *Human in systems (e.g., operators, maintenance people) are essentially alike and are, in general, adaptive and proactive. These are admirable qualities, but of limited scope. Adaptive and proactive behaviors can change systems continuously, but humans at the front end alone may or may not be able to recognize the potential impact that the changes can have on the system, especially the impact when several changes are put into effect simultaneously. Humans at the back end (e.g., administrators, regulators) tend to have sanguine ideas such as that the system [always operates] as planned, and that rules and procedures can fix the system at an optimal state. Mismatches caused by these two tendencies constitute latent hazards, which may cause the system to drift to failures.*

Just as with Loosemore's notion of risk, change in a system can travel in two directions. Outcomes of the change may be better, i.e., the state of the system may become closer to the system goal (in this situation, it is an opportunity) or worse than expected, i.e., the state of the system become further away from its goal (in this situation, it is a risk). Whatever the outcome, change involves potential for system development. However, there is no absolute good or bad about a change. All changes interact with each other and determine the state of a system. Thus, there exist tensions between the positive and negative changes. All that matters is how we facilitate the development of a system towards our goals while maintaining the dynamic balance of change. The tensions between *yin* and *yang* from *I Ching* and positive and negative feedback in System Dynamics provide great insights for managing changes in such fashion, which will be the theme for Part III.

4-3. Complexity and Accuracy

A Chinese sage, Lao-Tse, who is recognized as the founder of Taoism, once said of complexity: "The *Tao* that can be described is not the eternal *Tao*. The name that can be named is not the eternal name." (*Tao Te Ching* (*Book of Virtue*) Lao-Tse, 561 BC)

Why is the described *Tao* not eternal *Tao* and the named name not the eternal name? We should note that *describing* and *naming* are both products of language. Language is a human creation that helps us interpret the multitude of things and ideas that are originally name-less. Since language changes over time, describing and naming evolves and proliferates different interpretations and various understandings. Therefore, a consequence of linguistic activities and language limitation is that the described *Tao* is not invariant and eternal. Specifically, mankind creates the name and description, or notion, of "complexity;" these concepts are meaningful only when the phenomenon is pondered by human observers. Besides, the notion is not eternal; it differs from person to person. A complex mathematical problem to a layman may seem very simple to a skilful mathematician. What a mathematician might feel complex, such as the dance step of a ballet dancer, would be very simple to the dancer. Therefore, each person has his or her own perception of complexity. (Tuan and Ryan 2002 p.273-274) What really matters here is the limitation of being accurate in a complex activity, such as communication or quantitative measurement.

Centuries later the tradeoff between complexity and accuracy was highlighted again by Zadeh, best known for the concept of Fuzzy Logic. (Kóczy 2006; Parsons 2001 p.102-

104) In his seminal paper, *Outline of a New Approach to the Analysis of Complex systems and Decision Processes*, Zadeh (1973 p.28) suggests that "as the complexity of a system increases, our ability to make precise and yet significant statements about its behavior diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristics." In proposing what he called the *principle of incompatibility*, Zadeh (1973 p.28) questions the feasibility of analyzing complex systems with a conventional scientific approach "which equates the understanding of a phenomenon with the ability to analyze it in quantitative terms."

The same argument applies to the field of medicine. As previously discussed, the human body is an intricate combination of functional subsystems. Most people would agree that its complexity is no less than any other complex systems in Nature. For such systems, overly detailed study would actually prevent us from getting the big picture of the systems. The *Nei-Ching* or *the Canon of Medicine*, one of the classics of Chinese medicine, states: (Unschuld 2003 p.485-486)

> *Of the numbers [of the pairings with yin and yang], those which can be counted are [those of] the yin and yang in man…*
>
> *Count their [associations] and [you] can [reach] ten; extend these [associations] further and [you] can reach one hundred. Count these [associations], and [you] can [reach] one thousand; expand them further and [you] can reach ten thousand.*
>
> *[In contrast, the manifestations of] the yin and yang of heaven and earth cannot be counted and further extended [through enumerations]; they are referred to by images.*

The interplay of *yin* and *yang* is so complex and manifold that it cannot be described exhaustively in quantitative terms, but requires instead an eidetic notion or "image," as Unschuld puts it; as we would describe it, the interaction of ying and yang in constituting a system would comprise a *pattern*. That is, in the terms that we propose, Unschuldian "images" are in fact "patterns" of the changing processes. Ultimately, the statement concedes that the quantitative deduction would be endless and is not suitable for the study of the complex universe or life science. On the one hand, it negates the practicability of pursuing accuracy in complex settings. On the other hand, it reveals a different approach to the understanding of complex systems through pattern differentiation. In fact, at the core of this approach are the concepts of holism and dynamic balance. (Tang 2004 p.25)

Examples of effective, simple patterned reactions to complex environmental changes are throughout nature. Bookstaber (1999 p.18), for instance cites the example of the humble cockroach. Though possessing a simple body plan and concept, the cockroach is nonetheless proven remarkably able to adapt to variety of ecological niches throughout the world. The same contrast between accuracy and complexity can be found in Eastern and Western approaches to complex problems in medicine. (Tuan and Ryan 2002 p.275-276) Typical western medicine textbooks have chapters about different body parts and associated diseases. (Tierney et al. 2006) In contrast, TCM approaches the problem in a different way, instructing practitioners as to matters of holism and dynamic balance. (Tang 2004 p.26-27) The aim is for the approach to go beyond detailed examination and diagnose the system as a whole. Summary measures, as we have discussed, play an important role, and may not have quantitative components. Reducing uncertainty as to our opinion of another person's beauty, for instance, is purely subjective and taken in a single instant; when broken down into components, however, such an evaluation loses meaning. In the TCM view of risk management, making a detailed examination or using test results are not wrong, but they have to be summed up in the context of the whole system in order to understand a disease better. Otherwise, we may end up giving treatment to the surface of some deeper problems.

In fact, when such observational uncertainties are quantified "accurately" with probability and statistics, they are not made any more certain as many people might interpret. Despite what we might know within the bounds of our rationality, the remainder of the world is still uncertain. An unmeasurable uncertainty is in fact not, in a way of speaking, a risk at all when compared with a measurable uncertainty. In the latter case, we are able to obtain at least some idea of how uncertain we are, making the management of that uncertainty simply a practical problem. Unmeasurable uncertainties, which may have importance beyond what we can discern, pose the real problem. As Bernstein (1996 p.219) quotes Knight as saying:

> *Knight builds his analysis on the distinction between risk and uncertainty: "Uncertainty must be taken in a sense radically distinct from the familiar notion of Risk, from which it has never been properly separated… It will appear that a measurable uncertainty, or 'risk' proper… is so far different from an unmeasurable one that it is not in effect an uncertainty at all."*

This is why there should be significant doubt that there exists one single measurement of risk. Under the conventional quantitatively-based paradigm of risk, such a measure would have to exclude the unknowable uncertain and be limited merely to the knowable uncertain; it would either be highly accurate quantitatively and unusably complex, or simplified quantitatively but unusable inaccurate, a paradox that Gödel might find familiar. Indeed, no commonly agreed upon metric for risk has ever been set forth. “Its achievement remains one of the more important problems to yet to be solved.” (Elms and Brown 2006 p.8)

We propose that rather than adding to the complexity of the standard approach by proposing yet another alternative view on the knowable, a dynamic, modern practice of risk analysis should instead simplify complex phenomena in order to allow system managers to view their systems holistically, “seeing the big picture” and making decisions in a broader context inclusive of environmental, temporal, and system-internal factors.

4-4. Systems, Accidents, and the Risk of Change

Most systems are designed carefully to minimize random occurrences. So why do accidents occur in many of them? We believe that accidents are accidents because they are unexpected. If an accident is perfectly anticipated, it would not be deemed as a failure because it is very likely that we can rescue the system, but rather a success. To prevent accidents from happening, scientists have devised assorted accident models to explain how accidents are originated in order to identify missing uncertainties and strengthen system robustness. The domino model (Heinrich 1931) and Swiss cheese model (Reason 1990) are two of the most frequently adopted accident models. Those models essentially assume accidents cause damage to systems because systems are under attack by uncertain events that systems fail to defend against. Under such a mentality, strategies for risk management focus on identifying potential hazards and the preventive measures are nothing more than eliminating possible causes and increasing system defense accordingly. We critique this notion as being overly simplistic and ignorant of the internal balance of the system under consideration. Indeed, in its external focus, this concept strongly resembles the “germ theory of disease” which we critique in Sections 3-3-3.

	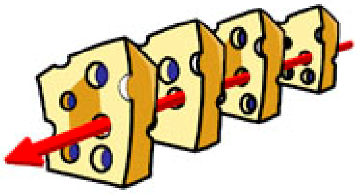
Domino Model	Swiss Cheese Model

Figure 4-1. Conventional Accident Models

As we can see, complex engineered systems are a collection of functional processes that are constantly changing. In other words, systems evolve over time, and in a complex setting, systems are constantly changing. Not only there are always accidents that we do not know, but known accidents also evolve and attack our systems in various different forms every time. Given such a presupposition, how do we think about accidents and risk?

4-4-1. Evolutionary View of Systems

For a basic, fundamental explanation of how systems change, we turn from the *I Ching* to the well-elaborated and developed theory of evolution. Its basic dictum for our purposes is that "all kinds of living things developed from very few simple forms through natural selection," which worked as a "process of gradual change in the characteristics of organisms over many generations." (Krausz 2000 p.48)

> *The great mystery of medicine is the presence, in a machine of exquisite design, of what seem to be flaws, frailties, and makeshift mechanisms that give rise to most disease. An evolutionary approach transforms this mystery into a series of answerable questions: Why hasn't the Darwinian process of natural selection steadily eliminated the genes that make us susceptible to disease? Why hasn't it selected for genes that would perfect our ability to resist damage and enhance repairs so as to eliminate aging? The common answer—that natural selection just isn't powerful enough—is usually wrong. Instead, as we will see, the body is a bundle of careful compromises. (Nesse and Williams 1994 p.14-15(3-4))*

In living systems, many diseases come from these "compromises" of natural selection over many generations; a classic example is the appendix, which despite its disfunctionality, we are still born with. In engineered systems, accidents may be caused over time by compromises of bounded rationality, which we will discuss in Part II.

In understanding a truly compromise-aware system, what is most important to understand is *the system itself* – not the particular disease. As Ness and Williams (1994 p.17-18(6-7)) attest in their examination of modern etiology, this is a simple fact of modern disease study: "…an evolutionary approach to disease studies not the evolution of the disease but the design characteristics that make us susceptible to the disease. The apparent flaws in the body's design, like everything else in nature, can be fully understood only with evolutionary as well as proximate explanations." That is, Nesse and Williams argue that we need to understand *why the accident happened* (the "evolutionary" explanation) as well as *how that accident happened* (the "proximate" explanation).

Nesse and Williams propose six categories of health problems that may be evolved over hundreds of thousands of years of human history, which are:

1. Defenses, (included in Section 3-3-2)
2. Infection (to be discussed in Section 4-3-2)
3. Novel Environments
4. Genes (to be discussed in Section 6-2-2)
5. Design Compromises
6. Evolutionary Legacies

What is striking for our reading is that besides defenses, infection and genes, the remaining three categories are all the result of gradual change over a long period of time. *Novel environments*, for Nesse and Williams (1994 p.19-23(8-11)), speak to the maladaptiveness of our bodies for the modern life of, as they put it, "fatty diets, automobiles, drugs, artificial lights, and central heating. From this mismatch between our design and our environment arises much perhaps most preventable modern disease. The current epidemics of heart disease and breast cancer are tragic examples." The fact is that many human systems, both biological and engineered, are still basically anachronisms, and the rate at which they are becoming anachronistic is accelerating. Further, we are still, biologically speaking, Stone Age creatures, with Stone Age adaptations; the most salient environmental conditions that beset modern humans – "a world of dense populations, modern socioeconomic conditions, low levels of physical activity, and the many other novel aspects of modern environments" (Nesse and Williams 1994 p.200(134)) – no longer pertain.

Another critical component in the understanding that we have of disease and accident is what Nesse and Williams (1994 p.19-23(8-11)) term design compromises. Evolution is generally accepted to be a matter of collected accident, and definitely far from a teleological process. As a result, both natural and engineered systems are rife with compromises, some the result of design, some accidental. A classic example is the upright stance we take for granted, for "(w)alking upright gives us the ability to carry food and babies, but it predisposes us to back problems. Many of the body's apparent design flaws aren't mistakes, just compromises. To better understand disease, we need to understand the hidden benefits of apparent mistakes in design." American economist, Michael Rothschild (1990 p.91-98), argues that, similar to complex organism, most complex organizations are "designed by compromise" as well.

Marais (2005 p.152-153), in her dissertation, provides examples of system compromise

- Directly decrease safety
- Increase coupling
- Increase complexity

The last aspect of the evolutionary theory of disease that need concern us is that of *evolutionary legacies*. Whether one is a gradualist or a punctuated-equilibrium theorist in evolution, what cannot be discounted is that evolution is a matter of the accumulation of small changes over multiple generations. In natural as in engineered systems, radical shifts are rare and difficult. For a contrast relevant to risk management, Nesse and Williams cite the example of a truck: "a popular line of pickup truck was struck from the side because the gasoline tanks were located outside the frame. But to locate the tanks within the frame would require a major redesign of everything now there, which could cause new problems and require new compromises. Even human engineers can be constrained by historical legacies. Similarly, our food passes through a tube in front of the windpipe, and must cross it to get to the stomach, thus exposing us to the danger of choking. It would be more sensible to relocate the nostrils to somewhere on the neck, but that will never happen…" (Nesse and Williams 1994 p.19-23(8-11)) Every Windows user may also be familiar with the notion of *reverse compatibility*; the idea that, software designed for an old version of Windows, perhaps, Windows NT or Windows 2000, should work on a newer version like Windows 7. To this day, there is still the legacy of these older systems in the form of compatibility mode that limits system performance and specifications to what older software expects.

In sum, systems are designed with *compromises*, *incrementally* over time; even those which are perfectly designed at the time of their inception may be obsolete when novel environmental conditions emerge (e.g. cold-bloodedness in reptiles and the theory of asteroid-based dinosaur extinction through global cooling). All these defects accumulate silently inside the system and become evolutionary legacies that may result in event more design compromises in the future. As risk managers, we must be cognizant of the etiology of our accidents – they may not only be state-based, single phenomena suitable for counting and quantifying. They may also be symptoms of a systemic disorder.

4-4-2. Accidents as a Developing Process of Functional Degradation

In his systemic accident model, Hollnagel (Hollnagel et al. 2006) argues that accidents are due to concurrence (unexpected aggregation) of multiple events. Thus, risk is an emergent, rather than a resultant phenomenon. His concept of functional resonance is shown in Figure 4-2.

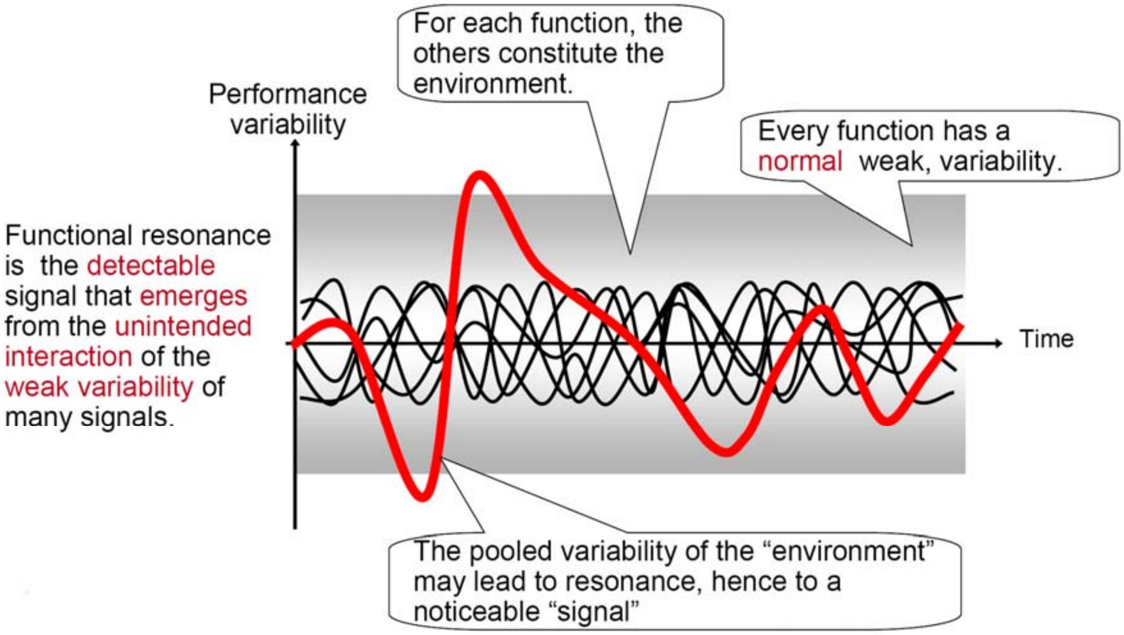

Figure 4-2. Functional Resonance Analysis
(Hollnagel 2004)

Our account of the etiology and causation of accidents concurs with that of Hollnagel's, to the extent that accidents can arise from performance variability synthetically, rather than through individual function or component failures. However, the benefit of the broader account that we give is that accidents come in with a great variety and are constantly changing – it is impossible to anticipate each and every of them effectively. A systemic view is required (Figure 4-3).

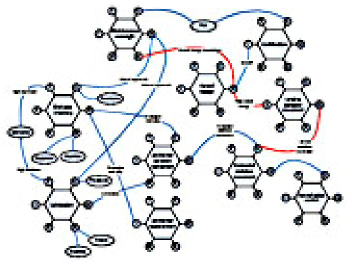	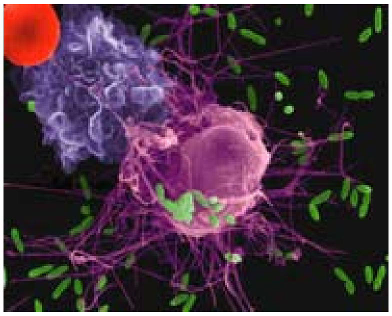
Systemic Accident Model	Immune System Metaphor

Figure 4-3. New Accident Models

A biomimetic view of risk can be seen in, for example, our human immune system as an "intrinsic" risk analysis system for our body. Our body is also facing a great variety of constantly changing, mutating invaders, e.g., virus, bacteria, bio-chemicals. There is no way our immune system can list all the invaders and protect our body accordingly. (Holland 1995; Holland 1998) (Nesse and Williams 1994 p.20-21(8-9)) What happens instead is that individual immune cells adaptively respond to the pattern of surface proteins on invading microorganisms, passing on this adaptation to fellow immune cells. At its basis, what the immune system is actually doing is identifying simple patterns that show that our body is under attack, then adjusting and adapting our body to those attacks.

If the immune system is a form of intrinsic risk analysis and response, then medicine may be considered as an "extrinsic" risk analysis system for our body. It is a core concept of our critique of risk management that current approaches to risk analysis follow the same patterns of diagnosis and solution that Western medicine does for healing. We argue that the application of TCM allows the risk manager to view system health as a dynamic process, resulting in a holistic approach that treats diseases (of human body systems) or accidents (of engineered systems) in a distinct, and we argue superior, method, as we have discussed in Section 3-3-2.

In our reading of TCM's impact on systems and risk management, what we know as accidents would be considered as a result of internal functional degradation that exceeds the system safety constraints. The process leading to an accident may come from the challenges of external variation exiguous to the system, or internal dysfunctions among various subsystems and components while the overall system itself changes over time to meet a complex set of goals and values. The accident itself is seldom a result from a single component failure but more often a systemic problem that has to be solved with a holistic perspective. "You may study for a year and learn nothing, then, unless you are disheartened by the empty results and give up, something will come to you in a flash." (Taleb 2005) Accidents develop in the same way: though of risk analysis and management are well-elaborated disciplines at this time, it is when we least expect it that accidents reveal themselves and allow us to diagnose a pattern. Everything in a system is irrefutably unpredictable because the system is constantly dynamic and changing.

4-4-3. Towards the Risk of Change

Indeed, systems evolve through constant change. As time goes on, numerous compromised decisions are embedded into the system. Even a perfectly designed system may become flawed and obsolete after significant changes to its environment. In our view, accidents are by definition unpredictable, and accidents are developing processes under change. In the view of the risk of chance, however, accidents are highlighted and are often the main focus in risk management. They are usually investigated through a search for a sequence of events that leads to failure without a thorough understanding of the roles and relationships in system dynamics of the whole.

Time is a dominant factor in risk. It matters especially in the face of irreversible decisions. One may recover money, one may recover product; one may never recover back time. Since all changes are embodied in the flow of time, it would be unreasonable to exclude the concept of time from that of risk. The conventional definition of risk – the risk of chance – is quantified as consequence multiplied by probability, with no time variable embedded in the definition. To consider risk in a complex setting, we need a new perspective on risk that takes system dynamics into consideration. We begin with a basic model which we may term the dynamic model of risk.

Assume that a general system is changing (moving) towards an established goal. Along the way, there will be all kinds of intrinsic boundaries (e.g., mechanical, environmental limitation) as well as extrinsic boundaries (e.g., economical, social, political limitation). Accidents happen when the system change exceeds one or more of these boundaries. For every change, there is the potential that the system will either move safely towards the goal (where the system succeeds), or accidentally exceed the boundaries (where the system fails or an accident occurs). Risk is fraught with a sense of danger because it carries a certain potential of causing an accident, not because of a chance of having an accident. The latter more often gives us a sense of luck (or a false sense of safety) that the accident will not happen. While *the risk of chance* indicates the expected consequence of an uncertain event, we would like to call the potential of drifting unpredictably towards one as *the risk of change*, which is the main topic of Part II.

RISK DYNAMICS <PART TWO>: RISK AS A POTENTIAL OF CHANGE

Thesis: There are some basic principles that govern the changes of a system. By understanding the principles of change, we open up a new perspective on risk and further clarify the relationship between risk and change.

In an ever more complex world, change is known as the constant, not a surprise. The pace of change is breathtaking with great variety, bringing with it new conditions to which all engineered systems in it have to adapt. Consider the popular exercise of collapsing the past 200,000 years of civilizational development into a single day. Humans spent the first 23 hours as hunter-gatherers; what we know as "modern industrial life" emerged in the last 90 seconds of that day. (Rothschild 1990 p.19)

It is change that necessitates human managers; if accidents were perfectly predictable according to machine-readable algorithms, and then any rote system, whether computational or human, should be able to manage a system. It is the unpredictability of human life and the necessity for adaptive change that makes risk management an accepted necessity. Decision analysis researcher Kirkwood's *System Dynamics Models: A Quick Introduction* (1998 p.17-18) puts it simply and well: "Some of the greatest management challenges come from change. If sales start to decline, or even increase, you should investigate why this change has occurred and how to address it. One of the key differences between managers who are successful and those who are not is their ability [to be aware of and] to address changes before it is too late."

Natural systems that underlie and support human systems also change over time; human beings are far from being the only change-variant entities that we must consider as risk managers. Given enough time, large infrastructure systems, such as dams and bridges, also change due to various natural influences (weathering, corrosion, etc.).

Change is inevitably accompanied by risk, which we call "the risk of change." Given the fact that systems are constantly changing, how do we analyze the associated risks? In the face of the occasionally impressive magnitude of the changes in nature – Rothschild's mammoth skeleton, for instance, (Rothschild 1990 p.27) – the chief challenges that we face are epistemological, and they may not have straightforward or immediately comprehensible solutions. We close with a consideration of Lamarck, who propounded the idea that "It is not… the form and character of the animal's bodily parts that have given rise to its habits and peculiar properties, but, on the contrary, it is its habits and manner of life and the conditions in which its ancestors lived that has in the course of time fashioned its bodily form, its organs, and its qualities." Because animals kept adjusting to the ever-changing world around them, the very concept of a stable species was meaningless to Lamarck. Life was fluid, forever reshaping itself into new forms in response to shifting circumstances." (Rothschild 1990 p.29) Today, the concept of Lamarckian evolution is discredited and cited chiefly as a historical curiosity, but its critique of the notion of species stability, and not its positive construction of theory of accumulated changes, contains the kernel of a truth about how we must consider risk. The sources of our answers will not be obvious, and they are independently applicable even if we ignore or hold constant their relative efficacy in their fields. Thus we can all regard Lamarck's lesson for risk managers as an apt one, even if we recognize that Lamarck's theory is discredited. So too we may argue for the acceptance of the validity of the risk of change as a qualitative notion, even holding *arguendo* the truth or falsity of the sources of our notion.

Chapter 5. The Risk of Change—Qualitative Notion

Thesis: We will define the risk of change as a potential of change through the metaphor of momentum, using a moving truck as an example.

Understanding risk alone is a daunting task. Defining the risk associated with change may sound impossible to most people especially when change comes in with an unlimited, if not infinite number of varieties. Among the myriad of changes in the world, movement is probably the most well-investigated and understood. The most basic constituent laws governing their movement are set forth in the famous *Laws of Motion* that Sir Isaac Newton proposed in 1687. Let us begin with an observation of a simplified change – the movement of a truck.

In Newton's *Principia Mathematica*, Newton's described "the 'System of the World'—the laws of motion of physical bodies—and laid bare the underlying mechanism of the universe. He showed that a single universal force—gravity—determined the orbits of the planets, the cycles of the moon, and the ebb and flow of ocean tides." It was, as Rothschild (1990 p.20-21) notes, "a universe of perfect predictability—a cosmic clockwork mechanism—where planets cycled endlessly along unchanging paths. Objects moved, but the 'laws of motion' never changed. In the stately order of the Newtonian universe, the future was indistinguishable from the past. History was meaningless in a world of endlessly repeating cycles. Passage of time could not imply forward movement or progress. As a matter of natural law, the world and all the stars and planets in the heavens would continue exactly as they were – cycling along orbits set by God at the Creation." Through elucidating essential natural laws or patterns of system behavior, Newton presented a parsimonious yet powerful model for that most basic of natural changes: movement.

Let us consider a truck tasked with regularly carrying of cargo from point A to point B. If we think about this question through the lens of the risk of chance, we will have to start with listing all possible situations or accidents that a moving truck can end up having. This will be a sizeable list: the brakes may fail, the driver may make a mistake, there may be internal engine or suspensions malfunctions, there may be a situation of accelerated wear due to exceeding the trucks' expected duty cycle, the truck may fall into a valley, the speeding truck may ram into a bus in front, a storm may break the main bridge in between and force a route change, etc., etc. The next step is an estimation of the consequences and probabilities for each of the situation or accident. Then, expected losses, i.e., the risks, are calculated and ranked.

What we have achieved with the rather reductive notion of the risk of chance is in fact very far from a reduction in cognitive load. We are faced with a massive proliferation of potential possibilities which can only be calculated and ranked with the aid of computers, and even then with significant theoretical difficulty.

What if we approach this situation from the perspective of a constant background of dynamic change? Following this idea, we look for the patterns of potential intrinsic failures and external factors that may come into play, and then attempt to systematize our understanding by identifying the most essential aspects of change at work in the situation. In this case, we may notice, for instance, that all accidents can be attributed to being out-of-control while moving, that a statistically significant portion of maintenance failures occur from insufficient attention to regular maintenance by the operator of the truck, and further that the aging of the truck across time affects both its susceptibility to externally-caused accidents as well as internal failures. We gain, in other words, a more practical understanding that offers distinct solutions aiming to relieve underlying causation. We gain an explanatory *why,* which may include design compromises, legacies, and other flaws or difficulties in the truck design, as well as a descriptive *how*, which examines the system at large and views its changes in the context of the overall state of background change for the "macro-verse" that the system participates in.

Let us focus for a moment on traffic accidents, in which we can easily identify a simple essential mechanism for: being out-of-control while moving. In this situation, the risk of failure is determined by whether the truck remains in control or not. Now our task as risk managers is to prescribe practices and systemic dynamics which will diminish the risk of the truck going out-of-control, with the desired result of reducing overall accident rate.

5-1. The Momentum of Change

5-1-1. Defining the System State Change and the Speed of Change

Before we can discuss the risk of change further, we should first ask "What is change?"

The dictionary definition of change states that it is: "[t]he act, process, or result of altering or modifying," or "A transformation or transition from one state, condition, or phase to another." (The American Heritage Dictionary of the English Language, 4th Edition 2000)

A *system state change*, then, is brought about through an "act, process, or result of altering or modifying," creating a "transformation or transition" from one state to another. How, then, may we define *system state*? We will explain this further later with our stock & flow concept analysis. For risk management, a strong candidate for a definition of system state is the notion of *risk climate*, or *risk culture*. System state seems to resemble the definition of risk climate (social science) / risk culture.

A critical component of understanding change is explaining the *speed of change*. We believe that the speed of change should be understood as a vector quantity. Change can be towards the system goal or away from it, but even if the change is not teleological or purposeful, it does nonetheless remain categorizable in a purposeful, teleological categorization. We believe that the speed of system change might be summed up as a simple equation:

$$\boldsymbol{v} \text{ (Speed of Change)} = \boldsymbol{\Delta s} \text{ (System State Change)} / \boldsymbol{\Delta t} \text{ (time)} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (1)$$

We say "*might be summed up*" because this is a beginning, but not overall satisfactory explication of the rate of change. Although it might be ideal to have a well-defined frame of reference – for instance, a Cartesian coordinate system used in describing the location – so that the system state can be quantified,. However, it does not seem to be possible at the current stage of research if the social, political, psychological etc., aspects of the system are to be included. Such factors cannot fit clearly into a simple schema as such. We may refer to this as a basic *quantification problem*. An analytical approach to an easy, total coordinate system may not exist. Thus, this model compels us to identify critical components in the system, and then measure changes among those components, using for example *system identification technique*. However, this approach may draw our attention to certain identified critical components and break the balance of attention needed for the system as a whole.

5-1-2. Risk as the Momentum of Change

We have succeeded to a limited extent in defining the risk of change, but with important and notable shortcomings which suggest the direction we must develop. Specifically, for complex engineered systems, instead of measuring the risk by the expected loss of potential hazards in a time-invariant manner, we should measure it by the changing potential of the system state in a time-variant manner. The simple Newtonian model we set forth thus far works as follows:

$$\boldsymbol{p} \text{ (Momentum of Change)} = \boldsymbol{m_c} \text{ (Consequence)} \times \boldsymbol{v} \text{ (Speed of Change)} \ldots\ldots\ldots\ldots \text{ (2)}$$

where

- The momentum (p) is a vector quantity and thus possesses a direction as well as a magnitude. When the direction of a change is helping the system moving towards its goal state, it is an opportunity; when the direction of that change moves the system away from its desired goal state, on the contrary we may term it a risk to the system.
- The consequence (mc) here represents the potential consequence(s) due to system changes.
- v is the speed of change as a scalar, representing the rate at which the system's monitoring variables are changing.

Now, we have an equation that is both time-variant and also consequence-variant. Intuitively, the larger the consequence and/or the faster the change is, the greater the momentum of change will be, i.e., the greater the potential of the system becoming better or worse will be. Thus, we may cast in comparative terms *small, rapidly approaching changes* as against, say, *large, slowly approaching ones*. Further, this account prioritizes *rapidly approaching risks and opportunities*, not only the basis of their magnitude, but also in terms of their immediacy, which has the beneficial side effect of incorporating or "baking in" a priority measure yielding much more useful set risk/opportunity management. (Interestingly, it is also not difficult to incorporate cost into this approach, if the opportunity cost of remedying risks or creating opportunities can be quantified. This has potentially significant implications for the risk management of projects, but is outside the scope of this paper). A moving truck is a useful analogy for this concept – a bigger and faster truck has more potential to cause severe damage. On the other hand, it has also more potential to carry more goods or passenger to the destination faster. Using our account of system risk, the decision-maker in charge of the truck thus may consider not only the risks associated with rate of change in the truck's position, but also the temporal priority of each – in other words, how soon each risk must be addressed or each opportunity created.

5-2. The Force behind Change

For the purposes of risk management, the concept of "force" has several meanings. The type of interdisciplinary work we are doing requires an understanding of force which will apply to a range of different meanings. Besides the physical forces that Newton introduced in his Laws of Motion, the concept of force has been used in many other social sciences. For example:

1. Mars exerts a gravitational **force** on Phobos and Deimos.
2. Competition is a **force** for change in industry.
3. The 2008 elections produced a major realignment in the balance of political **forces**.
4. The Internet has become a growing cultural **force** in the modern life.
5. Diet exerts a powerful **force** on health.
6. Regulation is an important **force** on the operation of a brokerage firm.

Initially, we should ask if these are all the same type of force, and whether all these types are appropriate to our discussion of risk analysis. The answer to the first question is plainly no; although these are all grammatical and lawful sentences in English, they have radically different meanings. In 1, force is physical; in 2, 5, and 6, force is a determinant in how an entity acts whether it is an industry, an organism or a company.

Since risk analysis deals with both physical systems (bridges, railroads, hospitals) as well as non-physical systems (companies, software, laws), we should seek a domain-agnostic definition for the term, that is, one that will hold true across the wide range of domains in which we will use the term. For the most general and applicable meaning, we turn first to the dictionary. Princeton's WordNet online dictionary lists the first two definitions as:

> *(n) force (a powerful effect or influence) "the force of his eloquence easily persuaded them"*
>
> *(n) force ((physics) the influence that produces a change in a physical quantity) "force equals mass times acceleration"*

This may not be entirely satisfactory, however. Different forces operate on different domains, so that for instance the force of law and regulation will act differently on a solution for a government agency than it might for a private company. And, indeed, a brief survey of organizational behavior literature shows both forms used in a variety of ways. For instance, at the project level, various breakdowns of the relevant forces we are categorizing exist ,e.g., SWOT (**S**trengths, **W**eaknesses, **O**pportunities, and **T**hreats) analysis, STEER (Socio-cultural, Technological, Economic, Ecological, and Regulatory) analysis, etc. Robbins and Judge's (2007 p.644-645) important *Organizational Behavior* lists six basic forces:

a) Changing nature of the workforce, e.g., more cultural diversity, aging population, many new entrants with inadequate skills

b) Technology, e.g., faster, cheaper and more mobile devices, cloud computing, deciphering of the human genetic code

c) Economic shocks, e.g., rise and fall of doc-com stocks, 2000-02 stock market collapse, 2008 financial crisis worldwide

d) Competition, e.g., global competitors, mergers and consolidations, growth of e-commerce

e) Social trends, e.g., social networking websites, retirement of baby boomers, rise in discount and "big box" retailers

f) World politics, e.g., Opening of markets in China, global warming effects, Iraq-U.S. war

The consulting firm PriceWaterhouseCoopers, in its previous iteration as Coopers & Lybrand, argued in a seminal definition that the four major categories of forces that drive organizational change are (Nelson 2006 p.298):

a) market forces,

b) rapidly changing,

c) changing political institutions and societies,

d) the internal need to improve performance and competitive situation.

While definitions of what force may (or may not) include vary, all these forces (natural, social, political, economic, legal, etc.) have in common that they define the way systems change over time. In all cases, a system state emerges from the interaction of forces. From the perspective of the system, then, there is another important aspect of force: *controllability*. We will discuss this in more depth shortly. For now, we conclude with the definition of force as an influence or effect, internal or external in origin and action, which defines the way that a system constitutes itself over time.

5-2-1. The Concept of Force

Here, we will give a formal definition of force.

$\boldsymbol{F}_{net} = \mathrm{d}\boldsymbol{p} / \mathrm{d}t = \mathrm{d}(\boldsymbol{m}_c \boldsymbol{v}) / \mathrm{d}t$ (Time Derivative of Momentum) …………………….. (3)

where

- The net force (Fnet) is a vector quantity indicating net force.
- dp/dt is the derivative of p, the momentum of change, across a period of time referred to as t
- d(mcv)/dt is the derivative of the consequence times the speed of change, v, over time period t.

This equation means that the net force on a system is equal to the rate of the momentum change it experiences. Further, this equation is sensitive to *opportunities* as well as *risks*: the time derivative of the momentum does not equal zero when the momentum changes *direction*, even if there is no change in its *magnitude*.

When applied, this equation casts forces as essentially being patterns/processes. A pattern or an order forms the building blocks of structure that compose a system. We use the expression $\boldsymbol{F}_{net}$ to incorporate the idea that we are after the results of a *functional process*, for that is what the system is composed of: the system is a dynamic set of functional processes; the separable components of which can be considered to have a *net force exerted upon them by change over time*.

5-2-2. The Influence of Force (Impulse)

We have derived an idea of the action of force over time, but we still need to explain further the influence of force. Our concern is with interacting forces. Changes are the result or symptoms of forces; the forces being the root of changes. To understand this quantity, we must introduce the notion of an impulse, or the action of a force across time. Our equation is:

$$\boldsymbol{I} = \int_{\Delta t} \boldsymbol{F} \cdot \mathrm{d}t = \int_{\Delta t} (\mathrm{d}\boldsymbol{p}/\mathrm{d}t) \cdot \mathrm{d}t = \boldsymbol{\Delta p} \text{ (Change in Momentum) } \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{ (4)}$$

where

- An impulse (I) is the summation of the effects that occur when a force (F) acts over an interval of time (Δt).
- The impulse (I) equals the momentum of change (Δp) produced by the force (F) in this time interval (Δt).

The primary importance of this equation is that it implies that the more powerful the force and/or the longer it acts on the system, the greater the influence it will have on the system. Intuitively, this is sensible. For example, consider corrosion in steel structures. Corrosion can be seen as an intrinsic force that deteriorates the system. Although the force may be weak, over years, its action on the system can result in a dramatic increment of the change in momentum, i.e., the risk. On the other hand, a strong force, such as an organizational change, can have great impact even in a short period of time.

Equivalently, the net force on an object equals the rate at which its momentum changes. The effect of force accumulates over time, yielding the time-variant measure we seek in order to portray the risk characteristics of dynamic, changing systems.

This is a critical measure in our system of risk. We will explain briefly how this combined measure applies to a variety of systems.

At the start, one of the most important results of an account of risk based on the equations we set forth is the idea that developing system-beneficial patterns (when $\boldsymbol{F}_{net}$ is positive) is one of the foremost goals of the risk manager. As may be recalled from our account of the evolution of systems, accidents may be seen as a developing process of functional deterioration with variable etiology (since many engineered systems, like human ones, are intrinsically compromised and/or legacy-oriented). The key part of this view is that it suggests that the most positive way to affect the sign (positive or negative) and magnitude of the $\boldsymbol{F}_{net}$ measure is through *changes* and *patterns* of behavior summed up across time. Senge (1994) describes the type of recommendation that our system produces:

> *"There was no dramatic policy change," says Pat Walls, a Federal Express managing director who is coordinator of the learning laboratory project there.*

> *"When you trace back the stories, you find out that all this change came from hundreds of little things that individuals were doing differently. It's like the old expression, "You are what you eat." If you start thinking differently, you see things differently. And all your actions start to change." Systems start to change accordingly. (Senge 1994b) [p88]*

The result, we believe, are risk interventions that produce real results. Just as genes are not the sole determinant of one's health (it is life styles and habits, after all, that determine the expression of your genes and your health), so too the initial design of the system should not be mistaken for its essential nature. The real system resides in the daily life that it covers; quite literally, "you are what you eat." Liang (2006 p.77-79) puts it in terms that so strongly echo Senge's that it is worth quoting at length:

> *Genomics studies have shown that gene expression is dynamic; its performance can be good, it can be bad. The gene expression of the good or bad is not pre-determined, but through internal and external environment and cell communication in all aspects of the message, just determined. Gene receive a message from a variety of nutrients, such as antioxidants, vitamins, minerals, trace elements, fatty acids, etc., which is why the right food and nutrients is very important. For example, the colon cells contain a gene inhibitor, but it needs to be activated by a fatty acid to play its anti-cancer role. Obviously, the right food and the intestinal environment are very important (to echo the views of Chinese medicine). Of course, in addition to food and nutrition, there are other factors that affect gene expression that can not be ignored, including sleep, exercise, lifestyle, environmental toxins, and spiritual status. As the saying goes, "You are what you eat." We cannot change genes, but through proper nutrition and lifestyle, we can open the possibility of good, healthy expression of the genes. On the other side, even if one's genes are a favorable genotype, if one has a daily routine of smoking, drinking, never exercising, eating junk food, being long-term stress-ridden and having one's diurnal cycle disrupted, a bad expression of our genes will be shown, planting the seeds of future chronic diseases.*

The structured design of a system (or its *genes*) and its daily life have a complex interaction. The "genes" for an organization, as we have seen with the evolution of natural organisms, may not be perfectly oriented towards its life. These maladaptive genes may not be evident until conditions emerge. In diagnostic terms, this is called *diathesis/stress* etiology – the *diathesis*, or system weakness, exists latent and unnoticed until brought out by an external *stress*. Should the systems' environment never exceed certain parameters, these latent diatheses may go completely unnoticed. The idea that there is an essential, reductive "genetic" component to accidents and systems is not an uncomplicated one.

We close our consideration of impulse with a cautionary note: even the best planning and recommendations may not adequately remedy every situation in risk management. Since we acknowledge that the basic genetic material of a system may be wrong or misguided without even knowing about it ("bad genes"), we should also acknowledge that even the best-intended interventions we may make in a system will still have unpredictable effects. It is ultimately, as Senge and Liang agree, "what a system eats" that makes it up, or constitutes it. We will turn to the notion of *constitution* in our discussion of TCM.

5-2-3. The Classification of Forces

In light of the insufficiencies of existing force frameworks, we offer the following account of possible sources and influences of the forces that interact on a system.

On our account, forces may be classified by *sources*: *intrinsic forces* (mainly due to natural conditions relating to the relevant system) and *extrinsic forces* (mainly resulting from human intervention).

To return to our corrosion example, corrosion is an *intrinsic* force since it comes from the physical characteristics of the material used to build, while corruption would be an extrinsic force since it is applied from without by humans.

Forces are not, by themselves, either good or bad for a system. The type of system we are discussing, as well as what timeframe within the system lifecycle we are looking at, has important implications on the effect of the force. For instance, for Cor-Ten steel, corrosion is a positive force, up to a point – rust on the exterior of a Cor-Ten structure seals away the corrodible interior, increasing its overall durability. However, for a plain steel structure, corrosion is a constant negative. The type of the system goals and its material structure are important determinants of whether a force will be good or bad for a system. Analogously, a force that produces increased operation of the system – for instance, higher water pressure for consumers for water delivered over a municipal water system – may, at different points in time, be good or bad for the system. A force which increases water pressure by 10% is a very different thing when the water system's pressure is at 20% than when it is at 120%.

Internal forces are not always within system control; similarly, external forces are not beyond system control. For example, in an organization, the organizational culture is an *internal* force, while national culture would usually be an *external* force. However, that internal organizational culture may be a legacy given to the current decision-makers; similarly, national culture might be thought of as a manipulable force if the relevant decision-maker was, perhaps, a media mogul like Carnegie or Murdoch, The lines between internal and external are not always clear. However, what is always necessary to ascertain is whether or not the force can be controlled, and whether it has a strong or weak effect.

Classification by Controllability

What makes a force controllable or uncontrollable? By control, we mean the ability to produce a result from a cause which the system manager manipulates; in other words, control over the system's destiny and eventual state. System inputs, design and operation are under control, and may be considered controls (in the noun sense) which can be manipulated; weather, the overall global economy, traffic, and the passage of time are all forces which cannot be controlled.

A system may also have a greater or lesser degree of control. For example, if a business is dependent on one supplier for a certain key raw material, and increases the number of suppliers from one to five, we might say that business has more control over its raw material inflow. For a reservoir, finding multiple sources of water to replenish the reservoir would be a means of increasing control over the stock of water held in the reservoir. The means by which a system produces a result we could term a *control measure*. For the business, the acquisition of additional suppliers, or for the reservoir, of additional water sources, constitutes a control measure. As we have quoted earlier in Section 1-2-5: (Bernstein 1996 p.197)

> *The essence of risk management lies in maximizing the areas where we have some control over the outcome while minimizing the areas where we have absolutely no control over the outcome and the linkage between effect and cause is hidden from us.*

Initially, we can see that consistency is an important condition of a control measure. Producing a different effect every time from the same control measure is a wildly unsuccessful control (imagine if something different happened every time you turned the water faucet!), so *consistency of effect* is an important distinguishing factor in control. Control of a force is determined by the ability to produce the same effect repeatably.

The context and environment of the controlled system has a significant effect on the importance of a control. For our examples, the business may be in an environment or a business climate that is strong or lackluster; similarly, for the reservoir, a drought or a flood makes the level of control over the reservoir's level more or less important. A lack of control may be an acceptable operating condition in a safe environment with relatively little that could go wrong. However, as the potential of failure and danger increases, more control becomes necessary in order for managers to maintain the health and integrity of their systems. For instance, a reservoir in an area with heavy, regular rain dispenses its water much less carefully than a similar reservoir in an arid, parched region; a business in a downturn watches its expenditures much more carefully than one in a boom period.

Even in areas which we may directly affect, nothing may ever be totally controllable, however, despite our best efforts to discern control or the lack thereof in our systems. Indeed, on account of dynamic change, there is always uncertainty, since conditions are constantly changing. However, even though there may not be a binary, dichotomous split between control/out-of-control, it is meaningful to speak of forces as being *more or less under control*. We may phrase it as a logical test:

If attempts to control the force produce the same effect with sufficient reliability, then the force may be said to be more or less under control.

Sufficient reliability will, of course, mean different things in different domains, and what the system has at stake in its operation will produce vastly different degrees of sufficiency. What is sufficient reliability to deem a control measure adequately efficacious – say, 15 in 20 – may be adequate for a domain like animal training, but highly unsafe and inadequate for a field like civil aviation. That is, mathematically speaking, control is always a quotient – never an absolute 0 or 1.

Control is a *sufficient* condition for a healthy system, but it is not a *necessary* one. That is, since all systems aim at healthy operation through controlled operation, all healthy systems are to some degree controlled. However, a well-controlled system is not necessarily a well-ordered, healthy one. Although most system managers tend to think of increased control as an unquestionable good, this is not always the case. There are plenty of systems that thrive on diminished or absent control, for example creative industries like writing, marketing, and advertising, as well as free markets systems according to laissez-faire economists. Further, since decision-maker attention is limited and must be directed, excessive control can produce a form of "control creep," where system managers become flooded with possible controls, introducing distraction and increasing the risk of failure.

Since control is a sufficient condition for system health, not a necessary one, and what is utterly necessary may not be known, it should be the goal of system developers to extend the forces over which the system has control. While the presence of control over a force does not necessarily mean that the system decision makers will use it appropriately, it is nonetheless true that more control usually, but not necessarily, good. Since system decision-makers are already operating with bounded rationality, we argue that attempting to un-bound that rationality so that system managers are able to search for the potentially non-existent utterly necessary controls would be ineffective and self-dooming. A wiser approach would be to simply incorporate some idea of the bounds of rationality into the control measures available to system decision-makers. We propose to do so with the notion of *degrees of control* – the idea that control is never absolute, and that only sufficient conditions for system success can be reliably obtained.

Classification by Influence

When we speak of a force's *influence* on a system, we refer to the total potential consequence exerted by a force on a system over a period of time. This type of effect, across time, tends to be ignored in current risk analysis, which is insensitive to time. We may systematize the forces on a system and the timeframe of their effects on that system quite simply and with revealing results. Let us begin with two opposite types of forces: *strong* forces and *weak* ones. Forces may exert their influence nearly instantaneously or over time, making it relevant to speak a time interval. That is, we can distinguish between *short* and *long* intervals of change. Amongst other specific influences, forces acting over a long period of time usually follow some sort of pattern. In this 2 x 2 matrix, strong/weak and long/short are not absolute, but rather relative, mutually dependent concepts that are similar to the relationship between *yin* and *yang*.

Table 5-1. Force Classification by Influence

	Strong Force	**Weak Force**
Long Interval	a) Profound influence	c) Considerable influence
Short Interval	b) Considerable influence	d) Limited influence

a) A **strong force** acting over a **long interval** of time usually causes **profound influence** to the system. We use the term profound to indicate that it causes fundamental qualitative change that requires reflection to fully understand. Examples of profound influences are those caused by culture, socialization, and climate change. Climate change is a perfect example. It may be imperceptible on a year-to-year basis and may even vary quite normally and naturally from an overall warming trend, but climate change takes decades and its effect is driven by a massive amount of global phenomena (oceans, atmospheric particles, ice packs) and its effect is usually highly significant. Moreover, since it is caused by the interactions of a set of complex natural and manmade systems, this type of change is typically quite difficult to control, requiring systems and system managers to adapt.

b) A **strong force** acting over a **short interval** of time causes **considerable influence** to the system. Management and assessment of these types of forces are an important part of the subject matter and practice of crisis management. These forms of influence are rare, and by definition unpredictable. Examples of this type of influence include influences cause by political force, the force of legal decisions, earthquakes etc. Both an unexpected legal decision (any of the recent federal and state decisions surrounding financial regulation are good examples) as well as a sudden natural disaster like an earthquake or hurricane are alike: they exert their force rapidly, causing significant impacts.

c) A **weak force** acting over a **long interval** of time usually causes **considerable influence** to the system. Examples of these types of forces are corrosion, influences caused by human habits, procedures, and gradual weathering. Because these patterns create large effects over time, we need to change patterns and habits in order to adequately address these types of forces.

d) A **weak force** acting over a **short interval** of time causes **limited influence** on the system. These types of forces are typically harmless or at worst latent diatheses awaiting trigger conditions to create a full-fledged failure. Influences like occasional human errors, accidents, and adverse natural conditions like rain can be considered limited influences. However, if an error or a slip is happening regularly, it should be classified as a bad habit, making it a form of considerable influence. Correcting these types of forces should not be a high priority for system managers; these types of influences tend to become problems only when system health is in a dire condition, in which case the negative effects of weak forces over short periods can precipitate "straw that broke the camel's back" events. Rather than attempting to reduce these potential negatives to zero, we argue that system managers should focus on maintaining system health.

The ability to promote the success of a system after a change in the environment does not necessarily follow from the most recent set of changes to the last obstacles to progress in the formation of the system. That is, the constant renewal of the system does not necessarily reiterate the logic of the initial formation of the system, or its initial dominant logic. Although the previous history of success for a system may be predicated on a certain type of logic, it does not guarantee its present or future success in a constantly varying world requiring different forms of logic. One of the fundamental characteristics of the forces confronting a system is their variability. The constant flow of challenges that must be solved in a constantly renewing system – for instance, a business – do not necessarily resemble each other nor accord to any type of dominant logic. As Chesbrough (2003 p.70-71) puts it:

> *The dominant logic is the prevailing wisdom within the company about how the world works and how the firm competes in this world to make money.... People within firms do not reevaluate their logical approach every time new information comes in. To the contrary, they search for ways to apply the dominant logic to interpret the new data. The shared assumptions behind the dominant logic will also help disseminate the meaning of the new information to others.*
>
> *Although dominant logic is useful and beneficial in coordinating the actions of employees in a variety of situations, it comes at a cost. The choice of business model constrains other choices, removing certain possibilities from serious consideration. Over time, the business becomes more entrenched in its current model and is not able to recognize the information that may point the way to a different and perhaps better model. This is the potential trap.*

5-3. The Inevitability of Change

Newton's Third Law of Motion states that every action has an equal and reciprocal reaction. Formally, we could state as follows:

$$\boldsymbol{f} = -\boldsymbol{f}' \quad \text{……………………………………………} \quad (5)$$

where

- f is an action and f ' is a reciprocal action. However, we can see at first face that this seems not to hold true for systems which experience emergent effects (like life) which are not assignable to any discrete part of the system. We seem to have a quandary with regard to developing a lawful system of rules for system change.

We may resolve this quandary with recourse to the fundamental principle in the Third Law of Motion, is the conservation of momentum; even in cases where the Third Law does not hold true, like complex systems, the principle of conservation of momentum still does. In risk dynamics, the law of reciprocal actions and conservation of momentum of system change holds true – but in a modified form. For an engineered system which exists in a real world environment (which is itself a system) every action contributes to overall change within the system of the environment. A tiny speck of rust on our greenhouse, or a small population of pests within a single system in the world, our greenhouse, may produce system-wide effects throughout the world which may return to affect us, even though their initial set of interactions may be small.

Thus, we can see that everything within not only the system we are concerned with, but also the environment that our system operates in, is unpredictably connected to a greater or lesser degree, and must be considered together. Small effects may chain into larger system-wide effects, the so-called "butterfly effect." Although a butterfly flapping its wings causes only a small set of determinate Newtonian physical effects, its interconnectedness to its relevant system – climate – means that just as a butterfly flapping its wings in one part of the world could theoretically cause a hurricane in another. A seemingly small and short-acting force in one area of the world considered as a system may cause an unpredictable magnified effect in another area of the system. This is particularly true for highly complex systems like those of the human body, which are highly interconnected.(Liang 2006 p.229) What happens to a small part may affect the whole, and since all things are interconnected a slight move in one part may affect the whole situation. In fact, every part of a system may be altered in some part by a small change. As an old Chinese adage puts it, "A fire on the city wall brings disaster to the fish in the moat." or "In a disturbance innocent bystanders get into trouble."

Since everything within the world as a system may be considered interconnected and with unpredictably chainable results, we argue that there exists a principle of conservation of momentum of change within the world as a system. We may state it formally. Suppose that we have a system, on which we insert a force creating a change, ***f***, with a certain momentum, ***p***. The measurable effect on the world is ***e***.

- Every p is greater than or equal to zero. The action of force is always, by definition, not zero.
- For every e there exists at least one f. Every effect in the world is the result of some cause, whether or not this can be traced.
- Not every c produces an e. Not every cause produces an effect. That is, the environmental results of our actions cannot be predicted with logical certainty.
- e is always greater than or equal to zero, even if it cannot be measured. Every effect has a magnitude, even if that magnitude is infinitesimally small. This is a restatement of our thesis with regard to the uncertainty of change: risk is a result of change, and since the momentum of change which that change produces (a function of e with respect to time represented as the speed of change) is constant, the presence of risk of change in the entire environment is a constant greater than zero, even if it is immeasurable. This is a concept remarkably similar to the Buddhist notion of karma, the idea that all actions by an individual have consequences which eventually return to the individual. Whether or not the effect of karma is measurable or not, karma may be said to be a basic corollary of the laws of cause and effect. This argument is basically that karma, even though it may be immeasurable, is never zero.

Apropos to our task as risk managers, this means that while a small change – for example, a weak force over a short amount of time – in the operation of the system does not *necessarily* result in an environment-wide result, small changes in system operation are, as we can acknowledge from empirical knowledge, *sufficient* to cause a environment-wide result. The magnitude of the result may be traceable in a deterministic fashion to the force that we enact, but the difficulty in obtaining this magnitude is so significant that we argue it is pointless. Since this magnitude changes over time, our measurements would also be obsolete as soon as we obtained them.

Rather, what we can measure and understand with depth is the directly measurable effects within our system of the force we place under our system's control – the only real resource we can use to adapt to change, since we are unable to change certain factors about our environment and since all factors in the environment are interlinked, meaning that all attempts to improve the system through manipulation of the environment are by definition probabilistic. For instance, for a greenhouse as a simple engineered system, the only factors available to us to manage the greenhouse's future with any degree of control are the forces within the greenhouse – lighting, air pressure, temperature, soil composition, etc. Forces such as weather and environment are controllable, but only to a very limited degree – while one might, for instance, attempt to control weather by setting the greenhouse in a location with favorable weather, such control would be incomplete at best.

To return to our example of a weak force over a short period of time with difficult-to-determine consequences, the idea that change is inevitable would lead us to become wary of the repetition of the action of a weak force over an extended period of time, due to the potential of producing a *considerable effect*. At the very least, a weak force over a small amount of time adds the small amount of matter and energy directly attributable that force into the system; at the most, it may radically alter the entire environment. However, as the amount of force changes, the state of the environment must change as well, and that change is always returned to the system from the environment. Thus, it is impossible for a system to operate without encountering change, since change is a constant feature of the system's interaction with its environment.

This principle means that the momentum of change exerted on the environment by the system is at least that amount of the momentum directly returning to the system from the environment. In other words, if we were to make a change to our hypothetical greenhouse's operation, the momentum of environmental change directly returning back to the greenhouse as a system would have a component which would vary with respect to the magnitude of our system change. For example, the more lights we put in, the more power we use; the effects of that power usage may be difficult or even impossible to trace (as far as contributing to, for example, climate change). Thus, it is impossible or at least impractical to reduce the amount of risk of change that the system experiences from the environment to zero, since producing constant change (at least a very small amount) and receiving the effects of that change from the environment is in the nature of a system. A reduction of risk in one parts of the system may eventually increase the risk of some other parts of the system, due to unpredictable environmental consequences from the environment brought on by the system change in accordance with the principle of conservation of momentum. This is the reason why unexpected events happen all the time in closed systems with a limited number of determinate parts. The only way to have no risk of change within a system is for a system to stop changing (removing the potential for success as well as failure), or a dead system.

Since, as we argue, the total amount of energy and matter within a system is not predictable because it changes over time and has an inherently unpredictable component, it is not reasonable to attempt to exhaustively enumerate and analyze the risks from even small changes, since risk is inevitable with change, and change is inevitable with progress. Further, the resources and attention of system managers is a limited quantity, and attempting to attend to an infinite range of potentially bad consequences is a self-dooming mission. Allocating them in only part of the system empirically eventually causes problems in the other part of the system. (Elms and Brown 2006 p.8) Rather, what is required is balanced change while remaining in control, which allows the system to harness the positive dimensions of the risk of change. Control of the forces within the system's capability and driving balanced change in a positive direction is the only real way for system managers to manage the underlying causes of risk.

We conclude our consideration of the inevitability of change with what may be considered the counter-argument made by the traditional account of risk. This counter-argument would hold that even though a fully satisfactory quantification of the risk and safety of a situation may never be made, the effort to obtain such quantification has merit in and of itself. In other words, "The act of trying to measure the risk involved is the source of knowledge. The acts of trying to assign values, combining them, questioning their verisimilitude, building the model are the great treasure of PRA: the key to the treasure is the treasure itself." (Epstein 2006 p.8) The traditional system tries to measure all possibilities through fault-tree/event-tree analyses then use those to improve the system. However, even as apologists for the traditional system will admit, these accounts are non-exhaustive, difficult and time-invariant. A fuller analysis like our account argues that we should look at the network of cause and effect chains operating within the system across time, from the perspective of the inevitability of change as driven by environmental feedback, in order to determine how to restore or maintain balance. Looking at the different fault-tree/event-tree analyses that the traditional account provides does give system managers useful cause and effect chains that place aspects of system operation under their control, but as we will demonstrate in our argument for the TCM paradigm, this is just the beginning.

Chapter 6. The Risk of Change—Quantitative Definition

6-1. Key Concepts of System Dynamics

The power of the concept of System Dynamics as we describe it is its ability to holistically encompass almost any type of business process. Just as Kirkwood (Kirkwood 1998 p.17) argues that "all… processes can be characterized in terms of variables of two types, stocks (levels, accumulations) and flows (rates)," system dynamics modeling is useful for managing complex processes that involve changes over time and are dependent on the feedback, transmission and receipt of information. (Sterman 2000) This is because, as Love et al. (Love et al. 1999) state, "the primary focus in system dynamics is the examination of the effect that one element has on another." This relationship focus means that system dynamics is an ideal modeling tool for analyzing the complex interaction of forces that affect overall system behaviors.

The technique of causal loop diagramming is our platform in this research for linking together the major causal variables of change. A causal loop diagram shows explicitly the direction and type of causality, which is fundamental in understanding change in a project system. It can be used to model the influences of inputs on outputs and vice-versa. That is to say, if variable A is causing a change in variable B, the direction of causality is from A to B. If an increase (decrease) in variable A leads to increase (decrease) in variable B then the type of causality is positive; otherwise it is negative.

Senge has undertaken interesting work in the area of causal relations. He has used the concept of the causal loop to show why certain process patterns develop over time, and theorizes that there are patterns of causal behavior (or archetypes), that can explain why events happen in certain ways. (Senge 1994a; Senge 1994b; Senge 1999) For example, one archetype defined by Senge is the "vicious circle." This is interpreted as "A implies an increase in B, which implies an increase in A which implies an increase in B …" and so on. In order to understand the inner mechanism and behavior of change events there is a need for a degree of experimentation. Such experimentation is not considered to be easy to implement due to the complex and dynamic nature of projects. (Love et al. 1999) We will draw on these concepts further as we delve into the diagramming of causal loops.

6-1-1. Causal Loop Diagrams

The concepts of *yin yang* opposition and reconciliation, as well as the *wu xing* system of organ correspondences, provide an abstract system which can be productively mapped onto engineered systems. The basic principle of *yin yang* theory suggests that everything is interconnected together in a system, and that that system's inclusionary and exclusionary sides are mutually opposed yet mutually reinforcing. *Wu xing* theory suggests that there exist positive and negative feedback loops within and between sub-systems – generative and restraining cycles, respectively – which we will examine in-depth at Section 8-2-3.

Much of the art of system dynamics modeling is discovering and representing the feedback processes, which, along with stock and flow structures, time delays, and nonlinearities, determine the dynamics of a system. One might imagine that there is an immense range of different feedback processes and other structures to be mastered before one can understand the dynamics of complex systems. In fact, the most complex behaviors usually arise from the interactions (feedbacks) among the components of the system, not from the complexity of the components themselves.

Let us consider a simple system governing system safety with two feedback loops in the case below. All dynamics arise from the interaction of just two types of feedback loops, positive (or self-reinforcing, labeled R or +) and negative (or self-correcting, labeled B or –) loops (Figure 6-1). Positive loops tend to reinforce or amplify whatever is happening in the system; negative loops counteract and oppose change. The positive loop on the left indicates that technological changes result in an increase in system performance in various aspects, which in turn drives more changes and technological development. This positive feedback should generate momentums that keep performance improving. The second feedback loop on the right is a negative loop. Clearly performance improvement can not continue forever, because as performance increase, system capacity is brought to its safety limits. This exerts a negative feedback on the pursuit of performance improvement. Both feedback loops act simultaneously, but at different times they may have different strengths. Thus one would expect increasing performance in the initial years, and then increasing safety concerns in the later years.

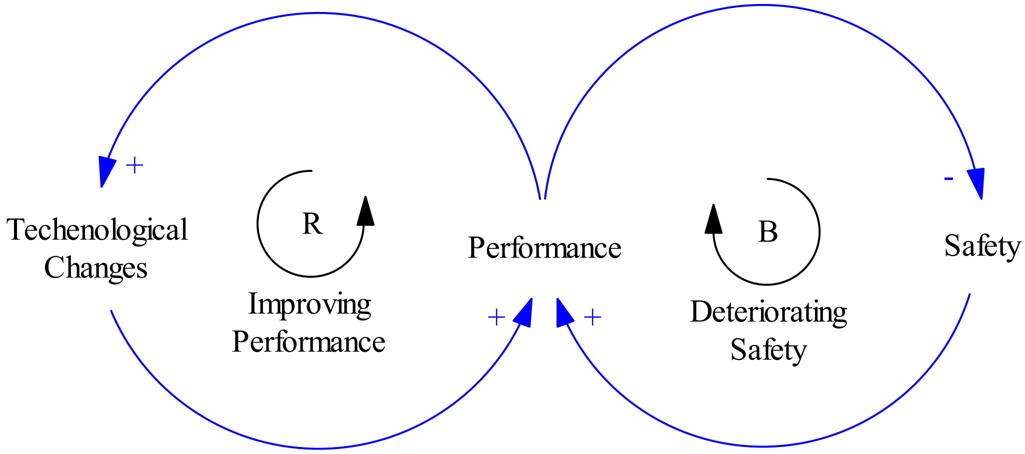

Figure 6-1. An Example of System Dynamics Archetype

6-1-2. Stocks[5] & Flows

Stocks and flows structure provides a useful tool for us to understand system dynamics. The difference between stocks and flows is as simply stated as Kirkwood (1998 p.17), for instance, does that "[a] stock is an accumulation of something, and a flow is the movement or [change] of the 'something' from one stock to another." In our later discussion regarding human body structure, we will find the TCM concept of *zang fu* and the notion of vital substances bear relationships very much resemble to that of the stocks and flows. First, we will set forth a basic understanding of stocks and flows, and then discuss the forms of data necessary to develop our understanding of a dynamic system.

Causal loop diagrams are useful in many situations. They are well suited to present interdependencies and feedback processes. They are used effectively at the start of a modeling project to capture mental models—both those of a client group and the modeler.

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[5] The word 'stock' here means a supply or the amount available of a certain resource in a system rather than the share in a company that is commonly used in finance, e.g., the stock market, or as a general term of farm animals.

They are also used to communicate the results of a completed modeling effort. However, causal loop diagrams suffer from a number of limitations and can easily be misunderstood or abused. And one of the most important limitations of causal diagrams is their inability to capture the stock and flow structure of systems. Stocks and flows, along with feedback, are the two central concepts of dynamic systems theory.

Stocks are accumulations. They characterize the state of the system and generate the information on which decisions and actions are based. Stocks give systems inertia and provide them with memory. Stocks create delays by accumulating the difference between the inflow to a process and its outflow. By decoupling rates of flow, stocks are the source of disequilibrium dynamics in systems.

Stocks and flows are familiar to all of us. The warehouse inventory of a manufacturing firm, the number of people employed by a business and the balance in a checking account are all examples of stocks. Stocks are altered by inflows and outflows. A firm's inventory is increased by the flow of production and decreased by the flow of shipments (and possibly other outflows due to spoilage or shrinkage). The workforce increases via the hiring rate and decreases via the rate of quits, layoffs, and retirements. Your bank balance increases with deposits and decreases as you spend. Yet despite everyday experience of stocks and flows, all too often people fail to distinguish clearly between them. Is the US federal deficit a stock or a flow? Many people, including politicians responsible for fiscal policy, are unclear. Failure to understand the difference between stocks and flows often leads to underestimation of time delays, a short-term focus, and policy resistance.

To clarify stocks and flows, system dynamics uses a particular diagramming notation (Figure 6-2 & 6-3). Stocks are represented by rectangles (suggesting a container holding the contents of the stock). *Inflows* are represented by a pipe (arrow) pointing into (adding to) the stock. *Outflows* are represented by pipes pointing out of (subtracting from) the stock. *Valves* control the flows. *Clouds* represent the sources and sinks for the flows. *Sources* are stocks from which a flow originating outside the boundary of the model arises; *sinks* represent the stocks into which flows leaving the model boundary drain. Sources and sinks are assumed to have infinite capacity and can never constrain the flows they support.

The structure of all stock and flow structures is composed of these elements. As the example in the figure shows, a firm's inventory is a stock that accumulates the inflow of production and is reduced by the outflow of shipments. These are the only flows considered in the model: unless explicitly shown, other possible flows into or out of the stock, such as inventory shrinkage or spoilage, are assumed to be zero. The clouds indicate that the stock of raw materials never starves the production rate and the stock of product shipped to customers never grows so high that it blocks the shipment rate.

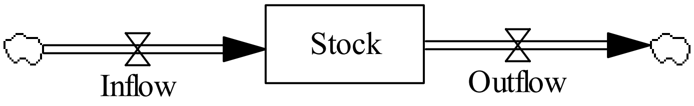

Figure 6-2. General Stock and Flow Structure

Figure 6-3. Example Structure

6-1-3. Types of Data

We turn to a consideration of forms of data in engineered systems. Forrester (1980) identifies three types of data needed to develop the structure and decision rules in models: numerical, written, and mental data. *Numerical data* are the familiar time series and cross-sectional records in various databases. *Written data* include records such as operating procedures, organizational charts, media reports, emails, and any other archival materials. *Mental data* span all the information in people's mental models, including their impressions, stories they tell, their understanding of the system and how decisions are actually made (as opposed to what is written in procedures manuals), how exceptions are handled, etc. Mental data cannot be accessed directly but must be elicited through interview, observation, and other methods.

Numerical data contain only a tiny fraction of the information in the written database, which in turn is miniscule compared to the information available only in people's mental models. It is generally accepted that most of what we know about the world is descriptive, impressionistic, and has never been recorded. However, such information is crucial for understanding and modeling complex systems. Since system dynamics is unusually sensitive to qualitative measures, it is a useful means of recording these unique forms of system knowledge for posterity. Imagine trying to manage a school, factory, or city using only the available numerical data or even the written data. Without the expertise of the participants, the result would be chaos. A complex of mental data structures and system and sub-system models tie together the school, factory and city.

Those constructs for which quantitative metrics and numerical data are available are sometimes termed "hard variables." "Soft variables," in contrast, are those for which numerical metrics and data are not available, including factors such as goals, perceptions, and expectations. Here, the terms we use betray a bias: the term "hard" is intended to show that numerical data are more accurate and real than qualitative data, seen by many as insubstantial and unreliable. In reality, Disraeli's old adage was right: there are "lies, damn lies, and statistics" – both hard and soft data can be biased, distorted, and unreliable. Further, no numerical data are available for many of the variables known to be critical to decision making. These might include customers' perceptions of product quality, the level of trust between a manager and subordinates, a purchasing manager's belief about the reliability of a supplier, employee morale, and investor optimism. These opinions – qualitative, system-based, and quintessentially human – in fact comprise the value that humans bring to these systems. It is through the operation of human systems that the most valuable measures of a system are obtained.

Thus, summary measures like pulse-taking in TCM provides an ideal example about the abundant information we may get from non-quantified data as opposed to the only measurable data, heart beat rate, which is used in Western medicine. (Tang 2004 p.177-179) Composite physiological measures like pulse, temperature and subjective mood are important measures of how the homeostatic systems in a human body are attempting to regain their balance. Similar summary measures are important in engineered system health as well.

6-2. Modeling System Behavior Change

Early in the development of System Dynamics, Forrester (1998 p.5) discovers several things about system behaviors and suggests people learn from modeling and simulations:

- Most difficulties arise from internal causes, although people usually blame troubles on outside forces.
- Actions that people take, usually in the belief that actions are a solution to difficulties, are often the cause of the problems being experienced,
- The very nature of the dynamic feedback structure of a social system tends to mislead people into taking ineffective and even counterproductive action,
- People have enough information about a system to permit successful modeling.

System dynamics focuses on *endogenous* explanations for phenomena that capture the dynamics of a system through the interaction of the variables and agents represented in the model. System theorists state that non-endogenous explanations, since they deal with *exogenous* factors over which the system has no control, are “no explanation at all; they simply beg the question, what caused the exogenous variables to change as they did?” (Sterman 2000 p.95-96) In the sample System Dynamics model we provide in Figure 6-4, the variable “Customer Satisfaction” can be considered as an exogenous input over which our system has little control. As Sterman (2000 p.95-96) continues, “The focus in system dynamics on endogenous explanations does not mean one should never include any exogenous variables in any models. But the number of exogenous inputs should be small, and each candidate for an exogenous input must be carefully scrutinized to consider whether there are in fact any important feedbacks from the endogenous elements to the candidate. If so, the boundary of the model must be expanded and the variable must be modeled endogenously.”

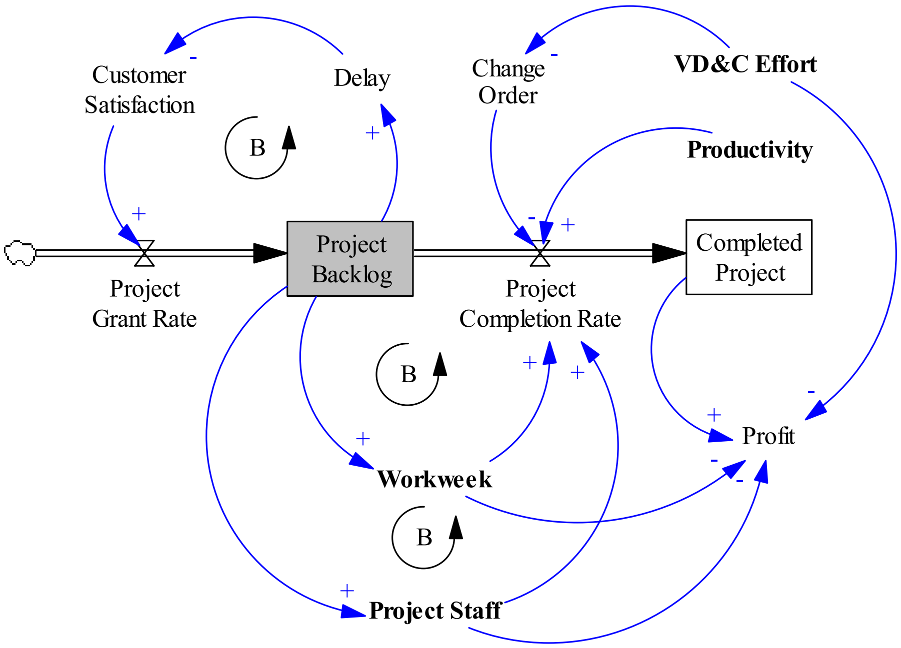

Figure 6-4. An Example of System Dynamics Model for Project Management

6-2-1. System Dynamics Modeling

In one of his early papers, Jay Forrester (Sterman 2000 p.84) draws an analogy between a flight simulator and a system dynamics model to explain the iterative, cooperative nature of a system with its environment and its human managers. For Forrester, the virtual world of modeling is embedded in the larger cycle of learning and action taking place in the real world. As shown in Figure 6-5, "simulation models (the virtual world) are informed by our mental models and by information gathered from the real world. Strategies, structures, and decision rules used in the real world can be presented and tested in the virtual world of the model. The experiments and tests conducted on the model feed back to alter our mental models and lead to the design of new strategies, new structures, and new decision rules. These new policies are then implemented in the real world, and feedback about their effects leads to new insights and further improvements in both our simulation and mental models." (Sterman 2000 p.88) Modeling is not a linear sequence of steps; it is a feedback process and inherently creative. Although there is no cookbook recipe for successful modeling, Sterman (2000 p.88) suggests a five-step iterative process that all successful modelers follow: (1) articulating the problem to be addressed, (2) formulating a dynamic hypothesis or theory about the causes of the problem, (3) formulating a simulation model to test the dynamic hypothesis, (4) testing the model until you are satisfied it is suitable for your purpose, and (5) designing and evaluating policies for improvement. The initial purpose dictates the boundary and scope of the modeling effort, but what is learned from the process of modeling may feed back to alter our basic understanding of the problem and the purpose of our effort. Results of any step can yield insights that lead to revisions in any other step.

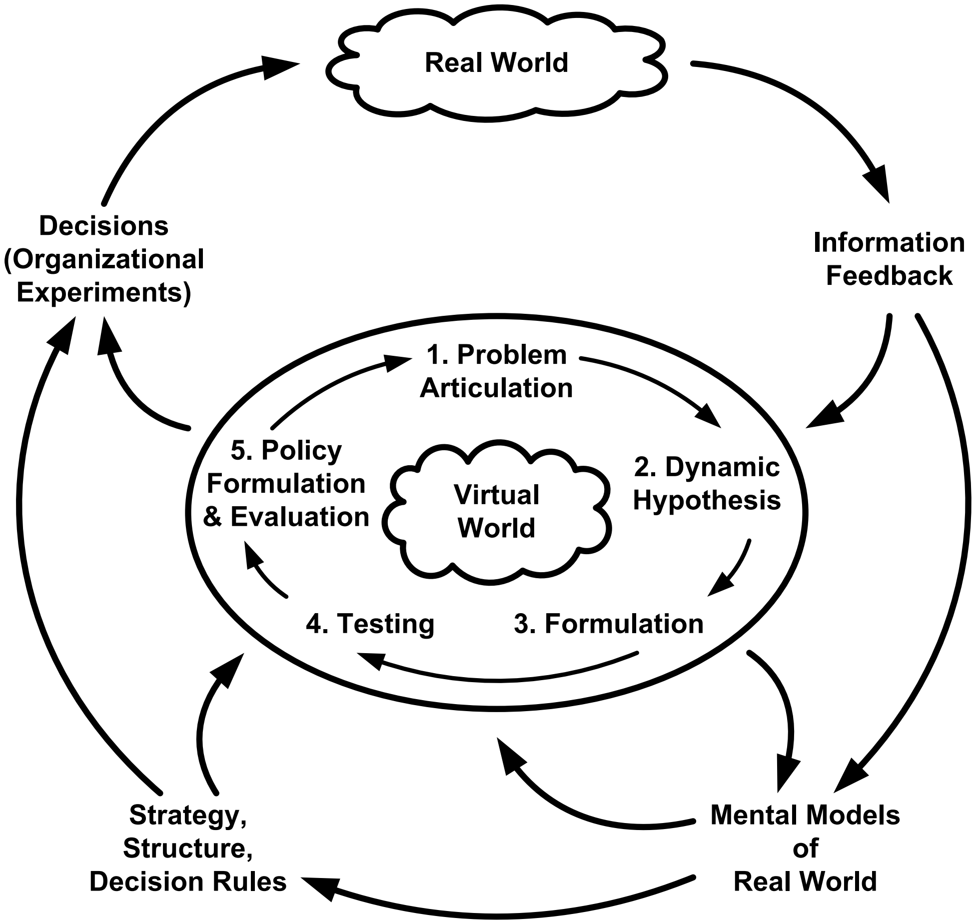

Figure 6-5. Modeling and Learning Process
Adapted from (Sterman 2000)

We propose that the virtual modeling should be used to assess risk in a forward-looking way. By obtaining an idea of system behavior through modeling, it is possible to obtain the most important quantity, time, that allows preventing risks. The status quo approach is primarily retrospective, investigating existing failures and then tracing backwards how they happened, then attempting with greater or lesser success to apply that to the next unforeseeable event. However, on our account, we believe that it is more useful to understand the current state of the system's health and adjust the system while it is in operation, preventing it from going into a deteriorative cycle and incurring a failure to begin with.

System Dynamics modeling can be used to simulate system behavior, habits, laws, policies, external forces, etc. However, risk management cannot be confined within the boundaries of the system, because in addition to balance of intrinsic and extrinsic forces within the system, internal and external forces outside the system's control also need to reach a balance with the environment.

We have learned that system behavior is an emergent phenomenon of the constituent parts of the system, and classified the manners in which the environment interacts with the system. What this means is that the system behavior model is actually composed of the behavior of interacting forces in the system and the results reflect the consequence of those interacting forces; whether or not the system achieves goals is an emergent property of the set of those interacting forces

The overall behavior of the system that adapts it to its environment may be termed its *adaptive behavior*, which is constituted of a record of system behavior data over time. With proper data analysis, a system can learn from its past experience, and change its behavior accordingly. System behavior modeling can be a useful way to record the dominant logic of a system at a given moment while still placing it in the context of an objective reality. Thus, System Dynamics can help policy-makers think about complex problems and avoid emotional bias in decision-makers, as well as the unhelpful consciousness created by the bias involved.

6-2-2. The Use of Models

Models are best used to judge and adjust current system conditions, and as a tool for recording system development. Rather than attempting to use an anticipatory model to directly develop preventive measures, we argue that systems should avoid the deterioration caused by unhealthy patterns persisting in their environments. That is to say, on our account, prevention is about adapting a system to its "current" environment, not attempting to keep it as closely as possible to some ideal desired state. Thus, the modeling step in our framework is intended to help record known behaviors of a system, provide us a way to examine the system holistically and from different perspectives, and expand the boundaries of our mental models for things that are unknown to us. In the current concept of model-based decision making, models are used as a tool to anticipate future scenarios and help to make decisions based on utility theory. We argue that the cumulative effects of persistent patterns in the system should be modeled as well. There are three reasons for our view of models.

1. Sophisticated nonlinear models are claimed to be able to foretell the future better, such as genetic algorithms, agent-based modeling, and neural networks. However, most of them are restricted to certain assumptions—System Dynamics for example assumes that there are continuous and deterministic flows in the system. (Kirkwood 1998 p.22) Moreover, all models are only simplified representations of the reality, be they linear or nonlinear. Essentially, "all models are wrong." (Sterman 2000 p.846) Likeness to truth is not good enough to be a truth. (Bernstein 1996 p.334) A model that is exactly the same as the real world will be as complex as the real world to be useful for us to gain insight from it. (Sterman 2000 p.34-37) Excessive reliance on and trust in computer models leads us to CAD (computer-aided disaster).
2. Even though a model may be real, what feeds into the model are merely past data. It is not possible for past data to tell us the future and we do not have access to future data either. Since all things are interrelated in the world, "past data from real life constitute a sequence of events rather than a set of independent observations, which is what the laws of probability demand." (Bernstein 1996 p.335) Eventually, history provides us only one sample of reality. Thus, we argue that past data are best used to construct precisely the present which is accumulated from those past data – but not to construct a fallacious construct of the future. The future is constantly changing and thus unpredictable, and no one can assure that current patterns of a system will persist over time to the future.

3. As we argued in Chapter 4, complexity and accuracy are mutually exclusive. To expand the butterfly effect metaphor, in a butterfly effect, it is easier to catch the butterfly than to quantify the effect, as Bernstein (Bernstein 1996 p.333) puts it. It may take an impractically long time for human beings to develop the methodology and computational power to quantify this complex world accurately. Thus, a more logically parsimonious and powerful form of explanation such as ours become necessary.

A similar account of the use of modeling has been set forth by Marais in the concept of Continuous Participative Risk Management (CPRM), which deserves mention in this context. CPRM arises from a detailed consideration of engineered particulars; as Marais (2005 p.157) cites it:

> *The main benefit of estimating risk lies in the achievement of a detailed understanding of the engineered system. --Royal Society Report, 1992*

For Marais (2005 p.157-158), risk management is composed of two components:

> *…on the one hand, of proving that an initial system design satisfies safety requirements, and, on the other hand, of best allocating limited resources to maintain risk at an acceptable level throughout the system's lifecycle. Managing risk effectively over the entire lifecycle requires first that risks be properly identified and assessed, and second that impacts of decisions in the present on the future behavior of the system be considered and understood.*

Marais (2005 p.157-158) further explains that "it is 'continuous' because the process of risk identification, assessment, and mitigation should continue throughout the system lifecycle and not be a one-time effort; and it is 'participative' because inputs from members at all levels of the organization are needed for an appropriate and extensive risk management effort." Marais recognizes that risk is not constant, new risks may arise, and old risks may change and consequently argues that continuous updating is necessary to ensure that risk analysis is accurate over the lifecycle. However, this position still partakes in the common mentality that risk (the risk of chance) must be managed, is identifiable, and as well is manageable. For a more parsimonious account such as ours, however, risk (the risk of change) is inevitable while something changes. Therefore, what has to be managed is not the risk but the change; what matters is not the anticipated accident that may or may not happen but the actual system health degradation that emerges over time.

6-3. The Risk of Change Analysis

6-3-1. Quantifying the System Inertia

In Section 5-1, we tried to define system mass of a system as a whole for the concept of momentum of change, but found difficulties relative to motion. Here, we can resolve these difficulties by defining system mass in terms of *system inertia*. In beginning to define system inertia, it seems plausible to interpret it as the assets of a system. With the same rate of change, it seems the greater the assets a system has, the greater risk or opportunity it will create. But as we have seen with dominant logics, as well as with organizational changes, the presence of a large set of current assets – reserve power to motivate the system forward, in other words – actually means that the influence of change will be smaller.

Consequence in risk of chance is the loss that a specific accident can create. But without a well-defined accident, it is not possible to quantify the consequence, let alone accidents that never happened before or we do not know exist. The constantly changing business conditions around a corporation, such as what BP has encountered after the Deepwater Horizon failure in 2010, are perfect example; what may have been profitable or unprofitable overall behavior in one set of circumstances may be the exact opposite in a new set of business circumstances. Aggressive leveraging of corporate assets is another example; what seemed like perfectly rational and well-documented dominant logic at a certain point in history, say high amounts of leveraged real-estate mortgaged based assets in 2005, is now recognized to be impractically complex in the set of economic circumstances pertaining at time of writing (2010). The mass of documented systems that fed into the mortgage-backed securities crisis do not aid in unraveling the economic mess they created; in fact, the sheer fact of their mass makes it *more* difficult to unravel.

To understand the operation of system dynamics in modeling system behavior, we argue that each behavior is a force driving system change, and quantifiable as a force. Systems Dynamics is for modeling general systems; the case study presented with this paper will use it to model a construction project. In order to extend System Dynamics to the risk representations of such complex engineered systems with respect to change and time, we propose the notion of *system inertia* (***m**c*), or the total amount of inertia of change possessed by a system. As system inertia increases, the consequence of change, whether good or bad, must also increase. This is as simple an axiom of system dynamics as the Newtonian axioms are of physical reality. Let us define the assets of the system as follows:

In common usage, the term "inertia" refers to an object's "amount of resistance to change in velocity" (which is quantified by its mass), or sometimes to its acceleration or momentum, depending on the context (e.g. "this object has a lot of inertia"). Physics and mathematics appear to be less inclined to use the original concept of inertia as "a tendency to maintain momentum" and instead favor the mathematically useful definition of inertia as the measure of a body's resistance to changes in momentum or simply a body's inertial mass. We can systematize system inertia through an understanding of system *mass*.

For a definition of mass, we will briefly survey physics. The methods by which physics deals with mass may be instructive in understanding the types of complex operations that become possible when we begin to speak of system change in terms of system inertia. Modern physics recognizes several different types of mass: *inertial mass* is the mass of an object measured by its resistance to acceleration. Inertial mass is found by applying a known force to an unknown mass, measuring the acceleration, and applying Newton's Second Law, $\boldsymbol{m} = \boldsymbol{F} / \boldsymbol{a}$. The inertial mass of an object determines its acceleration in the presence of an applied force. According to Isaac Newton's second law of motion, if a body of mass $\boldsymbol{m}$ is subjected to a force $\boldsymbol{F}$, its acceleration $\boldsymbol{a}$ is given by $\boldsymbol{F} / \boldsymbol{m}$.

Inertial mass is a measure of an object's resistance to changing its state of motion when a force is applied. It is determined by applying a force to an object and measuring the acceleration that results from that force. An object with small inertial mass will accelerate more than an object with large inertial mass when acted on by the same force. We might say that the body of greater mass has greater inertial mass.

Mass may also be determined by measuring a *mass deficit*, the residue of an accumulative process which should be familiar to theoreticians of stocks and flows. The amount of matter in certain types of samples can be exactly determined through electrodeposition or other precise processes. The mass of an exact sample is determined in part by the number and type of atoms or molecules it contains, and in part by the energy involved in binding it together (which contributes a negative "missing mass," or mass deficit).

Gravitational mass is measured by comparing the force of gravity of an unknown mass to the force of gravity of a known mass. *Active gravitational mass* is a measure of the strength of an object's gravitational flux, which is equal to the surface integral of gravitational field over an enclosing surface. Gravitational field can be measured by allowing a small "test object" to freely fall and measuring its free-fall acceleration. For example, an object in free-fall near the Moon will experience less of a gravitational field, and hence accelerate slower than the same object would if it were in free-fall near the earth. The gravitational field near the Moon is weaker because the Moon has less active gravitational mass.

Passive gravitational mass is a measure of the strength of an object's interaction with a gravitational field. Passive gravitational mass is determined by dividing an object's weight by its free-fall acceleration. Two objects within the same gravitational field will experience the same acceleration; however, the object with a smaller passive gravitational mass will experience a smaller force (less weight) than the object with a larger passive gravitational mass.

Of these types, inertial mass is the best definition for systems – systems' resistance to change or acceleration, since, as we have discussed, change can be seen as what systems are made of. We will use stock and flow analysis to define the terms of that change in useful mathematical terms. Although gravitational and deficit forms of mass demonstrate the types of operations that can be conducted with a concept of mass, such extension is beyond the scope of this discussion at this stage of research.

6-3-2. Quantifying the Risk of Change

As discussed in Part I, risk represents the potential in the future that a system will have an uncertain consequence, whether good or bad. The conventional definition of risk utilizes probability to quantify that uncertain potential of gain or loss. More precisely, risk is the expected value of the uncertain events that have potential consequences to the system. To distinguish such risk from what we have proposed, we call this kind of risk—*the risk of chance*. However, in the constantly changing world in which we live, one can well imagine that the probabilities of the uncertain events as well as their potential consequences are also changing over time. It is not possible to predict every future event that may occur in the system. The risk of chance is clearly limited in providing necessary protections against unpredictable fluctuations in such dynamic systems. For that reason, we proposed a new concept of risk – *the risk of change* – to represent this changing potential of the system. As defined in Chapter 5, it is measured by its momentum of change as shown in Equation (2).

$\boldsymbol{p}$ (Momentum of Change) = $\boldsymbol{m_c}$ (Consequence) × $\boldsymbol{v}$ (Speed of Change) ………….(2)

where

- The momentum (p) is a vector quantity and thus possesses a direction as well as a magnitude. When the direction of a change is helping the system moving towards its goal state, it is an opportunity; when the direction of that change moves the system away from its desired goal state, on the contrary we may term it a risk to the system.
- The consequence (mc) here represents the potential consequence(s) due to system changes.
- v is the speed of change as a scalar, representing the rate at which the system's monitoring variables are changing.

This should be intuitive: the larger the consequence and/or the faster the changes are, the greater the momentum of change will be, i.e., the greater the potential of the system becoming better or worse will be. A moving truck is a useful analogy for this concept: on the one hand, a bigger and faster truck has more potential to cause severe damage; on the other hand, it also has more potential to carry more goods or passengers to the destination faster. To measure $\boldsymbol{m_c}$, the consequence(s), is straightforward when the system in question is a physical object, such as the truck, since $\boldsymbol{m_c}$ equals to the mass of the object. The question is how do we quantify "mass" when the target system is complex engineered systems?

In such a case, instead of system mass, the consequence ($\boldsymbol{m_c}$) is measured by *system inertia*, which by definition is the resistance of system against change. In a sense, the increased efforts (the resistance to change) we make to support or stop the potential of change also represent a larger consequence, no matter bad or good, that might follow; hence, it discloses a higher *risk of change*. In this way, we do not have to identify the exact events or accidents that are going to happen in order to estimate the potential consequence.

Consider a "simplified" complex engineered system with a hydraulic metaphor—the flow of water into and out of the reservoir as shown in Figure 6-6. In such systems, the water levels of the reservoirs represent the accumulation of "substances." For example, a firm's inventory is a reservoir that accumulates the inflow of production and is reduced by the outflow of shipments. In a sense, reservoirs characterize the functional state of the system and provide decision makers with the information needed to act. Moreover, they accumulate past events and provide systems with inertia and memory. This metaphor was originated by Forrester in 1961 to explain the stock and flow diagramming conventions in System Dynamics as shown in Figure 6-7. (Sterman 2000 p.193-194) Indeed, it is helpful to think of stocks as bathtubs of water. The quantity of water in your bathtub at any time is the accumulation of the water flowing in through the tap less the water flowing out through the drain (assume no splashing or evaporation). In exactly the same way, the quantity of substance in any stock is the accumulation of the flows of substance in less the flows of substance out.

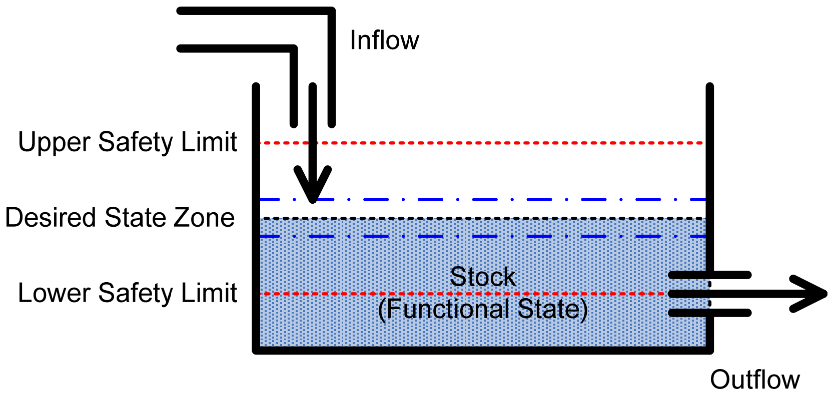

Figure 6-6. Hydraulic Metaphor of A Simplified Complex Engineered System

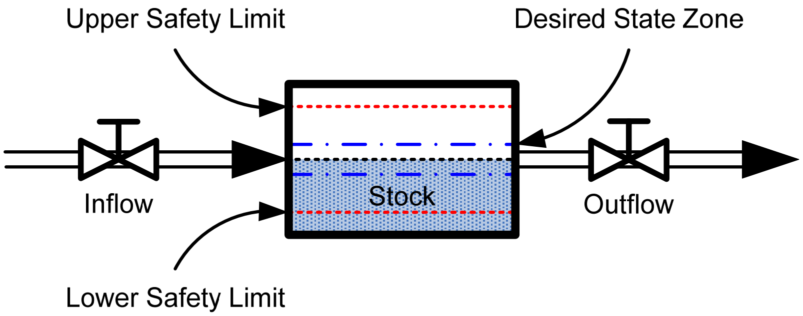

Figure 6-7. Stock & Flow Diagramming Conventions

The system functions best when its functional state is in the desired state zone. When it exceeds safety limits, the system is imbalanced. In complex engineered systems where these stocks vary, information about the size of the stock will feed back in various ways to influence the inflows and outflows. Often, but not always, these feedbacks will operate to bring the stock into balance. (Sterman 2000 p.197) One important reason for such phenomena is that the operators and decision makers are heavily involved in the system operation. Therefore, when the system state is approaching the safety limits, they try to save the system which creates a resistance to change. Intuitively, the further that the system approaches safety limits, the greater the intensity of the efforts to save it become. Thus, the difference between the safety limit and the current system state is inversely proportionate to the intensity of the resistance – what we call *system inertia*. Thus, we can then use the product of the multiplicative inverse of ΔS times a constant k, *system inertia*, to estimate the potential consequence (mc) of system change. This allows us to derive the risk of change through Equation (6).

$$\boldsymbol{p}\text{ (Risk of Change)} = \boldsymbol{m}_c\text{ (Inertia)} \times \boldsymbol{v}\text{ (Speed of Change)} = (k\,/\,\Delta S) * V_{net} \;\ldots\ldots\ldots\; (6)$$

where

- $mc = (k/\Delta S)$: System inertia. This is measured by the resistance of system against the acceleration of change. The resistance can be derived by the product of the multiplicative inverse of ΔS times the inertia constant k.
- k : Inertia constant. Different stocks have different importance to system operation. The inertia constant indicates the effort that the system is willing to pay for a difference between the current state and its corresponding safety limit. Money is a common quantification of the effort a system is willing to devote.
- $\Delta S = |\,S_{current} - S_{limit}|$: Safety buffer. This is the difference between the current state and the end state of the stock.
- v : ΔS over time. This has been defined in-depth in Chapter 5.

These variables allow us to derive another set of variables:

- $V_{net} = |V_{inflow} - V_{outflow}|$: Net flow rate. This is the speed of change for the particular stock.
- Scurrent : Current functional state.
- Slimit : System limitation. It denotes one of the three kinds of system limitation including Sdesired (desired state zone), Supper limit (upper safety limit), Slower limit (lower safety limit)

- Vinflow : Inflow rate.
- Voutflow : Outflow rate.
- T =ΔS / Vnet : Reaction time. It is an estimated time for the occurrence of functional disorders if the system continues the current pattern of operation.

Table 6-1. Risk of Change & System Health Criteria

$\Delta S = \lvert S_{current} - S_{limit} \rvert$	$V_{net} = \lvert V_{inflow} - V_{outflow} \rvert$	F_{net}	Risk of Change	System Health Condition
$S_{current} \geqq S_{upper\ limit}$	–	–	System Imbalanced	Hyperfunctional Disorder
$S_{desired\ zone} < S_{current} < S_{upper\ limits}$	$V_{inflow} > V_{outflow}$	$F_{net} < 0$	Risk = $(k/\Delta S)V_{net}$	Deteriorating –> Recovery
		$F_{net} > 0$	Risk = $(k/\Delta S)V_{net}$	Deteriorating –> Losing Control
	$V_{inflow} = V_{outflow}$	$F_{net} > 0$	No obvious risk	Deterioration Start
	$V_{inflow} < V_{outflow}$	$F_{net} > 0$	Opportunity = $(k/\Delta S)V_{net}$	Semi-Healthy (Downturn)
		$F_{net} < 0$	Opportunity = $(k/\Delta S)V_{net}$	Semi-Healthy (Upturn)
	$V_{inflow} > V_{outflow}$	–	Resilient	Self-Healing
$S_{current} = S_{desired\ zone}$	$V_{inflow} = V_{outflow}$	–	Highly resilient	Healthy
	$V_{inflow} < V_{outflow}$	–	Resilient	Self-Healing
$S_{lower\ limit} < S_{current} < S_{desired\ zone}$	$V_{inflow} > V_{outflow}$	$F_{net} > 0$	Opportunity = $(k/\Delta S)V_{net}$	Semi-Healthy (Upturn)
		$F_{net} < 0$	Opportunity = $(k/\Delta S)V_{net}$	Semi-Healthy (Downturn)
	$V_{inflow} = V_{outflow}$	$F_{net} < 0$	No obvious risk	Deterioration Start (Point B)
	$V_{inflow} < V_{outflow}$	$F_{net} < 0$	Risk = $(k/\Delta S)V_{net}$	Deteriorating –> Losing Control
		$F_{net} > 0$	Risk = $(k/\Delta S)V_{net}$	Deteriorating –> Recovery
$S_{current} \leqq S_{lower\ limit}$	–	–	System Imbalanced	Hypofunction Failure (Point D)

Table 6-1 shows all possible situations that a simple “stock and flow” system may have and the corresponding risk of change and the system health condition for each situation. The first column indicates the relative position of the current functional state compared to the limitations of the stock. The second column indicates the net rate of flow into and out of the stock. F_{net} denotes the net force of change which we will explain shortly in the next section. The fourth column shows the risk of change respective to each situation. The fifth column describes the system health condition for each situation. The healthy condition is when functional state is at the desired state zone and the net speed of change is at zero. Usually, a truly healthy condition is rare in a dynamic system. The first and the last lines indicate functional failures of the stock. Hyperfunctional failure means the excessive functioning of the system while hypofunctional failure meaning the opposite.

In case of a larger system, the system may consist with several functional subsystems, thus, with several “stocks and flows.” Each subsystem can be diagnosed with its (partial) health condition. But the health condition of the whole system has to be judged according to the interrelationships between subsystems. For example, one hyperfunctional failure of a subsystem may affect other subsystems and break the dynamic balance of the whole system. In other cases, a mix of several hyper- and hypo-functional failures may be neutralized and turn out to be good for the whole system. These pathological changes are further discussed in Step 5 of our proposed framework, which is discussed in depth in Chapter 10.

An interesting corollary of this chart is that resistance to change becomes cast in terms of system inertia. It may be argued that an inconsistent situation is presented by a system that is seriously in danger, yet is managed by people who refuse to change. Is the speed of change fast or slow in this situation? The danger present in the system is a force on the system. Resistance to change is created when the amount of effort that people are willing to devote to rescue the system is insufficient to pull the system out of danger – a form of system inertia.

Through the system dynamics model’s implications about risk analysis in engineered systems, system forces and their interaction can be drawn out in terms of a few indicators that define system state as an emergent property. We can then calculate what the system’s status indicators are, and close the gap between the current system state and desired system objectives, obtaining from this the system’s rate of change. From this value, the risk value can be obtained immediately. And it is obvious from this paradigm of risk that the rate of system state change maybe more important than the system state itself.

6-3-3. Defining the System Resilience

At first, the term “resilience” may seem straightforward. Common “folk” definitions from Merriam-Webster dictionary accept two types:

1. the capability of a strained body to recover its size and shape after deformation caused especially by compressive stress (this definition refers to the common concept of resilience – energy absorbed by material during elastic deformation – in mechanics as shown in Figure 6-8)

2. an ability to recover from or adjust easily to misfortune or change

In de Bruijne, Boin and van Eeten's comprehensive survey of resilience literature, they identify three forms of resilience: emotional, engineering, and ecological resilience. (de Bruijne et al. 2008 p.15) *Emotional resilience* is the ability to recover from adverse life events and display adaptive responses to environmental hardships; *engineering resilience*, as above, concerns a single system and it's the ability to recover from an extreme state. Of primary interest to us is the concept of *ecological resilience*, describing the amount of energy a system can absorb without shifting into another state. As with ecosystems, systems which adapt to change do not have a normatively valued original state, properly speaking. The proper state for a dynamic system is not a fixed state, but rather whatever is most adaptive to its given situation. The rate at which the new system state is reached is of importance in determining the risk of change. Remaining in control during the system's change is the most important determinant of the system's ability to survive.

In addition to the concept of ecological resilience, the threshold conditions of engineering resilience should be of interest to us. In physics and engineering, resilience refers to "the ability of a material to return to its former shape after a deformation" and is considered more or less synonymous to adaptability or flexibility." (de Bruijne et al. 2008 p.1) There exists a modulus of resilience which is the work done on a unit volume of material as the force is gradually increased from the origin O to the proportional limit. (Figure 6-8) This may be calculated as the area under the stress-strain curve from the origin O to up to the elastic limit E (the shaded area in the figure). The resilience of the material is its ability to absorb energy without creating a permanent distortion. Thus, from the origin O to the point called proportional limit, the stress-strain curve is a straight line; up until a certain point, there is a directly proportional limit between stress exerted on a system and the strain experienced by the system. The elastic limit is the limit beyond which the material will no longer go back to its original shape when the load is removed, or it is the maximum stress that may be developed such that there is no permanent or residual deformation when the load is entirely removed. Past the elastic limit, the relationship between stress and strain becomes unfixed. Similar to this "breaking point" in mechanical resilience, there exists a system state – catastrophe – where the risk management and preventive measures will no longer be capable of containing the powerful effect exerted by forces.

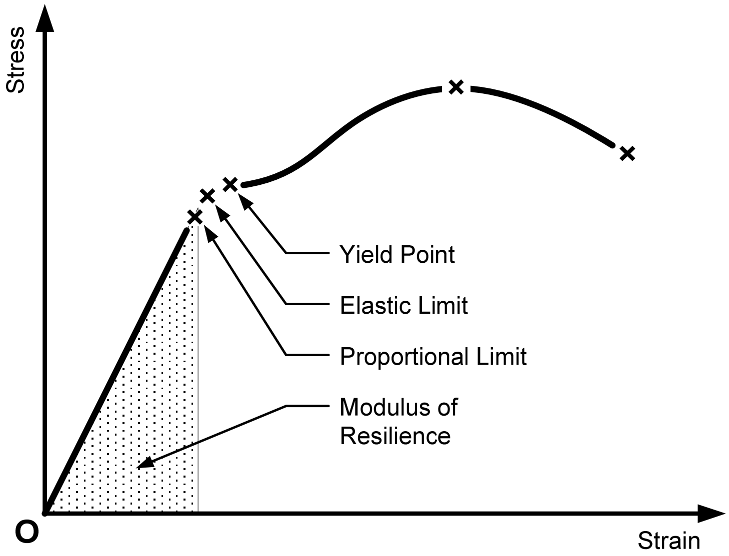

Figure 6-8. Modulus of Resilience

In addition to the types of resilience that de Bruijne et al. identify, there are also significant other forms, for instance organizational resilience; in management science where resilience is displayed in *high-reliability organizations*. For our purposes, we will use a concept of resilience rooted in the risk of change analysis we set forth. For complex engineered systems, we can give resilience a qualitative notion as follows:

System resilience is the amount of ***energy*** *the system can absorb before experiencing a catastrophic amount of stress.*

The *energy* here can be thought of as the "work" done by the interactiing forces that drive system changes. The causes of that stress, *pathogenic evil* (as we will discuss in Chapter 9), is a force which may produce systemic harm or wrong; the source of such system resilience, *anti-pathogenic qi* (also in Chapter 9), emerges from a homeostatic system operation.

Chapter 7. Implications for a New Approach to Risk Analysis

7-1. New Perspective for Risk Assessment

7-1-1. Navigating to Success

There are many cases where it is useful to see forces in the form of *force fields*. The geo-strategic notion political force in "spheres of influence" is a perfect example. Each government has its own political force field in accordance with its political power. The force field will certainly be more powerful within the jurisdiction and the influence is subject to decrease beyond that. In a similar manner, safety and accident-avoidance measures brought on by risk managers may be thought of as emergent (not resultant) *forces* exerting a force field. It is through the interactions and daily flow of changes that comprises normal work that accidents are driven in complex systems. (Hollnagel et al. 2006 p.77) Consider a forest system that thrives (is adapting/navigating) under the influence of both sunshine and rainfall (two force fields), too much sunshine may result in dry air and increase the possibility of a wildfire, while too much rainfall may flood the area. The forest has to maintain a dynamic balance in the constant interaction between sunshine and rainfall in order to flourish.

This normal adaption may sometimes develop a dominant logic, as we have discussed, which must be understood and at times altered for the sake of the system. This dominant logic creates what Dekker terms a "drift into failure." Most complex engineered systems are human monitored, to some extent; no system manager "chooses" to fail. Rather, "[it] is a metaphor for the slow, incremental movement of system operations toward (and eventually across) the boundaries of their safety envelope. Pressures of scarcity and competition typically fuel such movement and uncertain technology and incomplete knowledge about where the boundaries actually are, result in people not stopping the movement or even seeing it… Also, the departures from previous practice are seldom quick or large or shocking (and thus difficult to detect): rather, there is a slow succession of tiny incremental deviations from what previously was the 'norm'. Each departure in itself is hardly noteworthy. In fact, such 'departures' are part and parcel of normal adaptive system behavior, as organizations (and their regulators) continually realign themselves and their operations with current interpretations of the balance between profitability and risk (and have to do so in environments of resource scarcity and competition). It may be a good metaphor for how complex systems slowly move towards the edges of breakdown, but it lacks all kinds of underlying dynamic relationships and potentials for operationalization that could make it into a model." (Hollnagel et al. 2006 p.82-83) Such a situation is shown in Figure 7-1, where system state drifts across acceptable boundaries:

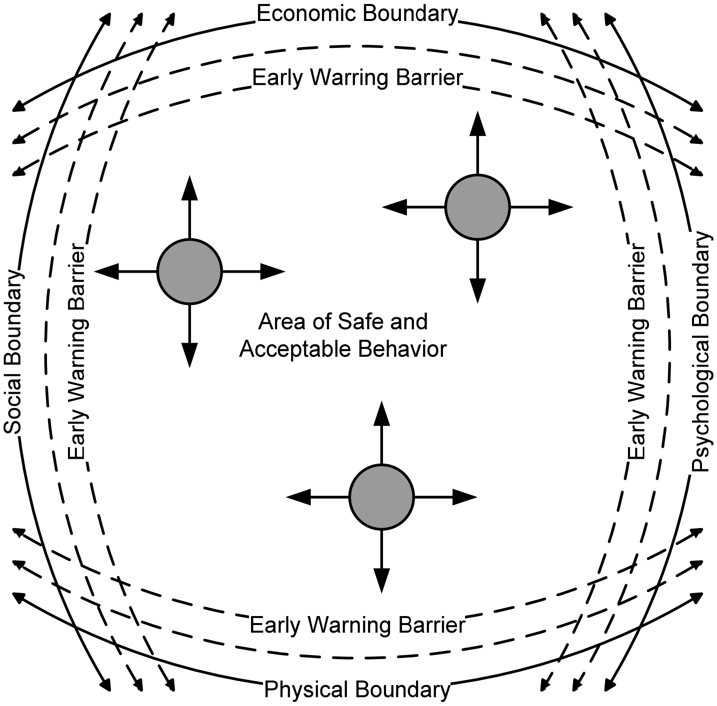

Figure 7-1. System Migrations in Safety Space
(Bea 2005)

To change a drift towards failure, risk management's interventions in a system must be involved in the "normal, day-to-day processes of organizational management and decision-making" where "we can find the seeds of organizational failure and success, and a role of resilience engineering could be to find leverage for making further progress on safety by better understanding and influencing these processes…" (Hollnagel et al. 2006 p.84) Implementing early warning measures, shown as dotted boundaries that identify signs of drift, prevent this type of failure.

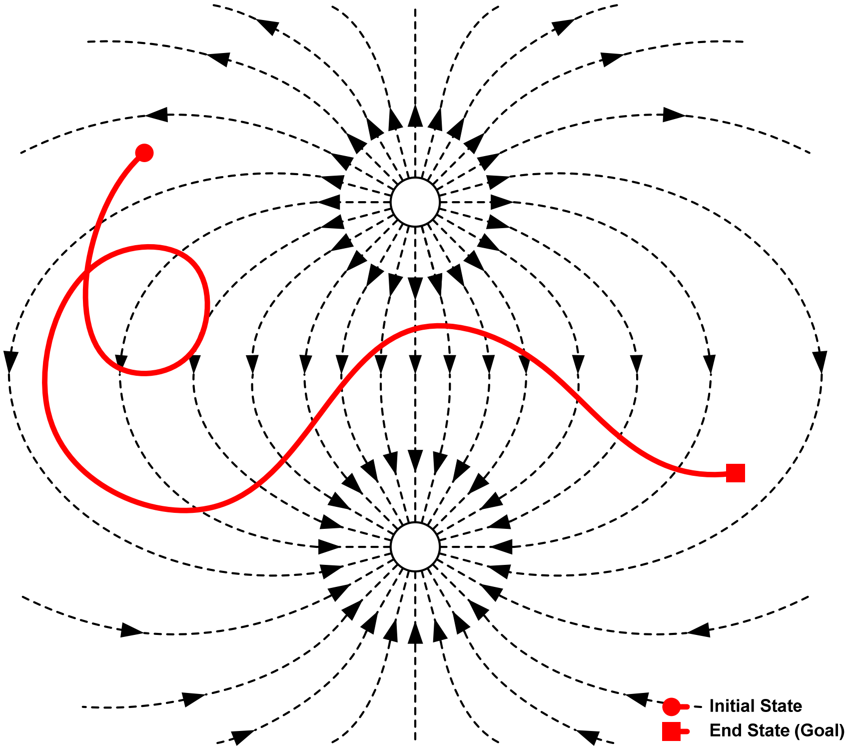

Figure 7-2. Illustrative Image for Navigating to Success

We believe, as Dekker (Hollnagel et al. 2006 p.83) also noted, that standard notion of drift in resilience engineering may be intrinsically flawed—it "may be a good metaphor for how complex systems slowly move towards the edges of breakdown, but it lacks all kinds of underlying dynamic relationships and potentials for operationalization that could make it into a model." We propose that a fuller picture of drift should emerge between safety boundaries, defined as all states except those which allow the system to reach its goals. As a system adapt to its environment towards its goals, the state of the system over time can be seen as a trajectory moving through various force fields at work (see Figure 7-2). Thus, defining system safety boundaries without resort to fixed, determinist notions of success or failure is then our next task.

7-1-2. Customized Accidents

The manner and form in which the system is constituted – the system constitution – makes a big difference in how it reacts to a given force field. It is notable that the influence under a certain force field may differ from the constitution of different systems, e.g., under the influence of a magnetic field, plastics and iron would perform very differently. Similarly, different laws or regulations affect companies in different business categories differently. And in health, a wide variety of factors like nutrition, weight, genetics, age-related illness, and metabolic particularities complicate totalized measures like USDA-set recommended daily allowances (RDA) of vitamins and nutrients. (Liang 2006 p.65-66) Let us examine some of the manners in which systems' reactions to forces may differ.

Subjectivity

The strength of subjective measures, as we have discussed, is also a prominent feature of the TCM view of disease. Eliciting subjective measures of a patient's well-being allows us as physicians and risk managers to provide truly customized diagnoses – customized to the extent that they flow into the daily practice of and activities of a person's life, and thus in to the substance of their systems as made of change.

Recall that we set forth a simplified Newtonian model for system causes and effects, complicated in great deal by the butterfly effect and other chaotic, emergent behaviors of even the most determinate systems. Taking special relativity into consideration in our frame of reference, we might be able to define the consequence with respect to different frames of reference, such as different cultural frames of reference or different value systems, so that the risk varies with different perspectives. Obviously, a risk of $1,000 loss means very different things to a rich person and a poor person. As discussed in Part I, there are no absolute objectives in complex systems. Thus, subjectivity needs to be considered.

The perspective-invariant notion of Newtonian mass that we have discussed is the measure of an object's resistance to changes in either the speed or direction of its motion. A relativistic notion of mass is variant with perspective, and includes a contribution from the kinetic energy of the body. This mass grows larger the faster the body moves until a theoretical threshold of c, the speed of light, at which the object becomes almost unfathomably large. Unlike the invariant Newtonian version of mass, a relativistic notion of mass depends heavily on the observer's frame of reference.

This opens up the notion of the relativity of risk. As Kaplan and Garrick (1981 p.2) put it, "…under attempts to pin it down, the notion of absolute risk always ends up being somebody else's perceived risk… This brings us in touch with some fairly deep philosophical matters, which incidentally are reminiscent of those raised in Einstein's theory of the relativity of space and time." Insofar as there is no absolute notion of risk when defined as the risk of chance, accepting a risk-of-change analysis seems the only rational means of manging future change.

Conflicts between Different Values

Risk managers' values are not always those of the systems they manage. Disease, as it is commonly noted in public service announcements of various types, "knows no boundaries." So too with accidents: the forces that create accidents, like diseases, are not shaped by the same forces that shape the human beings they affect. What makes a system fit for operation does not necessarily make it better or less well-suited for coping with accidents and disasters.

Consider disaster response systems as an example. The subjects of disaster response efforts are rarely, if ever, the same people as those who respond to disasters. Thus, disaster responders are always outsiders dealing with outsider factors: bureaucratic inertia, paperwork, cumbersome legal procedures and so on. The system of risk management, in this case, becomes a negative form of pressure on people and actually may increase negative risks. A smart system manager must align the interests of disaster responders with the interests of the subjects of their efforts. As Chesbrough puts it, those who bear risk (researchers) and those who get the credit for those risk-taking ideas (sales) usually are not the same people in the process; thus, this creates a negative tension in the system. (Chesbrough 2009 in last class) To avoid an endless vicious circle of negative factors, policy making should adjust incentive schemes and reward systems to avoid conflict.

7-1-3. System Health Cycle & Health Conditions

The primary challenge confronting risk analysis from the systems health perspective is to understand when a system may loose its dynamic stability and become unstable.

(Hollnagel et al. 2006 p.17) Conventional wisdom has it that developing accidents are usually harder to detect but easier to cure in the early stages, and easier to detect but harder to cure in the later stages. A system can look strong on the outside but already be sick on the inside, showing only inconspicuous warning signs and minor random failures, but indeed situate itself dangerously on the cusp of a precipitous fall. Chesbrough's (2006) depiction of the underlying patterns of technology life cycle[6] in the constantly changing world of technology, as well as Collins' (2009) theory of five stepwise stages of fallen great companies[7] both try to describe the developmental trends of a system. By understanding the variable health conditions of the system, we can substantially increase the chances of detecting functional deterioration early, allowing the system to restore its necessary dynamic balance and prevent the accident from happening.

Figure 7-3 shows an example of such a system health cycle. Here, we identify four critical points within the cycle, with each marking a particular shift in the system's health condition.

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[6] The notion of technology life cycles can be well explained with a simple S curve. The performance of a technology is graphed on the y-axis, while the x-axis shows the time since the technology first appeared. Four distinct stages, namely emerging, growth, maturity and decline, in the technology's evolution may be observed. Chesbrough, H. W. (2006). *Open Business Models : How to Thrive in the New Innovation Landscape*, Harvard Business School Press, Boston, MA. [p.89-92]

[7] The five stages of decline are (1) hubris born of success, (2) undisciplined pursuit of more, (3) denial of risk and peril, (4) grasping for salvation (5) capitulation to irrelevance or death. Collins believes that, by understanding theses stages of decline, leaders can substantially reduce their chances of falling all the way to the bottom. Collins, J. C. (2009). *How the Mighty Fall : And Why Some Companies Never Give In*, Collins Business : distributed by HarperCollins Publishers, New York, NY.

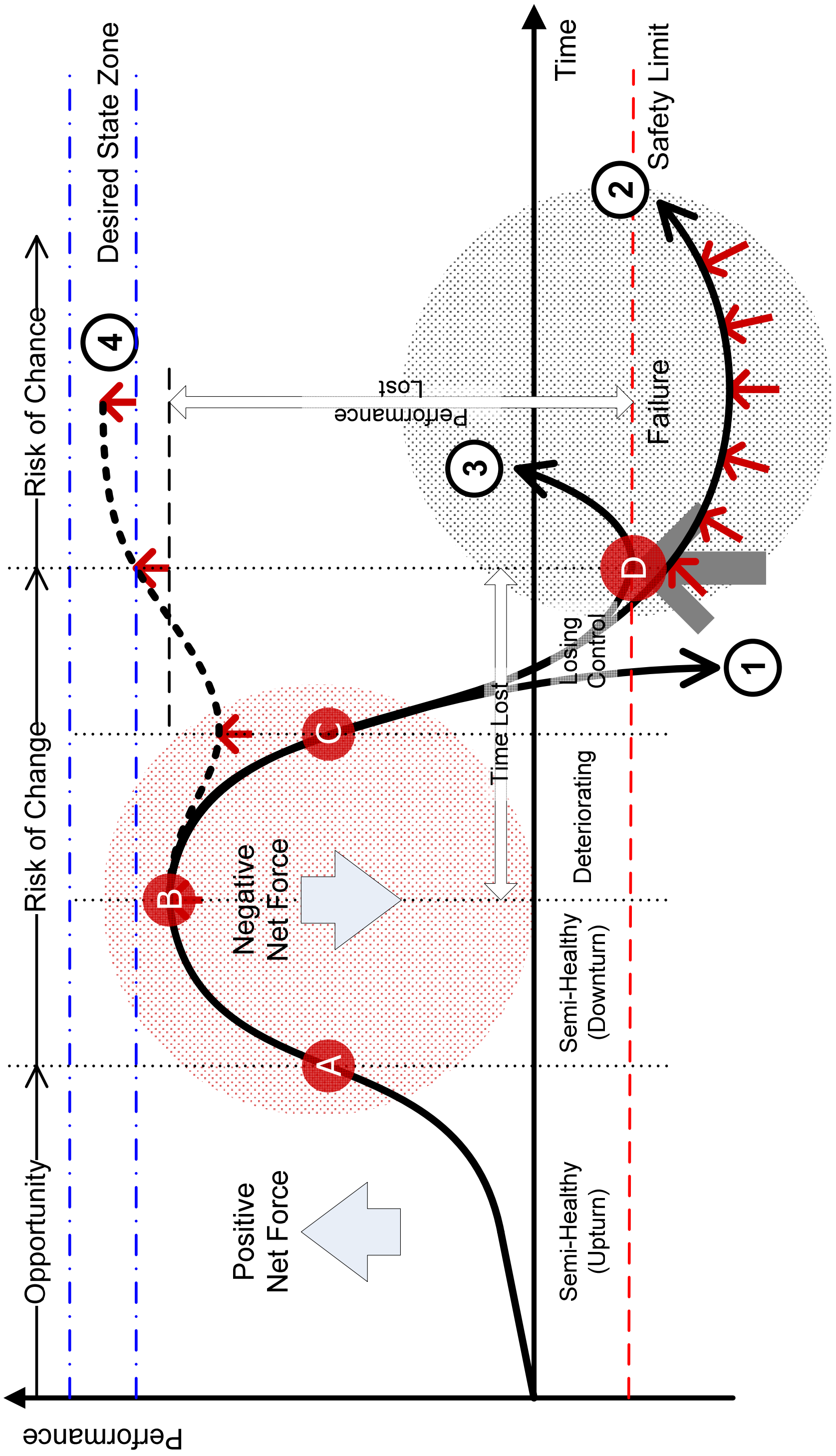

Figure 7-3. System Health Cycle & Health Conditions

- Point A: At Point A, the rate of positive change and its momentum reach their maximum value. This is the beginning of functional degradation. People generally deny believing that the system starts degrading at this stage since the system is growing with a full speed. The condition at Point A (Fnet = 0, acceleration of change = 0) can be an ideal early warning sign.
- Point B: At Point B, both the rate of change and its momentum equal zero. This is the last chance for the system health control to step in and rescue the system without having much physical loss. The force of dominant logic (Chesbrough 2003 p.70), however, makes people hesitate to make any change since the system has been growing (although gradually slowing down) and has its best performance at this point. The condition at Point B (the speed and momentum of change = 0) can be an ideal trigger for reflex actions, at which point the system may instantaneously respond to the situation in order to protect itself.
- Point C: At point C, both the rate of change and its momentum reach their negative maximum value. The system moves away from the desired state zone at a full speed. An interactive risk management approach (Bea 2005) is ideal for this stage (between Point B and D). Point C indicates a point of no return. Any rescuing efforts after this point would cost the system considerable time and resources with limited benefits.
- Point D: Point D is where system became imbalanced and unstable. Accidents or random failures may break out beyond this point to most people's surprise. Crisis management has to step in to minimize the loss at this stage.

There exist four possible scenarios that may occur at the end of the cycle.

- Scenario 1: The system breaks down without an attempt at rescue.
- Scenario 2: The system is rescued with limited resources and recovers slowly over a long period of time.
- Scenario 3: The system is rescued before it fails (a near-miss) with considerable investment of resources but returns to merely its beginning state of performance. In other words, all of its previous performance gain is lost.
- Scenario 4: The system is adjusted smoothly and achieves its desired functional state with small efforts and little performance loss during the process.

As Woods and Cook (Hollnagel et al. 2006 p.72) argue, "One part of assessing a system's resilience is whether that system knows if it is operating near boundary conditions. Assessing the margin is not a simple static state (the distance of an operating point [current system state in our account] to a definitive boundary [safety limit in our account], but a more complex assessment of adaptive responses to different kinds of disturbances. Incidents are valuable because they provide information about what stretches the system and how well the system can stretch. These complexities are illustrated by one kind of pattern in adaptive response called 'decompensation.' Cases of 'decompensation' constitute a kind of incident and have been analyzed in highly automated systems such as aircraft or cardiovascular physiology. The basic decompensation pattern evolves across two phases. In the first phase, automated loops compensate for a growing disturbance; the successful compensation partially masks the presence and development of the underlying disturbance. The second phase of a decompensation event occurs because the automated response cannot compensate for the disturbance indefinitely. After the response mechanism's capacity is exhausted, the controlled parameter suddenly collapses (the decompensation event that leads to the name)."

This *decompensation* response is very similar to what we describe in A-B-C-D—the first phase being A-B and the second phase being C-D. During A-B, the system has its existing positive momentum to resist negative disturbance. Due to that positive momentum, it is difficult for us to notice negative changes since the system is still moving forward (performance is still increasing). If we focus on monitoring system performance as an indication of failure, we will think the system is doing great at this stage, but the system is secretly deteriorating without noticeable warning signs. When system state arrives at point B, positive momentum; the system starts moving backwards and negative events or accidents happen.

In Woods and Cook's (Hollnagel et al. 2006 p.73) words, "Consider the challenge for a person monitoring these kinds of situations. When disturbances occur, the presence of adaptive capacity produces counter-influences, which makes control appear adequate or allows only slight signs of trouble over a period of time. Eventually, if no changes are made or assistance injected, the capacity to compensate becomes exhausted and control collapses in the form of a major incident or accident. The apparent success during the first phase of the event can mask or hide how adaptive mechanisms are being stretched to work harder to compensate and how buffers are being exhausted. This makes it difficult for monitors to understand what is occurring, especially as the first phase may play out over relatively longer time periods, and leads to great surprise when the second phase occurs."

Woods and Cooks (Hollnagel et al. 2006 p.72-73) provide a way to detect the situation. “In these situations, the critical information for the outside monitor is not the symptoms per se but the force with which they must be resisted relative to the capabilities of the base control systems. For example, when a human is acting as the base control system, as an effective team member this operator would communicate to others the fact that they need to exert unusual control effort (in our account people will try rescue the system which leads to our definition of k). Such information provides a diagnostic cue for the team and is a signal that additional resources need to be injected to keep the process under control. If there is no information about how hard the base control system is working to maintain control in the face of disturbances, it is quite difficult to recognize the seriousness of the situation during the phase 1 (A-B) portion and to respond early enough to avoid the decompensation collapse that marks phase 2 (B-D) of the event pattern… To determine if this adaptive behavior is a signal of successful control or a sign of incipient failure requires an assessment of the control capability of the base system in the face of various kinds and sizes of disturbances.”

In our method, we propose to analyze the interaction of forces, establish system behavior model the reveal the situation occurs during A-D. Besides the signs Woods and Cook suggested, we propose to perform the risk of change analysis to obtain additional information for judging the situation.

Conventionally, the determination of failure is based on the functional performance of a system. The idea is that the closer to the safety limit the functional state is, the riskier the system becomes. Then, the risk of chance is assessed by estimating the probability that the system’s state will exceed safety limits and the consequence when it happens. Standard risk management strategies aim at pulling the performance indicator back to its normal range. However, when systems are dynamic and interconnected, such approaches to risk management may backfire if the overall dynamic balance of the system is not taken into consideration. The abnormal indicators have to be assessed in the broad picture of the system in order to have an accurate diagnosis of functional deterioration. Only if the abnormal performance results in damage to the system’s dynamic balance and a series of warning signs and random failures appear can we diagnose the system as unhealthy and being prone to accidents. Conversely, if the abnormal performance appears without causing damage to the system, the system cannot be diagnosed with a functional disorder. One thing to note is that the curve of the health cycle may vary from system to system according to their constitutions and the specific functions in question. To follow up this matter further would be a whole different discussion and would take us beyond the scope of this research.

7-2. New Strategies for Risk Management

Given the new definition of risk we set forth, we propose a set of different strategies for risk management:

7-2-1. Continuous Adaptation to Change

To implement a truly change-oriented risk management system, continuous adjustment to change is required. Constant incremental adjustments paying attention to small changes will help prepare the adaptation to unexpected changes (Chesbrough 2003 p.13) A system in a generally better state of health will have more available resources to cope with sudden risks. In addition, managers and constituent system components accustomed to constant small changes will be better adapted to significant changes. Diabetes is a perfect example. Having in place well-established paradigms of proper dieting, health maintenance activities and management of sugar intake not only reduces the risk of diabetic crises, but also allows rapid recovery from them. (Aubrey 2010)

For incremental adjustments to unfolding events, the key is to start small and learn from the unexpected. People tend to think there will be more risk when the goal is far away, and that the risk will become zero after achieving the goal because the farther the system is away from its goal, the more risk there is of not reaching the goal and the more chances accidents will happen. However, from the perspective of system dynamics, it is most risky for a system to be right at the goal. In such a situation, the system cannot be any closer to the goal; at that moment, all forces work against it, such that any little change might pull the system away from the goal. The solution is to be more alert when the system is close to the goal, and to set one goal after another.

Ultimately, what must be set in place are durable, lasting patterns of system behavior that promote increased system health. Such a process may not have a fixed ending point, for risk management is a journey without end. It is a journey we must take, however, because the current definition of risk (based on the risk of chance) is self-doomed to inaccuracy because it is based on the risk of chance. Risk of change cannot be predicted in a static risk-of-chance system. And as long as the system keeps changing, the risk of change remains constant. Thus, static risk management systems grow gradually more and more out of date as time goes on. Force will usually result in both positive and negative effects on the system, unless the force is parallel to the direction and system objectives. (Nesse and Williams 1994 p.136)

7-2-2. Accommodating to Change by Engineering for It

Goals provide the logical basis for trade-offs that arise in the course of change. Goal setting is a subjective process and of critical importance to the analysis for risk of change because the direction of the net force or the force fields will be meaningful only if the goal exists. In other words, only with a goal can a force be identified as either a resistance or an assistance which results in opposite momentum to the system. We argue that goals should be aimed at increasing longevity and health rather than optimization. As in Taleb's account (Taleb 2005 p.15), "The objective of risk management is not optimization, but longevity."

Bounded Rationality

A key assumption in modern psychological studies is the boundedness of human decision making, a topic we touched on with the mention of finite versus infinite games. The world in which we live is simply too complex and too rapidly-moving to have a full grasp of. Thus, we use *heuristics* to reduce the complexity of the world to a manageable level, but not without complication. As Sterman (2000 p.598-603,629) puts it, "…we use various heuristics – rules of thumb – to enable us to make reasonable decisions in the time available. However, sometimes these heuristics produce systematic errors and cause the quality of decision making to fall far short of rational behavior. Research in behavioral decision theory has documented a wide range of these heuristics and identified many errors and biases to which they frequently lead." The problem is compounded by time-pressured, high-stake decisions which are irreversible. These must be made on the basis of incomplete information. "And yet many irreversible decisions must be made on the basis of incomplete information. Irreversibility dominates decisions ranging all the way from taking the subway instead of a taxi, to building an automobile factory in Brazil, to changing jobs, to declaring war." (Bernstein 1996 p.15)

It is interesting to contrast the traditional notion of bounded rationality against standard psychological Prospect Theory, a view propounded by psychologists. In Kahneman and Tversky's view, people are flawed rather than just imperfect as Simon suggested in bounded rationality (Taleb 2005 p.187-190) That is, human beings for Kahneman and Tversky are doomed to make incorrect decisions leading to an irrecoverable state for which we must devise automated systems. But the opposite seems to pertain, per Simon; that is, despite being bounded decision makers, humans retain the ability to make wise and proper decisions based on an incorrect view of the relevant risks and rewards. Since heuristics are the basis for the bounded decision makers, we will examine some of the problems with heuristics at a deeper level.

Problems of Heuristics

Despite the highly variant character of modern life, rules do have their value; as Taleb (2005 p.186) says, "we just follow them not because they are the best but because they are useful and they save time and effort." However, for a variety of reasons we have drawn out – amongst them, limited knowledge, constant evolution of the underlying system, non-teleological "evolved" forms of systems – there is no central paradigm for any rule set that is both complete and consistent. Taleb (2005 p.190-191) sums it up well: "The problem with us humans is not so much that no Napoleon has showed up so far to dynamite the old structure then reengineer our minds like a big central program; it is that our minds are far more complicated than just a system of laws, and the requirement for efficiency is far greater…. The fact that your mind cannot retain and use everything you know at once is the cause of such biases. One central aspect of a heuristic is that it is blind to reasoning."

As we have seen with dominant logics, many habits which may have at one time cultivated the strength of the system when one state of affairs pertained may end up becoming negative, even have a deadly cumulative final effect, when the original set of conditions has been gradually forgotten. Most of these problems are systemic issues that require a complete, holistic concept to solve. What are required are balanced, accurate methods of analysis to find no way to solve this problem.

Goal Setting & "Satisficing"

Another strategy to avoid resistance towards goals is goal setting. As we have discussed, many decisions have to be made with limited information. Solutions: 1. Use heuristics 2. Goal Setting (satisficing vs. optimizing) (Sterman 2000 p.601-602; Taleb 2005 p.186-187)

An alternative to heuristics is the notion of "satisficing" – the idea that we may revise the *system goal* if an unchangeable force, e.g., environmental forces, is acting against the system. Should this be the case, we may have to revise the goal and modify our system, e.g., sustainable design, so that the force becomes assistance rather than resistance. An example of this is the Netherlands' state development goal against the increasing sea level problem. Instead of attempting to fight a losing battle against ever-increasing tides, the Netherlands has changed goals from a defensive strategy, e.g., building levees, to incorporating the sea into the landscape – a more environment-friendly solution. They have changed the resistance from the sea into a support for development. (Delta Works Online 2004)

The Netherlands, facing global warming and a sea level rise, have fundamentally rethought their urban planning, land use, and housing policies to adjust to an inexorable, unpreventable sea level rise. Sea level rises, instead of being a public catastrophe, could be acclimated to and even leveraged to produce better quality of life. The key to this approach is accepting that sea level rise is an inevitable change, and adopting policies that harness and adapt to that change, instead of attempting to fight it. "Learning to flood" is the biggest change in the Dutch water management contemplation. Rather than status quo policy that attempts to fight rising sea levels through aggressive dehydration of soil (potentially risking even worse terrain collapse disasters). The "green adaptation" concept incorporates the removal of artificial barriers, the proliferation of smaller, rapidly deployable reservoirs, and adaptation to regular floods. Floating houses, public buildings, and canals are just the beginning.

Water management in the Netherlands is a national affair, and water policy is decided by a local Water Conservancy Bureaus in parallel. Local governments put forward a new urban planning, which must be sent for review to the Water Conservancy Bureau, which confirms that it has no negative impact on water resources management after the implementation.

7-2-3. Resilience as a New Form of Insurance

In his concept of resilience engineering, Hollnagel (2008)[8] suggests that we shift our perennial focus on diagnosis and prevention of failure to a focus on success. He believes that all outcomes (positive and negative) are due to performance variability. Such an idea, however, neglects changes in the environment. Hollnagel surely is right about his view of safety which is defined as the ability to succeed under varying conditions, a concept that resembles the potential new approach to risk analysis that we discussed in Chapter 7 and TCM's viewpoint on maintaining a healthy life.

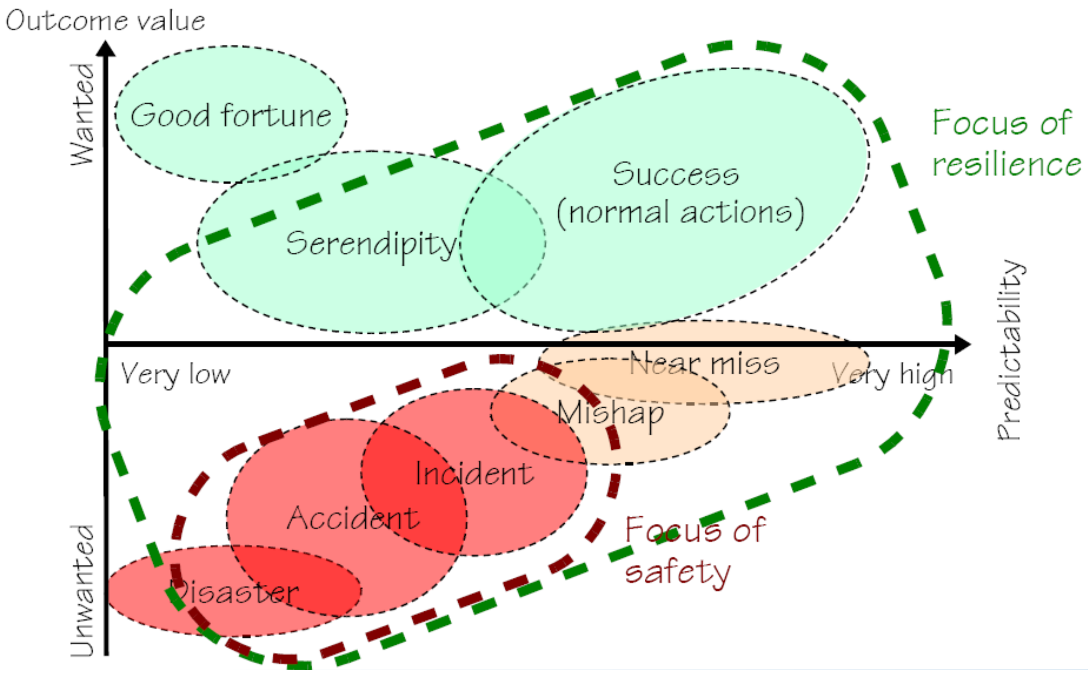

Figure 7-4. Range of Event Outcomes
(Hollnagel 2008 presentation slides)

The momentum of change can be either a risk (if it pulls the system away from the goal) or an opportunity (if it pushes the system towards the goal). Change is most likely to pose risk if it is not under the control of the system. Indeed, systems without any change will involve no risk; however, there will be no opportunity for success either. Conversely, systems without poor internal control may experience opportunity and risk

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[8] From Professor Hollnagel's presentation in a meeting at UC Berkeley, April 1, 2008.

attendant with change, but will be less able to harness that risk than a system that adapts itself intelligently. Thus, the best way to make progress towards system goals is to keep the system under control and moving towards its goal states while it changes, or in other words, *maintaining a state of dynamic balance*. The mechanics and vocabulary of this balance so strongly resembles TCM's concept of dynamic balance that we argue it is necessary to introduce them into risk management through our research.

Negative outcomes are caused by failures and malfunctions.

All outcomes (positive and negative) are due to performance variability..

Safety = Reduced number of adverse events.

Safety = Ability to respond when something fails.

Safety = Ability to succeed under varying conditions.

Eliminate failures and malfunctions as far as possible.

Improve ability to respond to and recover from adverse events.

Improve resilience.

Figure 7-5. Risk Analysis Focuses
(Hollnagel 2008 presentation slides)

> *"The art of progress is to preserve order amid change and to preserve change amid order." –Alfred North Whitehead (Rothschild 1990 p.253)*

We term *resilient* systems those which are able to execute this core concept of being able to maintain controlled progress along a risk/opportunity continuum in the context of a constant level of change. In a sense, the existing fields of resilience engineering and high reliability organization (HRO) both intend to mathematically increase the system's inertia constant k, because an increase in the mass of a system (a larger number) and the rapidity of its progress towards its goal (a higher positive number) represent an increase in system resilience. Thus, resilience engineering and HRO both attempt to insure system health by *maintaining positive momentum*, thus, from the perspective of a traditional risk manager, reducing the adverse consequence of change.

The current system of insurance transfers risk from the system managers to the insurers. A new approach, insurance with resilience, tries to actively invest in system health and creates positive momentum to resist negative changes that might deteriorate the insured system. This approach informs the plethora of public-service-announcement advertisements and messages that we are bombarded with daily by insurance companies. It is more than simply good public image and advertising for a health insurer to remind us, through expensive national television advertisements, to eat our vegetables and exercise; it also has a measurable quantitative effect on the amount and level of payouts which an insurer must make.

The effect of resilient insurance exists in a background of a current policy of (medical) insurance which pays for "diseases" but not for "health." Literally, insured people are given money when they are sick, but must pay when they are healthy. (Liang 2006 p.114) In a sense, such policy rewards "treating diseases" but not "maintaining health." (Liang 2006 p.192) A high-resilience, high-momentum reward system would reward people who keep the relevant system – in this case, their bodies – in normal operation, not those who upset the system by bringing it to its limitation by maximizing profit or performance.

Reserved Power

Reserve power is unused system capability which may be deployed to react to changing circumstances. Examples of reserve power are unused production capacity and temporal safety margins. Each subsystem in an engineered system has its own safety boundaries as well, and its own forms of reserve power. A system may be robust – with high limits – but past those limits there may be irrecoverable conditions. Having reserve power expands those limits making the system resilient. Our goal is maintaining dynamic balance, but maintaining balance at times makes opponents of our account think that we are not trying to optimize the system. Our answer is that we should understand the system's operation and safety limits, and keep the system within limitations to make it operate in the safe zone; we can set goals outside of system limitations, but this requires development of reserve power. Reserve power allows systems to cope with the consequences of unanticipated change. Optimizing system performance means approaching the system safety limits, increasing risk of failure.

A truly resilient system must develop *reserved power*. By reserved power, we do not necessarily mean physical backup facilities, but instead the general ability to rescue a system in danger by bringing up its positive momentum. In the dynamic context, illness and health are opposing and mutually required sides of the human body. Thus, increasing the human system's positive momentum is the way to most effectively decrease the chance of illness. Treating disease by merely bringing negative momentum back to zero is not enough. Pursuing health is about creating positive momentum. The more strain that a system can take (the more negative momentum it can counter-act) the healthier the system.

For purely engineered systems, this concept is often expressed idiomatically as the concept of "insurance" or "an insurance policy." For instance, International Business Machines' research and development policy was seen by its CEO as "both an investment in the future, and an insurance policy against its many uncertainties." (Chesbrough 2001 p.2) That is, developing the rate of growth and profitability of IBM's portfolio of technologies was seen as the soundest policy for coping with an industry based on continual, accelerating technical progress. The author of *The Theory of the Growth of the Firm*, Edith Penrose explains why firms conduct their own internal research expresses this in the same terms: "After all, the specialized firm is vulnerable. Its profitability and very survival as a firm are imperiled [*sic*] by adverse changes in demand for the types of products in produces and by increased competition from other producers... In this view, internal industrial research is both an option for future growth and, even more, an insurance policy against adverse changes in the firm's environment." (Chesbrough 2003 p.200)

Reflex Mechanism

When a system's operation is understood, it is possible to develop automatic reactions. We do not suggest it in this research but future researchers may want to explore this; automatic reflexes help a system stay in control while changing. Reflex mechanisms can help. However, reflex mechanisms may form a type of dominant logic, retarding system growth.

7-3. Towards a New Approach to Risk Analysis

7-3-1. The Two Paradigms of Risk

For the risk of chance, consequence vs. probability matters. For the risk of change, time and rate of change vs. consequence matters. Each form of risk has its own goals. The goal of the risk of chance approach is absolute safety and anticipation of every fault. The goal of the risk of change is simply maintaining relative stability or balance.

An important difference between the traditional paradigm of risk of chance and the risk of change approach we propose is opportunity. The traditional notion of optimizing performance is an essentially risk of chance controlled, while the prolonging of longevity is an area controlled by risk of change. In traditional risk-of-chance paradigms, risk and opportunity are different sides of the same coin; opportunity cannot occur without risk. However, a risk-of-change approach explains how risk and opportunity come from the same source – they are different momenta of change, in different directions (as explained in Chapter 5).

A powerful effect of the new questions we are asking with regard to the risk of chance is that the answers we obtain fit into a holistic picture, not a series of pigeonholed fault/event-tree scenarios. Under a traditional risk-of-chance approach that attempts to draw “reasonable man” expectations out of admittedly stochastic and thus inherently unpredictable measures, systems are doomed to have a constant stream of events that always come suddenly, without any warning, so that systems survive or fail based on how accurately they have anticipated circumstances. However, if basic assumptions are revised and success and failure are seen in terms of the risk of change concepts, novel system events become comprehensible as forms of gradual change, allowing system managers to monitor the changes in conditions over time, constantly performing minor adjustments in real time.

As the concept of *yin yang* might suggest, risk of change and risk of chance are not mutually incompatible nor mutually exclusive concepts. Risk of chance plays an important role in the system we propose. For instance, since the properties of the system’s material are determined by nature, the risk of material failure varies according to risk of chance. The science of material failure is well-established, but rather than having an entirely chance-driven epistemological paradigm that sees system events as fundamentally random, our system uses a holistic picture of the risk of change to orient systems and decision-makers towards positive behaviors that create opportunity and reduce risk. Thus, a traditional risk-of-chance approach might attempt to arrive at a system's material composition through a consideration of "worst-case" stress-strain scenarios, selecting a material most capable of resisting an adequate amount of stress while also being acceptable inexpensive. A risk-of-change oriented approach would instead ask how the material is used and applied in the context of the system, and the function of the material as a question of risk of change, arriving at an idea of the material's importance relative to functioning of the system as a whole. Table 7-1 lists major differences between the two paradigms of risk.

Table 7-1. Risk of Change vs. Risk of Chance

	Risk of Change	Risk of Chance
Definition	The momentum of change Risk = $\boldsymbol{m}_c * \boldsymbol{v} = (k/\boldsymbol{\Delta S}) * \boldsymbol{V}_{ne}t$	The expected loss of accidents Risk = Consequence * Probability
Focus on	System State / Behavior Changes (how it happens)	Accidents / Events (whether or not it happens)
Uncertainty	The intrinsic fluctuations of variables (environment changes) the effects of added forces on system behaviors latent behaviors / factors incomplete knowledge of the system	The occurrence of existing events / accidents unexpected events / accidents
The Use of Experience	To analyze the effect of system behaviors on the system state	To analyze the chance of anticipated events
Data Source	from the individual system	from average systems

7-3-2. Promoting System Health through Adaptive Control

Change is inevitable and indispensable to success. Without change, there would be no risk, but no opportunity either. The challenge that change presents is to maintain control while changing. A system aimed at stasis, a state without change, produces at best an entirely deterministic situation with no risk nor any opportunity, which is what the complex-system paradigm has suggested to be wrong. Risk management will be advanced not through calculating risk more accurately, but rather through increasing our knowledge about how systems can interact with changing forces and maintain balance while the system evolves towards its goal.

Thus, understanding the current state of the system and knowing where the system is being driven are important because together they define the risk of change and how dynamic balance can be maintained. This new approach to risk analysis is fundamentally about managing change rather than managing risk. Just as modern medical systems in mature societies are increasingly exploring geriatrics, and the curing of chronic diseases instead of simply accident and injury control, so too should risk analysis move forward past merely accident palliation. (Nesse and Williams 1994 p.182) In Part 3, we will at length discuss how to manage these changes.

RISK DYNAMICS <PART THREE>: ANALYZING THE RISK OF CHANGE

Engineered systems in the information age are becoming increasingly complex. Technological innovations are introduced into systems on a daily basis, and systems nowadays are interdependent and interconnected with each other in a way never seen before. In the face of this increasing complexity, our capability for making sensible decisions is seriously challenged. (Qudrat-Ullah et al. 2008) Such a challenge manifests in catastrophic events where early warning signs are constantly overlooked because their importance was misjudged; quite often, the wrong problems are solved when catastrophes were developing (an "error of the third kind" as we quote Mitroff and Featheringham referring to it in Section 4-1-3).

Conventional risk analysis proceeds with a retrospective and detailed approach striving for concrete evidence on how catastrophes happened. There are two obvious problems with such approaches:

1. Rescue attempts for the system usually start after a catastrophe takes place, thus accident investigation is usually separated from the rescue operation.
2. Although lessons learned from such investigation are generally beneficial to the "prevention" of the next similar accident, precision and focus in the investigation make it difficult to apply to the next event which is usually complex and unforeseeable.

Just as Bookstaber (1999 p.18) states, “precision and focus in addressing the known comes at the cost of reduced ability to address the unknown.” While simple phenomena in detail may uncover the gaps in our knowledge, considering complex phenomena in detail may prevent us from seeing the bigger picture of the problem. As discussed in Section 4-2-2, there is always a trade-off between complexity and accuracy. General, essential coarse decision rules and responses, although suboptimal for any one situation, are more satisfactory for a wide range of unforeseeable situations. As we show, TCM provides profound insights in this regard.

Risk exists in the constant changes and challenges that complex engineered systems face in a dynamic world. By understanding the changing health conditions of a system, we can substantially increase our chance to detect its functional deterioration at an early stage, restore its necessary dynamic balance and make the system more resilient to possible accidents. TCM approaches to healing are, thus, reviewed and applied as the basis of our proposed risk analysis methodology – the adaptive system-health control framework. Unlike conventional approaches to risk analysis, which pay close attention to the possibility and consequence of unusual events and try either to reduce the risk or react to the events, in this framework, the focus, is no longer trying to manage the risk since it is an inevitable result under changing conditions. Instead, we propose to understand system constitution and structure and monitor system behaviors under its normal operation, detect signs and events that manifest functional disorders and restore its dynamic balance to prevent system from deteriorating before anything catastrophic happens.

Chapter 8. Theoretical Foundations of Traditional Chinese Medicine (TCM)

We have discussed some theoretical concepts of traditional Chinese medicine or TCM practice up to now. To wit, these are a focus on constant change, an etiology concerned with composite signs evincing homeostatic balance, an inductive methodology centering on clinical observation instead of experimental axioms, and the notion of the healer as chiefly concerned with strengthening the internal systems and flows of the patient. In order to develop a full system of risk management, we need a vocabulary of concepts and a coherent metaphysical and theoretical construct which will allow us to develop the holistic, dynamic viewpoint required for management of the risk of change. These are terms we have used extensively in critique; we will explore more fully their meaning and implications, as criteria, in the system of risk analysis that we propose. The bases of this vocabulary and philosophical system are already developed and existent: it is TCM itself. Thus, we turn now to exposition of TCM concepts relevant to risk management and their application.

At the outset of TCM theorization, just as with the Western tradition, ancient Chinese doctors relied on philosophical ideas to explain complex phenomena in the human body. Thus, an "in-depth understanding of the theoretical framework of the Chinese medical system including its philosophical underpinnings is essential in order for TCM to be practiced effectively." (Leung et al. 2003 p.47) Among those, *yin yang* and *wu xing* theories shed light on complex phenomena; TCM concepts of constitution, vital substances and human body structure provide new ways of understanding complex engineered systems, and the concept of *Tao* and *qi* underlie these as the basis of these ancient traditions.

Tao

The *Tao* is literally the "way of events," a concept that defines the way the universe and our body systems operate. The *Tao* defines the parameters of how human beings interact with the physical world physiologically, as well as how we interact socially with the mental world. It is also a cosmological concept, "a way of nature, a way of the seasons, planting and harvest—it is a way of virtue, a way of heaven, a way of life, and a way of death. The *Tao* pervades every aspect of life and being. In later Taoist schools, *Tao* ultimately means something very much akin to God. *Tao* always remains cosmic and eternal. It is the oneness. The goal of life was to flow with the *Tao*, as individuals, families, groups, and society." (Sheikh and Sheikh 1989 p.68-69)

The colloquialism "the way of things" is an adequate, if brief, description of the concept of the *Tao*, and it signals some of the difficulties that traditional paradigms of meaning have with the concept. The most canonical interpretation of the *Tao* is commonly accepted to be the 6th century BC text which we refer to as the *Tao Te Ching*. Later exegetical and religious traditions assigned more or less normative dimensions to the *Tao*, but at its core, the concept of *Tao* is, much like its phonological expression, wildly polysemous. Briefly, the idea of the *Tao* is cosmological in that it makes claims to the order of the universe, metaphysical in that it claims to lay bare an essential order to the universe, and ontological in its description of conditions and forms of being. The *Tao* is not a teleological construct like moral rightness or utility that drives towards an end state; rather, it may be thought of as a non-teleological yet essentialist notion of how the world operates. (Sheikh and Sheikh 1989 p.68-69)

The concept of *Tao* has general and specific meanings which are useful in the practice of understanding and managing the risk involved in complex systems. That is, there is a "way of things" which pertains to the universe in general, as well as a specific "way of things" which apply all things, living (people and animals), inanimate (rocks, air, water), and animate (cities and corporations). That is, the universe has a *Tao* which is literally how the universe plays out across time; this universal, cosmological *Tao* is the word's most commonly used form. However, determinate physical entities like human beings, trees, rocks, and clouds may be said to have a *Tao*. Institutions and abstract entities like armies, corporations, marriages and friendships also have their own respective *Tao*. Processes like life, business and war also have their own *Tao*.

The Concept of Qi

The TCM-philosophical concept of *qi*, loosely translatable as "vital power" or "life energy," interweaves through the *Tao*-driven universe. *qi*-energy "is at the basis of all phenomena in the universe and provides continuity between coarse, material forms and tenuous, rarefied, non-material energies." (Maciocia 2005 p.42)

One of the most important features of *qi* is its creativity. "*Qi* was first referred to in Taoist writings, which developed the idea that 'the world begins with *qi*'. In ancient China, philosophers believed that *qi* was the fundamental substance that made up everything in the world and that all things came into being through the movement and flux of *qi*." (Leung et al. 2003 p.63) This is more than merely folk cosmology; the constitutive, creative aspects of *qi* as explored in TCM take into account the Einsteinian notion of matter as a form of energy. Although the TCM concept is invariant to core Einsteinian relativistic concepts like the interplay of mass and velocity, *the risk of change* concept adds this awareness and provides a mature, complete risk concept for engineered systems just as TCM does for human systems.

The constantly shifting material basis of *qi* is an important feature of the concept of *qi*. The Chinese etymology of the character shows some of the difficulty with the concept:

> *The [Chinese] character for qi indicates that it is something that is, at the same time, both material and immaterial: 氣 (Qi) = 气 means "vapour," "steam," "gas" + 米 means (uncooked) "rice." This clearly indicates that qi can be as rarefied and immaterial as vapour, and as dense and material as rice. It also indicates that qi is a subtle substance (steam, vapour) deriving from a coarse one (rice). (Maciocia 2005 p.41)*

The concept of mutually required opposition from *yin yang* theory sheds some light on the physical status of *qi*. For exegetical theorists like Zhang and Rose, "*Qi* is the interchange of *yin* and *yang*" (Leung et al. 2003 p.64) Thus, there need not be a determinate physical basis for *qi* like bodily substances, nor must it be a completely immaterial concept like kinetic energy; it can be both, occasionally neither, and at all times located in the interplay between the physical and the immaterial. As Macioca (2005 p.41) continues, "The reason it is so difficult to correctly translate the word '*Qi*' lies precisely in the versatile nature whereby *qi* can assume different manifestation and be different things in different situations."

By locating *qi* as a substance/energy which has a constantly shifting metaphysical status, "(it) therefore completely sidesteps the dilemma that has pervaded Western philosophy from the time of Plato to the present day, that is, the duality and contrast between materialism and idealism. Western philosophy either considered matter as independent of man's perception, or, at the other extreme, considered matter as a mere reflection of ideas… [In Chinese philosophy, however,] the infinite variety of phenomena in the universe is the result of the continuous [aggregation] and dispersion of *qi* to form phenomena of various degrees of materialization." (Maciocia 2005 p.42)

The application of our concept of *qi* will be further explained in Section 8-3-2.

8-1. Yin Yang as a Way of Simplifying Complexity

Yin yang theory is dialectic and materialistic theory based on the belief that the world is a material whole and results from the mutual action of two complementary but opposite material forces, termed *yin* and *yang* (Figure 8-1). Ancient Chinese thinkers understood and explained the universe in terms of constant changes in accord with this theory. The earliest reference to *yin* and *yang* can be traced back to *I Ching* or the *Book of Changes*. (Maciocia 2005 p.3) The explanatory functions of *yin yang* theory make it a powerful means of simplifying complex phenomena and helping to see the nature of things.

The exact features of *yin yang* theory deserve some explanation. A core concept of *ying yang* theory is what we term *mutually reconciling opposition*. We return again to Sheikh and Sheikh's (1989 p.69) study of TCM to explain the concept at length:

> *The yin and yang represent the fundamental dualities, opposites, and polarities of the universe; yet, they also represent the unity of the circle and the Tao. This duality within unity often presents a problem for Western students of philosophy and medicine. The circle represents the whole universe and contains all aspects of the universe, including opposites: yin/yang, black/white, female/male, night/day, earth/heaven, death/life, and so on. It is the unity containing the duality. They are opposite, yet contained within the same circle. They are different yet the same. The yin contains the yang and the yang contains the yin.*

Although we recognize a distinction between two ends of the spectrum – *yin* and *yang* – there is also a constant shift and interplay between the two that defines each. Thus, "*yin* and *yang* represent opposite but complementary qualities. Each thing or phenomenon could be itself and its contrary. Moreover, *yin* contains the seed of *yang* so that *yin* can transform into *yang* and vice versa." (Maciocia 2005 p.3) In other words, nothing is totally *yin* or totally *yang*.

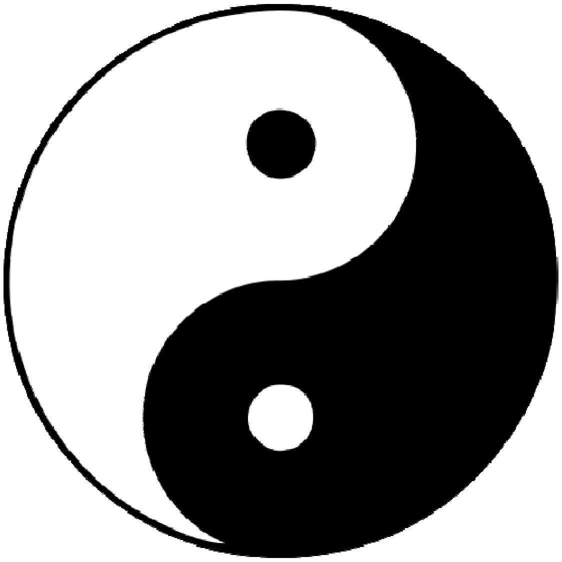


Figure 8-1. Yin Yang

8-1-1. The Notion of Yin Yang

The origin of *yin yang* theory is thought to have derived from the peasants' observation of the cyclical alternation of day and night and thus the changes of sunlight and shade over different sides of a mountain. *Yin* (literally "shady place" or "north slope") is the dark area blocked by the mountain's bulk, while *yang* (literally 'sunny place' or "south slope") is the brightly lit portion. As the sun moves across the sky, *yin* and *yang* gradually trade places with each other, revealing what was obscured and obscuring what was revealed. Similarly, as the day turns into night, *yang* giving away to *yin* and vice versa. (Leung et al. 2003; Maciocia 2005; Song 1988; Zhou 2004)

From these original observations, the theory of *yin* and *yang* expand to the attribution of everything in the universe as having the opposing aspects of *yin* and *yang*. *Yin* is usually characterized as slow, soft, insubstantial, diffuse, cold, wet, and tranquil. It is generally associated with the feminine, birth and generation, and with the night. *Yang*, by contrast, is characterized as hard, fast, solid, dry, focused, hot, and aggressive. It is associated with masculinity and daytime. (Leung et al. 2003; Maciocia 2005; Song 1988; Zhou 2004) See Table 8-1 for a list of attributes that correspond to *yin* and *yang*.

Table 8-1. Examples of Yin and Yang Attributes

	Yang	**Yin**
Locality	Top	Bottom
	Outside	Inside
	Left	Right
	South	North
	Sky / “Heaven”	Ground / “Earth”
Time	Day	Night
Seasons	Spring	Autumn
	Summer	Winter
Temperature	Hot	Cold
Humidity	Dry	Damp
Brightness	Light	Darkness

The cyclical nature of transformations between yin and yang make them, in philosophical terms, “a duality in time.” (Maciocia 2005 p.5) Matter and energy are different states, just as night an day are, and contain within each part is the potential for its complementary part. As Macioca (2005 p.5-6) continues,

> *Every phenomenon in the universe alternates through a cyclical movement of peaks and bases, and the alternation of yin and yang is the motive force of its change and development. Day changes into night, summer into winter, growth into decay and vice versa. Thus the development of all phenomena in the universe is the result of the interplay of two opposite stages, symbolized by yin and yang, and every phenomenon contains within itself both aspects in different degrees of manifestation. The day belongs to yang but after it reaches its peak at midday, the yin within it gradually begins to unfold and manifest. Thus each phenomenon may belong to a yang stage or a yin stage but always contains the seed of the opposite stage within itself.... [As shown in Figure 8-2,] exactly the same happens with the yearly cycle and we need only substitute ‘spring’ for ‘dawn’, ‘summer’ for ‘noon’, ‘autumn’ for ‘dusk’ and ‘winter’ for ‘midnight’.*

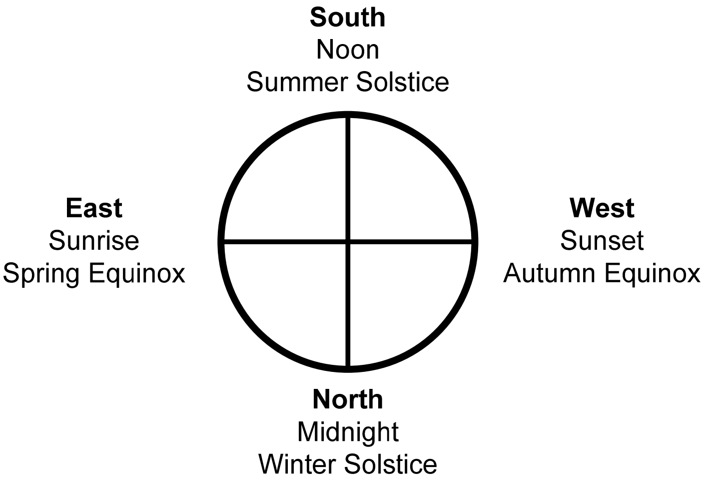


Figure 8-2. Yin Yang in Daily and Seasonal Cycle
(Maciocia 2005 p.5-6)

Similar to the concept of *mass-energy equivalence* in the special theory of relativity, *yin* and *yang* signal different states of matter. *Yang* symbolizes the more immaterial, pure and ethereal states of matter, while *yin* symbolizes the more material, dense, coarse and solid states of matter. Thus, liquid water is in a *yin* state, while the vapor resulting from application of heat to water is a *yang* form of matter. Similarly wood in a solid state is a *yin* form while the heat and light generated by burning are a form of *yang*. Condensation, accumulation and agglomeration are *yin* states of matter; dispersion, separation and evaporation are *yang* states of matter. Just as in modern physics, these states are not independent of each other, but rather change into each other. Indeed, there may be extreme forms of each where *yang* is totally immaterial and corresponds to pure energy and *yin* in its coarsest and densest form is totally material and corresponds to matter. Although there are only two portions of a *yin yang* dichotomy, each dichotomy admits an infinite range of intermediate possible states of aggregation or dispersal; just as we recognize five (or seven) basic colors yet an infinite number of possible color combinations, so too there exist an infinite possible number of states of aggregation. (Leung et al. 2003; Maciocia 2005 p.6; Song 1988; Zhou 2004) Thus, we can add a few more qualities to the list of yin and yang attributes:

Table 8-2. More Examples of Yin and Yang Attributes

Attributes	Yang	Yin
Form	Energy	Matter
	Immaterial	Material
	Non-substantial	Substantial
	Fire	Water
Motions	Ascend	Descend
	Active	Quiescent
	Fast	Slow
	Expansion	Contraction

8-1-2. Relationship of Yin Yang

There are three aspects of the *yin yang* relationship: (— 1994 p.19-23; Leung et al. 2003 p.53; Maciocia 2005 p.7-8; Song 1988 p.24-28; Zhou 2004 p.19-24) The opposition and interdependence of *yin* and *yang*, the universality and divisibility of *yin* and *yang*, and the dynamic equilibrium and mutual transformation of *yin* and *yang*. We will discuss each briefly in turn.

The Opposition and Interdependence of Yin and Yang

Yin and *yang* represent opposite stages of an alternating cycle, or opposite but complementary states of aggregation as previously explained. “Nothing in the natural world escapes this opposition. It is this very inner contradiction that constitutes the motive force of all the changes, development and decay of things… Although yin and yang are opposite, they are also interdependent: one cannot exist without the other. Everything contains opposite forces that are mutually exclusive, but, at the same time, depend on each other. Day cannot come but after the night and vice versa; there cannot be activity without rest, energy without matter or contraction without expansion.” (Leung et al. 2003 p.53; Maciocia 2005 p.7-8)

From the perspective of systems thinking, the tangible material substratum or structure of the system belongs to *yin* and the intangible functionality of the system belongs to *yang*. Without the material substratum, the functionality will not work; without the functional activities, the material substratum cannot be produced. The system's functionality and material substratum facilitates and constrains each other. This opposing relationship (constraining) creates a negative (balancing) feedback between *yin* and *yang*; the interdependence relationship (facilitating) creates a positive (reinforcing) feedback between them. The development and change of everything in the universe come from this opposition and interdependence relationship of *yin* and *yang*. Without either one of them, development and change cease and the system breaks down. We have touched on this concept briefly in Part I with our discussion of the idea that everything is changing and that systems are made up with change. *Yin yang* theory locates this change at the most basic level of system constitution and system performance. These relationships are the motive force of dynamic balance and mutual transformation.

The Universality and Divisibility of Yin and Yang

The exact cosmological arguments made by *yin yang* theory may be summed as follows:

- Everything in the university pertains to yin or yang.
- This attribution is not intrinsic but rather relative.
- The divisibility of yin and yang is endless.
- Holism pertains throughout.

Yin and *yang* are descriptions of complementary opposites rather than absolutes, a way of describing the interactions of natural forces occurring in the world. No *yin yang* dichotomy is fixed; every *yin yang* can be viewed from another perspective. All forces in nature can be seen as having *yin* and *yang* states, and the two are in constant movement rather than held in absolute stasis. This applies as well in social constructions – e.g. value judgments like good and evil, rich and poor, honor and dishonor – yet it is often used in those contexts as a warning, since by its principles extreme good will turn to evil, extreme wealth to poverty, extreme honor to dishonor. (Song 1988 p.24-28; Zhou 2004 p.18)

The concept of mutually required opposition is not distinct to the TCM tradition. A tripartite mutual opposition, for instance, informs the Judeo-Christian notion of the "holy trinity," just as the ancient Greek gods might be said to be a constant state of *yin yang* consolidation and dispersion. *Yin yang* theory is unique, however, in its dynamic nature and its broad application to the natural world. Rather than an abstract play of ideas or explanatory concepts divorced from inductive observation, *yin yang* is quite literally a way or *Tao* of existence. Sheikh and Sheikh (1989 p.69-70) describe the intellectual effects of this theory aptly:

> *To the Western mind, things are black and white or black or white. But in the Eastern way, things are black/white. In the [Western] tradition, all opposite are warring forces. The chief battle is good against evil. One must triumph, and we must be sure that it is good. In the Eastern way, the inseparable yin and yang gently wrestle with each other. Nothing in the universe is one or the other. Everything contains yin/yang. They are part of the same reality. They are merely opposite polarities of the same magnet, and it is impossible to have one without the other. Westerners have great difficulty with this concept. We hold that light battles with darkness, life with death, good with evil, positive with negative.*

Since *yin* and *yang* are relative, not absolute, in so far as nothing is totally *yin* or totally *yang*, and everything contains the seed of its opposite, nothing can be properly said to be "*yang*" or "*yin*." In engineered systems, this concept finds a counterpart in the notion that the system's balance is maintained dynamically and influenced by various internal and external forces (as discussed in Part II). As Macioca (2005 p.7-8) puts it:

> *Everything pertains to yin or yang only in relation to something else. For example, as heat pertains to yang and cold to yin, we might say that the climate in Barcelona is yang in relation to that in Stockholm, but yin in relation to that in Algiers. To give another example from Chinese dietary principles, vegetables are generally yin and meat generally yang. However, within each category there are degrees of yang or yin quality: thus, chicken is yang compared with lettuce but yin compared with lamb… Although everything contains yin and yang, these are never present in a static 50:50 proportion, but in a dynamic and constantly changing balance. For example, the human body's temperature is nearly constant within a very narrow range. This is not the result of a static situation, but of a dynamic balance of many opposing forces.*

Because everything pertains to *yin* or *yang* and *yin* and *yang* facilitate and constrain each other, the universe can be seen as organic, constantly shifting yet self-contained whole. *Yin* and *yang* not only exist between two mutually related objects or phenomena (systems), but also exist inside each object or phenomenon (system). Thus, the divisibility of *yin* and *yang* is endless. For example, night pertains to *yin* and day pertains to *yang*, yet from dust till midnight is the *yin* of *yin*; from midnight to dawn is the *yang* of *yin*. During the day, morning is the *yang* of *yang*; afternoon is the *yin* of *yang*.

Using the *zang fu* system of internal flows as example, *zang* is *yin* and *fu* is *yang*. Among the five organ systems in *zang*, Lung, Spleen and Kidney are *yin*; Heart and Liver are *yang*. To take one step further, inside the Heart, there are *yin* parts and *yang* parts and so forth.

The Dynamic Equilibrium and Mutual Transformation of Yin and Yang

In summary, our account of dynamic equilibrium and *yin yang* centers on the following:

- Dynamic equilibrium in certain ranges, similar to the concept of resilience.
- Under certain condition, yin and yang can transform into each other.

Since *yin* and *yang* are in balance with changes in one affecting the other, changing the relative proportion of each is a form of balance. However, when one aspect rises to a certain degree, the restriction from the other side will be strengthened and can inhibit the rising side. If the ebb and flow between *yin* and *yang* are beyond normal levels, the rise of *yang* for example, restriction from *yin* may be insufficient and thus the equilibrium between them would be broken leading to disease. This phenomenon resembles to the concept of resilience that under certain degrees of deformation, a system can restore its normal function after the influences are removed. Once the deformation exceeds its limitation, however, the system cannot recover by itself, a condition similar to material stress/strain interaction.

There are two conditions for *yin yang* transformations: a primacy of internal conditions, and the notion of time. In naturally observed *yin yang* transformations, things can change only through internal causes primarily, and external causes secondarily. Further, change takes place only when the internal conditions are ripe. “For example, an egg changes into a chick with the application of heat only because the egg contains within itself the capacity of turning into a chick. Application of heat to a stone will not produce a chick. The second condition is the time factor. *Yin* and *yang* can transform into each other only at a certain stage of development, when conditions are ripe for the change. In the case of the egg, the chick will hatch only when the time is ripe.” (Maciocia 2005 p.7-8)

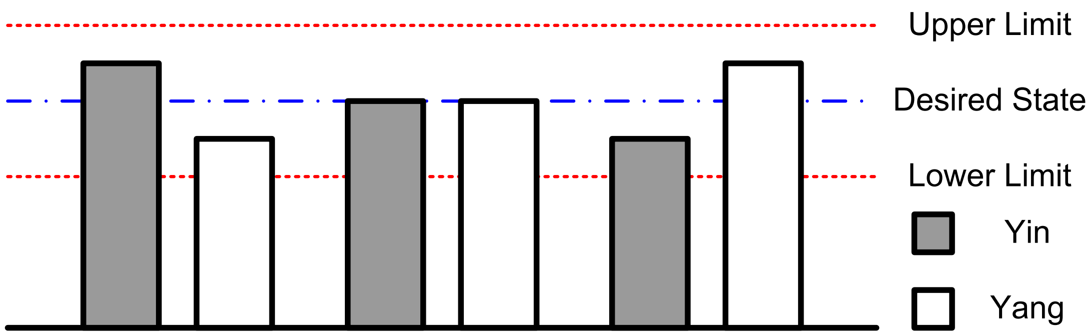


Figure 8-3. Dynamic Equilibrium between Yin and Yang

8-2. Wu Xing as a Self-Organizing Structure

Based on observations of the natural world, ancient Chinese people recognized continuous patterns of transformation and change in the universe. Initially, these observations were interpreted using *yin yang* logic, but later these interpretations were expanded using a new theory called *wu xing*

Yin yang and *wu xing* are similar concepts in that each explains changes in the world, but yin yang simplifies it to only two states, and cannot accurately fit real world situations. *Wu xing* represents changes with a more elaborate system capable of fitting more concrete examples. It is written out of *yin yang* relationships, for *wu xing*'s generative and restraining cycles are *yin yang* relationships. Both are tools for achieving dynamic balance.

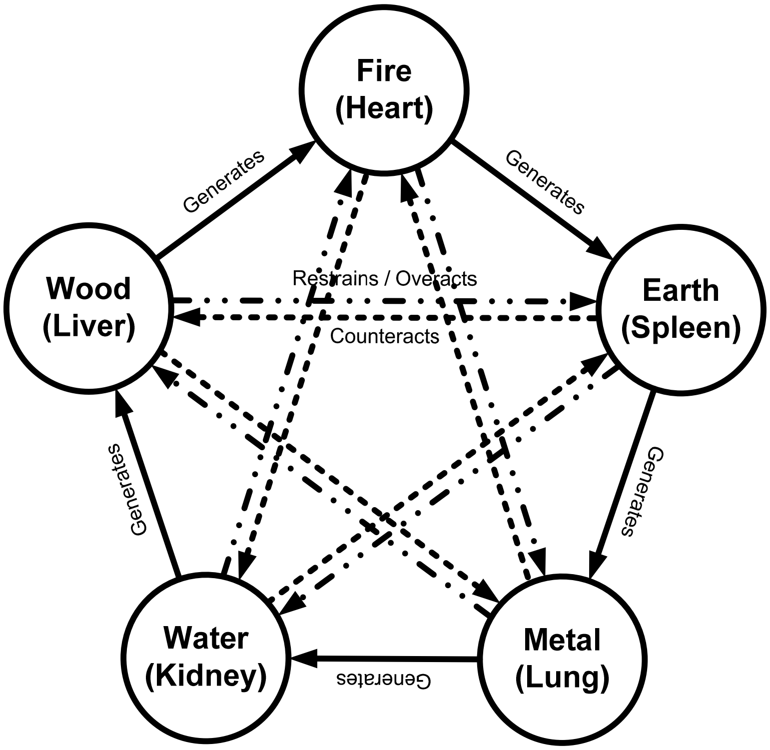


Figure 8-4. Wu Xing Cycles
(Maciocia 2005; Sheikh and Sheikh 1989; Zhou 2004)

8-2-1. Notion of Wu Xing

Similar to the Western world, the Chinese world came up with the ideas of elements; for the Chinese, the elements are Metal, Wood, Water, Fire, and Earth. Each has its own endogenous properties as well as relationships to each other. Wood, for instance, has the property of growing upwards and outwards, so everything that represents ascension and growth is symbolized by wood. Similarly, fire is characterized by warmth and upwards movement. (Maciocia 2005 p.21; Sheikh and Sheikh 1989 p.77-79; Tang 2004 p.27-32) These natural properties are grouped into, the *wu xing*, or the *five elements*, usually translated as *five phases*, *five movements* or *five steps*.

8-2-2. Correspondences of Wu Xing

The system of correspondences is an important part of the *wu xing* theory. This system is typical of ancient Chinese thought, linking many different phenomena and qualities within the microcosm and macrocosm under the rubric of a certain element. The ancient Chinese philosophers saw links between apparently unrelated phenomena as a kind of "resonance" or correspondences among them. Some of the main correspondences are shown in Table 8-3:

Table 8-3. Main Correspondences of Wu Xing
(Maciocia 2005; Sheikh and Sheikh 1989; Zhou 2004)

	Fire	**Wood**	**Earth**	**Metal**	**Water**
Seasons	Summer	Spring	None	Autumn	Winter
Climates	Heat	Wind	Dampness	Dryness	Cold
Directions	South	East	Center	West	North
Stage of Development	Growth	Birth	Transformation	Harvest	Storage
Grains	Beans	Wheat	Rice	Hemp	Millet
Planets	Mars	Jupiter	Saturn	Venus	Mercury
Numbers	7	8	5	9	6
Times of Day	11am-3pm 7pm-11pm	11pm-3am	7am-11am	3am-7am	3pm-7pm
Yin Yang	Utmost yang	Lesser yang	Center	Lesser yin	Utmost yin
Yin Organs	Heart	Liver	Spleen	Lungs	Kidneys
Yang Organs	Small Intestine	Gall Bladder	Stomach	Large Intestine	Bladder
Sense Organs	Tongue	Eyes	Mouth	Nose	Ears
Tissues	Vessels	Sinews	Muscles	Skin	Bones
Secretions	Perspiration	Tears	Saliva	Mucous	Spittle
Tastes	Bitter	Sour	Sweet	Pungent	Salty
Emotions	Joy	Anger	Pensiveness	Sadness	Fear
Colors	Red	Green	Yellow	White	Black
Sounds	Laughing	Shouting	Singing	Crying	Groaning

Various different phenomena would be unified by an indefinable common quality, much as two strings would vibrate in unison. Thus, one of the most typical aspects of Chinese medicine is the common resonance among phenomena in Nature and in the human body. Some of these correspondences are commonly verified and experienced all the time in clinical practice, some may seem far fetched, but the feeling remains that there is a profound wisdom underlying all of them that is, at times unfathomable.

8-2-3. Interrelationships of Wu Xing

The system of *wu xing* was used for describing interactions and relationships between phenomena. It was employed as a device in many fields of early Chinese thought, including seemingly disparate fields such as geomancy or *feng shui*, astrology, TCM, music, military strategy and martial arts. Essential to the very concept of *wu xing* is the various interactions among them. Different philosophers stressed different relationships among its five elements. Thirty-six different arrangements of the five elements are mathematically possible. The four most common ones are described below: (Maciocia 2005 p.23-26)

1. Cycles of Balance

a) Generating (Creating) Cycle (cf. positive feedback, yang)

In this cycle each element is generated by one and generates another. Accordingly, Wood, for example, is generated by Water, and it generates Fire, a sequential stage that is sometimes expressed as “Wood is the child of Water and the mother of Fire.”

b) Restraining (Controlling) Cycle (cf. negative feedback, yin)

In this cycle each element restrains another and is restrained by one. Accordingly, Wood restrains Earth, for example, but is restrained by Metal. The restraining cycle ensures that a balance is maintained among *wu xing*.

There is also an interrelationship between the generating and the restraining cycles. For example, Wood restrains Earth, but Earth generates Metal, which restrains Wood. Furthermore, on the one hand Wood restrains Earth, but on the other hand it generates Fire, which, in turn, generates Earth. Thus a self-regulating balance is kept at all times.

The mutual generating and restraining relationships among the elements is a surprisingly powerful tool for understanding complex system behavior. Many self-regulating balancing processes seen in nature and in the human body are regulated by processes that work much like ancient concepts of dynamic balance would dictate, most obvious amongst them the notion of homeostasis.

2. Cycles of Imbalance

a) Overacting (Over-restraining) Cycle

This follows the same cycle as the restraining one, but in it, each element “over-restrains” another, so that one causes another to decrease. This happens when balance is broken and, under the circumstances, the quantitative relationship among the elements breaks down so that, at a particular time, one element is excessive in relation to another.

To return to a comparison with natural phenomena, the destructive actions of human beings towards nature, especially in this century, provide numerous examples of this cycle.

b) Counteracting (Insulting) Cycle

This cycle is literally called “insulting” in Chinese. It takes place in the reverse order to the restraining cycle. Thus, Wood counteracts Metal, Metal counteracts Fire, Fire counteracts Water, Water counteracts Earth and Earth counteracts Wood. This also takes place when the balance is broken.

Thus, while the first two cycles deal with the normal balance among the elements, the second two deal with the abnormal relationships among the elements that take place when the balance is broken.

Table 8-4. The Law of Wu Xing
(Sheikh and Sheikh 1989 p.81)

Heart **Circulation/Sex**		**(Fire)** **(Fire)**	**Small Intestine** **Three Heater**		**(Fire)** **(Fire)**
Child of	Liver	(Wood)	Child of	Gallbladder	(Wood)
Controlled by	Bladder/kidneys	(Water)	Controlled by	Bladder/kidneys	(Water)
Mother of	Spleen/pancreas	(Earth)	Mother of	Stomach	(Earth)
Controller of	Lung/colon	(Metal)	Controller of	Lung/colon	(Metal)
Stomach		**(Earth)**	**Spleen/Pancreas**		**(Earth)**
Child of	Small intestine / three heater	(Fire)	Child of	Heart, circulation/sex	(Fire)
Controlled by	Gallbladder/liver	(Wood)	Controlled by	Gallbladder/liver	(Wood)
Mother of	Colon	(Metal)	Mother of	Lung	(Metal)
Controller of	Bladder/kidneys	(Water)	Controller of	Bladder/kidneys	(Water)
Lung		**(Metal)**	**Colon**		**(Metal)**

Child of	Spleen/pancreas	(Earth)	Child of	Stomach	(Earth)
Controlled by	Heart, small intestine, circulation/sex, three heater	(Fire)	Controlled by	Heart, small intestine, circulation/sex, three heater	(Fire)
Mother of	Kidneys	(Water)	Mother of	Bladder	(Water)
Controller of	Gallbladder/Liver	(Wood)	Controller of	Gallbladder/liver	(Wood)
Bladder		**(Water)**	**Kidneys**		**(Water)**
Child of	Colon	(Metal)	Child of	Lung	(Metal)
Controlled by	Stomach, spleen/pancreas	(Earth)	Controlled by	Stomach, spleen/pancreas	(Earth)
Mother of	Gallbladder	(Wood)	Mother of	Liver	(Wood)
Controller of	Heart, small intestine, circulation/sex, three heater	(Fire)	Controller of	Heart, small intestine, circulation/sex, three heater	(Fire)
Gallbladder		**(Wood)**	**Liver**		**(Wood)**
Child of	Bladder	(Water)	Child of	Kidneys	(Water)
Controlled by	Lung/colon	(Metal)	Controlled by	Lung/colon	(Metal)
Mother of	Small intestine, three heater	(Fire)	Mother of	Heart, circulation/sex	(Fire)
Controller of	Stomach, spleen/pancreas	(Earth)	Controller of	Stomach, spleen/pancreas	(Earth)

8-3. Constitution, Vital Substances and Human Body Structure

8-3-1. Concept of Constitution

Within the conventional paradigm of western medicine, a disease such as influenza is considered to be caused by viruses. However, certain types of immune system types – immuno-normal and immuno-suppressed, for instance – pre-dispose one to be infected with influenza or not. Thus, we might consider infection with influenza itself to be a symptom of a deeper causative pattern. For instance, if we are considering an influenza patient who is a heavy two-pack a day smoker, a course of treatment which concentrates solely on anti-viral medicine could fail at preventing a recurrence of influenza or an even more serious respiratory system complication (e.g. lung cancer, emphysema, heart disease, etc.)

If we consider deeper than simply surface symptoms – those of the influenza virus – and instead investigate the root causes of influenza incidence, a set of co-morbidity factors may emerge, such as suppressed immunity against viruses or behavior patterns which induce diatheses that pre-dispose an individual to infection such as frequently being cold after a good sweat, or experiencing recurrent physical fatigue from work. In our reckoning, the long-term causative patterns pre-disposing this individual to harm not just from influenza, but also from a complex of co-morbid diseases would be termed *pathogenic evils*. We mean *evil* not in the sense of their being normatively good or bad, but rather in the sense that they are a force which may produce systemic harm or wrong, in addition to constituting by themselves some form of systemic harm or wrong. English, unfortunately, lacks a term for a harmful influence on behavior other than "evil." Two-pack-a-day smoking, for instance, enacts a force on patterns of bodily system operation – addiction is a classic example – which is independent of the actual chemical impacts of smoking. Although smoking may have chemically identical effects at the circulatory and respiratory level in a habitual and an occasional smoker, its neurochemical and thus behavioral correlates are radically different in a habitual smoker, developed through repeated smoking. Such a behavioral factor which literally affects how a system or body constitutes itself should be considered, as we have established, as a *force*.

In addition to the forces at work in creating a sickness such as influenza, we can recognize that there are also factors which reduce the risk of contracting influenza; not being an immuno-suppressed individual is most commonly accepted as being at least one of them. Such a factor we would consider to be a form of *anti-pathogenic qi*.

The concept of *anti-pathogenic qi* as we use it describes a form of anti-pathogenic factor which transcends particular disease scenarios (or, in the terminology of risk management, certain event-tree and fault-tree scenarios). If viruses are the root cause of influenza, everyone who contracted would experience the same symptoms. However, diversity of symptom in different individuals is significant. All influenza patients do not present with exactly the same symptoms. Fever, cough, nasal congestion, sniffling, sore throat and headache are all different symptoms of influenza that may or may not occur in a patient infected with influenza, and furthermore are also symptoms of completely unrelated diseases. For instance, fever, sore throat, headache and cough are all symptoms of Ebola as well as influenza. Clinicians in the East as well as the West recognize the basic concept of independence of symptom and cause, attributable to early practitioners of TCM.

While pointing at a virus as causative of influenza is indeed satisfactorily un-criticizable at this time (and thus acceptably valid science), the virus theory of influenza does not, of itself, explain why different symptoms of influenza exhibit themselves in different patients, nor how such symptoms develop. Such variation as may exist in different people's reactions to the influenza virus occur because of how the patient reacts to the presence of the virus; lifestyles and behavior patterns may be one cause of such variation. Elderly and very young individuals, for instance, are known to have more severe reactions to influenza than other populations, but this effect is due to the immune system states of these populations, not because of anything particular about influenza as a virus. Such discrepancy in reactions represents different degrees of disturbance to the dynamic balance of our body systems. (Song 1988 p.181-196; Tang 2004 p.42-43; Zhou 2004 p.121)

Just as influenza requires risk analysis and management at an individual level, to understand the discrepancy in system reactions to change, we must first understand the discrepancy between different systems through how these different systems constitute themselves through the operation of their sub-systems as well as through their daily interactions with their environments. This is what we refer to as *system constitution*. System constitution is composed of the specific characteristics of structural form, functional capability, and (system-wise) psychological performance that reflect the ability of a complex system to stay healthy and maintain themselves across time. Individual systems develop their unique constitutions based on various innate and acquired factors during their progress through stages of conception, growth and aging.

Understanding the constitution of a system reveals its specific formation, capability, and its ability to defend against attack and adapt to changing conditions. Constitution also determines a system's susceptibility to the onset of negative changes (downtrends, reduced performance, catastrophic system failure, etc.), and determines its reaction in such events. As a result, the pathological patterns that we induce may vary according to system constitution and therefore require different treatments for restoration of balance.

Elements of Constitution

Physicist and systems theorist Fritjof Capra proposes in his book *The Web of Life* that living systems possess three similar qualities to engineered systems: the presence of a *pattern of organization* (the configuration of relationships that determines the system's essential characteristics), a *structure* (the physical embodiment of the system's pattern of organization), and a *life process* (the activity involved in the continual embodiment of the system's pattern of organization). (Capra 1996; Kastenberg 2007a) The first two terms have an unfortunate atemporality, however, which makes it insufficient for our change-oriented account. For systems as we conceive of them, *pattern* and *structure* are constantly changing quantities and cannot be treated as static, deterministic theoretical constructs.

The systems paradigm of TCM proposes a set of surprisingly isomorphic terms which map precisely onto Capra's, while embedding the notion of time. Per the TCM paradigm, we propose that the constitution of systems consists of *psychological performance*, *structural form* and *functional capability*.

Psychological performance refers to the patterns of human and organizational behavior, such as organizational culture, morale and competitiveness which occur within a system. The physical structure of a system and its functional capability affect its psychological performance and vice versa. Greater social and cultural environments and the past experiences of the system may also have considerable influence on its psychological performance. Unlike the standard systems-theoretical concept of pattern of organization, psychological performance deals with the notion of organizational behavior across time, not merely as a single essentialist "snapshot" of an organization.

Structural form includes the physical structures, facilities and machinery that are visible in the system and the relationships between each functional subsystem. This corresponds to the systems-theoretical concept of structure. The conventional systems-theoretical notion, however, deals only with the system's initial reification by considering the system's *original* pattern and its effect on subsequent organizational behavior. Since organizations change across, sometimes quite radically, Capra's account that requires constant revision of a system structure concept in order to stay current. In contrast, the TCM notion of *structural form* holds that even though the system's constituent components may change, the relationships between functional sub-systems constitute a persistent structure which constrains and determines functionality across time.

Functional capability is the result of a balanced relationship between subsystem functionality and the circulation of vital substances. The presence of functional capability reflects the harmony and integrity of a complete structural form. This corresponds to Capra's only change-oriented term, *life process*, which is the activity involved in the continual embodiment of the system's pattern of organization.

Formation of Constitution

Constitution forms as the result the interaction of various factors from both inside and outside the system. *Innate factors* provide the basis of the system constitution and it further evolves under the influence of *acquired factors*.

Innate factors are the foundation or “seed” of constitution formation. They are the premise of a strong and healthy system. In a sense, the innate factors impose various constraints at the outset of a system. For example, for a company as a system, the conditions of its parent system which defines the initial capital and resources that are available to the system, the system’s goals, assumption and mission concept which outline the scope of its future development, and the industry sectors or geographical regions where the system located are *innate factors* on the potential competition that the system will be facing.

Acquired factors are those factors that the development of a system depends on for continued self-constitution through healthy operation. In biology, this would correspond to the concept of “nurture” rather than “nature.” Acquired factors refer to those factors which the system does not begin with, but must utilize in order to develop and maintain itself. For instance, a company as a system that fosters a good organizational culture with coherent policies and procedures and employs high-quality human and natural resources generally develops and maintains a strong and healthy constitution. Otherwise, its system constitution may become weak, indicating that the system is prone to failures.

System Health Criteria

Elms (1998) proposes the “healthy-system criteria” for assessing the deterioration of system health. The five criteria Elms suggests are *balance*, *completeness*, *cohesion*, *consistency*, and *discrimination*. A system is perceived as healthy if all of the criteria are fulfilled. Figure 8-5 shows the idea of a healthy system and the five healthy-system criteria.

System dysfunction takes on different forms according to which criteria are not met according to Elms. Specifically, a *balance* failure in the system indicates that some of the elements are too large and others are too small with regard to the system’s purpose; a *completeness* failure illustrates a system in which elements are missing that are essential to its fulfillment; a *cohesion* problem represents that some connections are missing between elements in the system; a *consistency* failure occurs when elements or connections in the system are inconsistent either with each other or with the system's purpose; finally, *discrimination* problems arise primarily in management or information systems when various parts of a system and the way they interrelate are not clear. Elms' view of system health, however, is rather static and does not take into consideration the constant and accelerating changes and fluctuations that complex engineered systems consistently encounter.

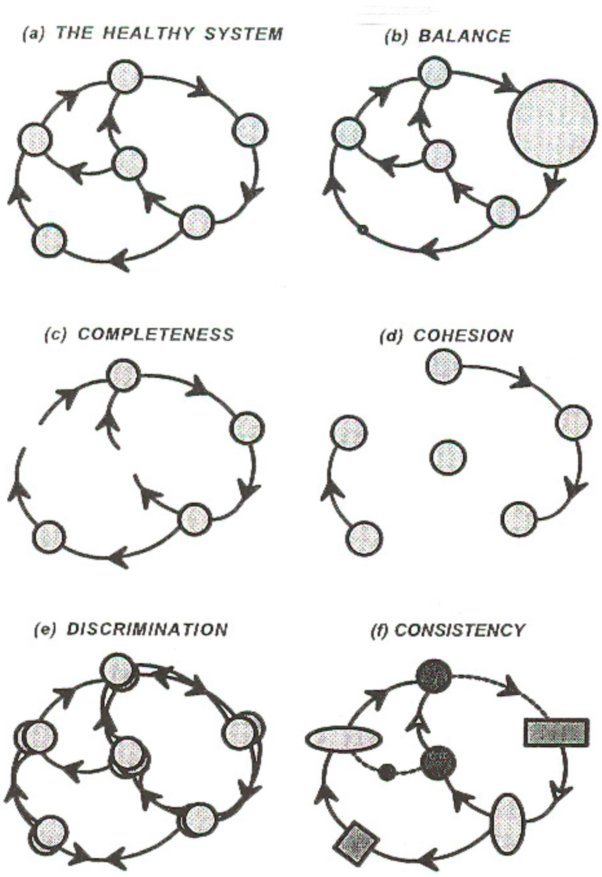


Figure 8-5. Healthy System Criteria
(Elms 1998)

In our view, a system is a collection of functional processes. Influences from in and around the system interact and eventually determine the performance of the system. Therefore, a healthy state of the system represents the emergence of a dynamic balance among these interacting forces. The criteria for judging the health of a system require a comprehensive consideration of the following aspects:

- Structural condition includes the completeness and balance of system form, organizational structure and the quality of each component parts.
- Functional condition includes the functional level of each subsystem and the overall balance and coordination between them.
- Operational capability includes overall performance across time of the system in terms of domain-specific criteria such as productivity, profitability, efficiency, quality, etc.
- Adaptation capability includes adaptability and reaction capability to the changes of natural and social environment
- Psychological stability includes the consideration of human factors such as organizational behavior, organizational change, motivation, leadership, morale, etc.

The Application of the Concept of Constitution

Differences in system constitutions depend on the functionality of subsystems and the sufficiency of vital substances within systems, which reflect the intensity of *anti-pathogenic qi*. Such differences results in different etiologies of disorder, pathological changes and responses to pathogenic evils and treatments. In fact, system constitution greatly influences system susceptibility to certain pathogenic evils and determines whether system health deteriorates or not. Constitution also determines the system's reaction to an attack and the treatment received, in accordance with the concept of customized accidents that we have discussed in Section 7-1-2.

With different constitutions, systems experiencing the same accident may manifest with different pathogenic patterns which require customized treatments for each system. For example, a fire at a chemical plant would be very different from one in a residence in terms of their causality and consequences even though they are both fires. They should be treated in different ways. This is why we claimed that every accident is customized to each specific system.

8-3-2. Vital substances

The human body is a complex organism requiring certain substances to supply its operation. Those substances which functional system activity could not take place without are termed *vital substances*. While the account that TCM provides of bodily systems may not conform to generally accepted scientific theories of how the body works, it is TCM's internal consistency and its theory of the transformation of vital substances which we are concerned with extracting. A project of "recovery" or apology for TCM is not the purpose of this work. A certain level of clinical distance may be required when we begin to speak in terms which may, at first glance, appear to be merely mystical or solipsistic concepts. Although TCM may not have an adequate account of, for instance, cellular structure, osmotic fluid interchange, protein transcription or any of the other fundamental concepts which modern biology takes for granted, an exact correspondence between every TCM concept and a biological phenomenon is not required for TCM to function as an adequate account of system risk.

A truck's engine as a system is a perfect example. Fuel – gasoline or diesel, as the case may be – is required for internal combustion in the engine to start and run. The process of the engine creating motive power for the car is a functional activity that is accomplished by the combustion of fuel inside the engine. The car would stop moving if there was insufficient fuel for the engine. (Tang 2004 p.51-64) In TCM, vital substances include *essence*, *qi*, and *blood*. The prevalence of *essence* determines innate constitutional strength and resistance to external pathogenic evils. Adequate *essence* forms the basis for growth, development and reproduction; deficiency of *essence* can manifest in problems such as developmental delays. Through the function of *zang fu*, essence can be transformed into *qi*. *Essence*, it should be noted, is a very different concept than *qi*; essence is a property of the material from which the system is composed, while *qi* is the definitionally immaterial manifestation of that *essence* (— 1994; Leung et al. 2003; Maciocia 2004; Zhou 2004) "The meaning of '*blood*' in [TCM] is different from its meaning in Western medicine. In [TCM], *blood* is itself a form of *qi*, a very dense and material one, but *qi* nevertheless. Moreover, *blood* is inseparable from *qi* itself as *qi* infuses life into *blood*; without *qi*, *blood* would be an inert fluid." (Maciocia 2005 p.60)

Chinese philosophers and doctors believed human beings *qi* to be the result of the interaction of the *qi* of *Heaven*, or the essential nature of the environment, and *Earth*, the natural environment. This concept stresses the interaction between the human *qi* and natural forces. In TCM, the relationship between human beings and their environment must be taken into account in determining etiology, diagnosis and treatment. Just as *qi* is the substratum of the universe, it is also "the root of a human being." (Maciocia 2005 p.43) The constitution of *qi* itself may range, according to *yin yang* theory, from the subtle and rarefied to the very dense and coarse. Different types of *qi* flow in an orderly way and transform into each other; together, they result in a concept of the body which proponents of the modern-physics paradigm of the human body would find familiar. All the various types of *qi*, however, are ultimately one *qi*, merely manifesting in different forms.

The concept of *qi* as a form of energy in a human body system is explained simply by the physician and philosopher Tang. Tang (2004 p.54-55) explains *qi* with the allegory of a closed circuit of a battery, wires and a light bulb. The battery contains materials that produce electricity. It has a cathode (usually noted as negative, in Chinese "*yin*") and an anode (usually noted as positive, in Chinese "*yang*"), which are analogous to the *yin essence* and *yang essence* of the human body. The glow of the light bulb is the manifestation of the material potency contained in the battery just as the vitality shown in life activities is a manifestation of the health of a person. Electricity is transmitted to the light bulb as current, or a flow of electrical charge. In this manner, the battery transmits the power generated through the interaction of its differentially charged cathode and anode. This power produces different effects depending on what device it is transmitted to. For example, it glows when it is connected to a light bulb; it heats up when it is connected to an electric radiator; it creates mechanical power when it is connected to a motor.

In the TCM model of the human body, *qi* functions similarly to the current in the light bulb. Through the interaction of *yin and yang essences*, certain molecules or micro-substances start to flow, transmitting the power of *yin and yang essences* to the tissues, internal organs and *zang fu* systems which in turn use this power to perform various physiological activities. In a strictly materialist sense, *qi* may even be thought of as the flow of certain physical substances in our body, perhaps even at the molecular level, that is motivated by the interaction of *yin and yang essences*. The power of such flow and the information transferred during the process are of critical importance to the metabolism, growth, development of the human body.

The state of flows and their interactions with the environment that bodily systems deal with signify health. Thus, "balance and harmony of this [flow] means health.

Imbalance or disharmony of the flow of [*qi*] results in illness. This idea illustrates a fundamental Eastern notion [of diseases]: illness resides in the entire person. The diagnostic system in [TCM] consists of an evaluation of the state of balance of [*qi*, or vitality.] This assessment takes place not only in the whole person… but also in each specific organ, function, or [meridian system]. The therapeutic system aims to bring [them] back into balance at all levels of a whole person.” (Sheikh and Sheikh 1989 p.68-69)

These vital substances are, on the one hand, the material basis of the body’s functional structure (i.e., *zang fu* organs) and thus essential ingredients for maintaining its functional activities; on the other hand, they are the products of those functional activities in life. In a sense, the relationship between vital substances and the functional structure is similar to that of *yin* and *yang*, one of mutually required opposition. Life processes in TCM are constant transformations between vital substances and functional structures. (Lu and Lui 1998 p.98)

The concept of vital substances as we use them is not similar to substances as discussed in Western medicine. The highly developed ontological constructs of chemistry, biochemistry, anatomy, and physiology that form the basis for Western medicine are of little concern in TCM. Vital substances are an understanding based on the observed functionality of a modeling concept in various activities of life. “Substances” that relate to certain physiological function are studied as a single vital substance. In other words, each of the vital substances usually consists of various different chemical and biochemical substances. The relationships between the sufficiency of each vital substance and the various activities in life are organized to arrive at an accurate perception of *what is going on* in our body systems. (Kaptchuk 2000; Tang 2004)

Figure 8-6 shows the formation of vital substance and their relations with each other and the *zang fu* organs. The *zang fu* organs here are not the typical Western concept of internal organs which sees each organ only in its material-anatomical aspect, while TCM sees each *zang fu* organ as a complex combination of functional system encompass its anatomical entity and its functional activities. (Maciocia 2005 p.97) *Essence* determines basic constitutional make-up, strength and resistance to *pathogenic evils*. In TCM’s semi-mystical account of human character, essence is formed at conception when the *yin essence* of mother blends with the *yang essence* of father.

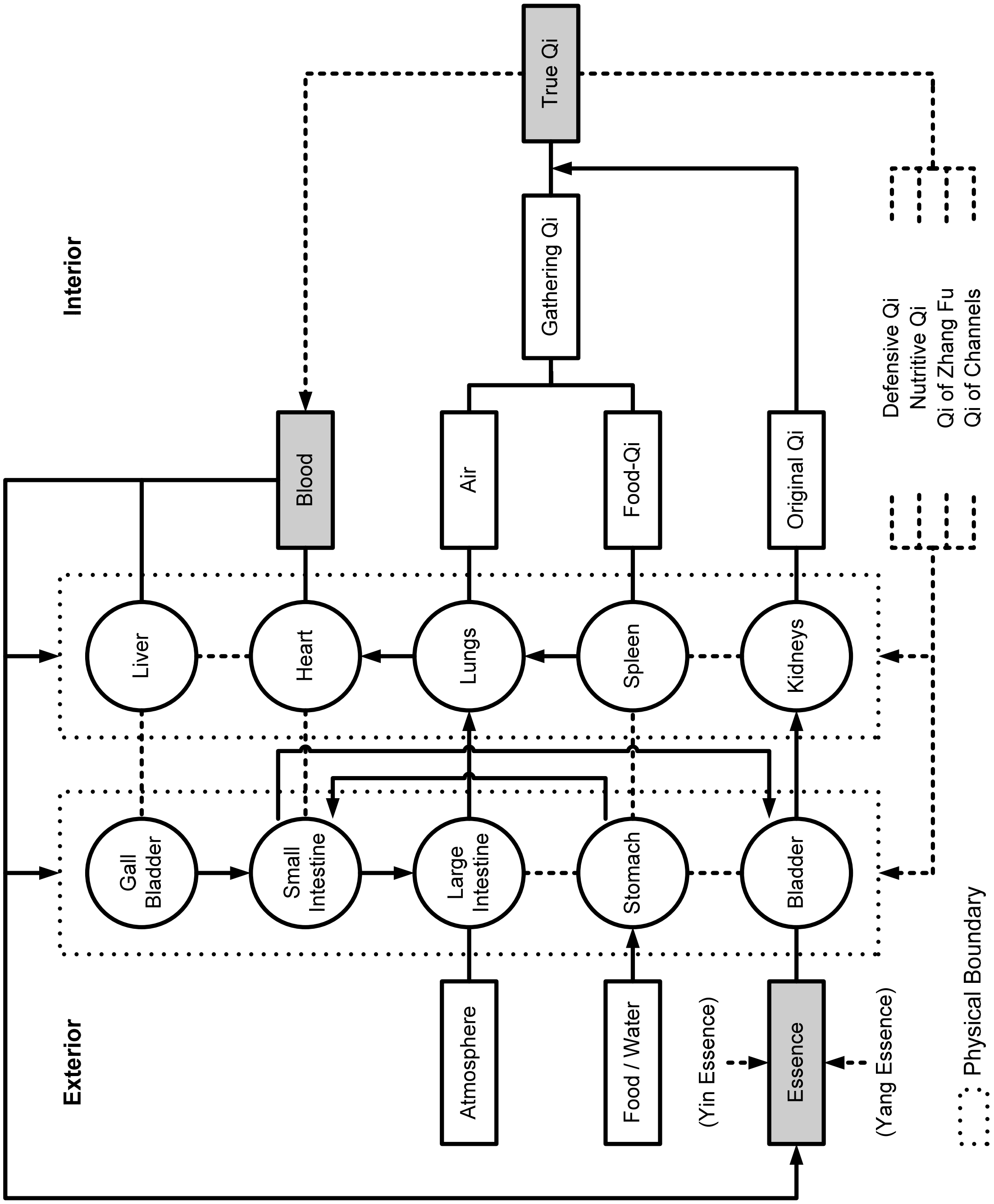


Figure 8-6. Transformation of Vital Substances in TCM

TCM's account of the transformations and flows that vital substances encounter in a bodily system is surprisingly complex. There are multiple forms of *qi*. For instance, *original qi* is a dynamic and rarefied form of *essence* having its transformation through the "kidneys." Food on entering the "stomach" is first "rotted and ripened," and then is transformed into *food qi* by the "spleen." *Food qi* then goes to the "lungs" where, combining with *air*, it forms *gathering qi*.

The exact forms of these transformations are not as noteworthy as their structure and the meanings embedded therein. Since *food qi* is extracted from food and is the basis for the production of all *qi* and "blood," it is easy to see what importance TCM attributes to the quantity and quality of the intake of system sustenance. *Gathering qi* is transformed into *true qi* through the transformative process of *original qi* through the catalytic effect provided by the lungs. True *qi* is the final stage in the process of refinement and transformation of *qi*. *Qi* in various forms, such as *defensive qi*, *nutritive qi*, and *qi* of *zang fu* and the meridian channels, circulate in the channels mapped by the meridian system and nourishes structures of the body identified in *zang fu*. Finally, *blood* originates through the transformation of *food qi*; the "spleen" sends *food qi* upward to the "lungs," and through the pushing action of "lung" *qi* this is sent to the "heart," where it is transformed into *blood*. The *blood* is then propelled through the body by *qi*. (Kaptchuk 2000; Maciocia 2005; Tang 2004) We will explore more of the import of these transformations in the case study.

8-3-3. Human Body Structure

An engineered system is a complex organism like the human body. Likewise, to ensure the stability and prosperity of the system, besides dealing with the various influences from the environment, we need also to maintain a state of balanced operation within the system. This requirement of balanced operation makes the varied subsystems of an engineered system similar to the different *zang fu* sub-systems of a human body. According to TCM, if the *zang fu* organs hold together and operate in harmony, the system as a whole is able to accomplish complicated activities in day-to-day life. If each *zang fu* structure operates in its own way without coordinating with other structures, the system as a whole will eventually break down. Complex engineered systems follow this rule almost without exception; only if all subsystems work together in a coherent fashion can the whole system keep developing and growing. (Tang 2004 p.284)

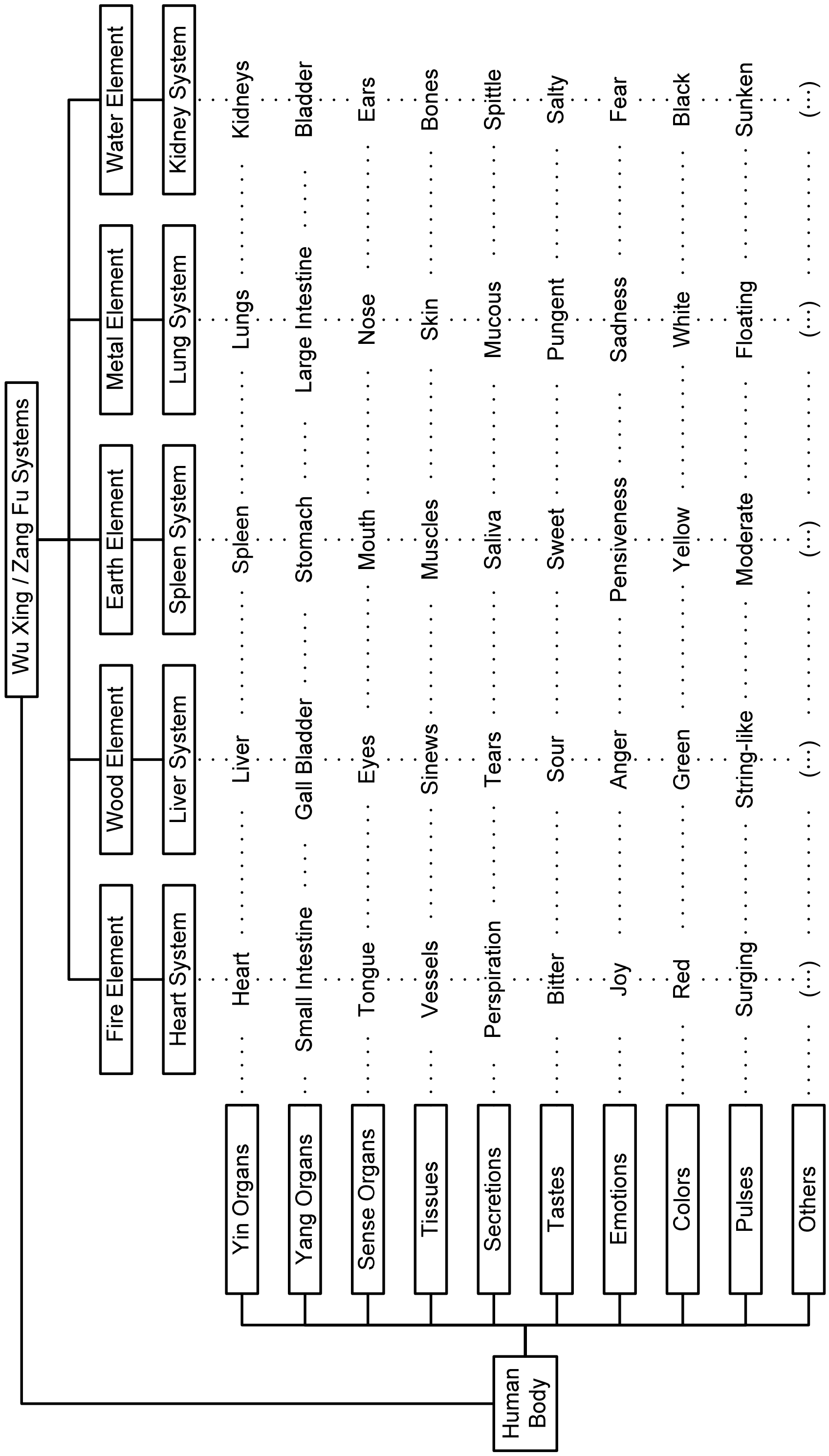
The level of *zang fu* functionality is mainly determined by the sufficiency of flow of *essence*, *q*i, *blood* and vital substances. A *zang fu* characterization of the human body in fact resembles the internal combustion engine of our truck. The body's vital substances can be compared to the fuel in the truck's fuel tank. Only with sufficient fuel does the engine deliver a sufficient level of performance. However, insufficient fuel delivery to the truck does not necessarily indicate a problem with one particular component; a fuel line, an engine part, or a fuel tank component, for instance, may all be to blame. Similarly, in a human system, different vital substances are stored in different *zang fu*; therefore, the insufficiency of a certain vital substance will result in the functional deterioration of its corresponding *zang fu*, although that insufficiency does not necessarily indicate deterioration within only one *zang fu* sub-system. Just as we would attempt to resolve the problems of fuel delivery in our simplified engineered system, the truck, through a consideration of the entire system of fuel flows, so too in *zang fu* treatment such functional deterioration would aim at improving the overall function of, or tonifying, the insufficiency of vital substance identified according to the patient's presentation. (Tang 2004 p.308-309)

Initially, medicine and *wu xing* concepts were separate; Chinese doctors, early on, started to develop a knowledge base of symptoms and disorders of the organs separate from any notion of philosophy. However, lacking a system to organize their knowledge, *wu xing* theory became useful as an externality, onto which organ interactions were mapped. The mapping system changed over the years; in the beginning there were two mappings, first a locational mapping siting material resonances in bodily organs, then a more modern mapping addressing the functional relationships between each *zang fu* sub-systems. The transition is that the elemental characteristics (e.g. fire going up, water going down) are mapped onto functionalities (e.g. fire going up is mapped to the heart, water going down to kidneys).

Typically, *wu xing* is based on fixed relationships amongst the five elements (creating, restraining, counteracting cycles). The Chinese medical community gradually adapted this theory to developments and innovations in medical practice, culminating in the *Qing* dynasty's formalization of Chinese medicine in the 9th century A.D. Today, *wu xing* is recognized as being a mechanistic theory based on fixed one-to-one correspondence relationships of generation and destruction, etc., arranged in a cycle. This critique led to the development of *zang fu* theory, a functional revision of *wu xing*, which deals with how vital substances circulate within each organ, abstracting out the organ correspondences to functional relationships of organ systems. This does not take place as a paradigm shift, but rather as a system of gradual change; the theories are not opposed to each other.

Wu xing is not a perfect system for mapping engineered systems. Put in terms of Gödel's incompleteness theorem, it is almost perfectly complete, but as a result, insufficiently representative. *Zang fu* complexifies and adds on to *wu xing* organs-elements symbolic system, adding important concepts like channels of flow (the meridian system), the importance of the flows of vital substances, and cycles of excess and deficiency. In *zang fu* theory (*yang*), the flow of vital substances (*yin*) determines the functional strength of organ systems.

The system of material correspondences is the key to understanding *wu xing* theory and its application in *zang fu* as shown in Figure 8-7. A standard feature of TCM accounts of health since their inception, *wu xing* is the system of material correspondences that categorizes objects and phenomena within microcosms and macrocosms into five distinct qualities characterized by the five elements. Ancient Chinese philosophers believed in a concept of transparency corresponding roughly to the notion of linguistic transparency, or the idea that words re-iterate their meanings (suggesting, for instance, that there is "blueness" to the word "blue" that extends across languages). For Chinese philosophy, things evoke change in other things not because of an external cause, but "because they 'connect' or 'elicit' what is already a 'disposition' in things." (Kaptchuk 2000 p.44) In other words, change reflects the internal conditions of the things being changed, a concept often translated as a kind of *resonance*. Components of the human body, for TCM, display resonances similar to elements of nature. Although seemingly arbitrary, there is indeed reason to some of these correspondences which have borne out verification through practice, for instance those cited by Maciocia (2005 p.25). However, the veracity of these correspondences is, again, not our primary concern; what we wish to extract from this system of correspondences is the relationship between correspondences.



	Fire Element	Wood Element	Earth Element	Metal Element	Water Element
	Heart System	Liver System	Spleen System	Lung System	Kidney System
Yin Organs	Heart	Liver	Spleen	Lungs	Kidneys
Yang Organs	Small Intestine	Gall Bladder	Stomach	Large Intestine	Bladder
Sense Organs	Tongue	Eyes	Mouth	Nose	Ears
Tissues	Vessels	Sinews	Muscles	Skin	Bones
Secretions	Perspiration	Tears	Saliva	Mucous	Spittle
Tastes	Bitter	Sour	Sweet	Pungent	Salty
Emotions	Joy	Anger	Pensiveness	Sadness	Fear
Colors	Red	Green	Yellow	White	Black
Pulses	Surging	String-like	Moderate	Floating	Sunken
Others	(…)	(…)	(…)	(…)	(…)

Figure 8-7. Correspondence of Wu Xing / Zang Fu Systems
Adapted from (Zhou 2004)

Physiologically, TCM utilizes the *wu xing* theory of material correspondences as a modeling rule to draw relationships among *zang fu* structures and the correspondences between them and other manifestations in behavior and pattern, as shown in Figure 8-8. On TCM's account, the formation process of vital substances, meridian systems, the patient's lifestyle, diet, and various habits in life are all related in a series of bi-directional *ying yang* relationships that together affect the human system as a whole. Such a complex system is developed from this that it is easy for an objective observer to agree with Wu's view (Wu 2005; Wu 2008) that the systems concepts of *wu xing* and *zang fu* in TCM are an ancient form of systems theory.

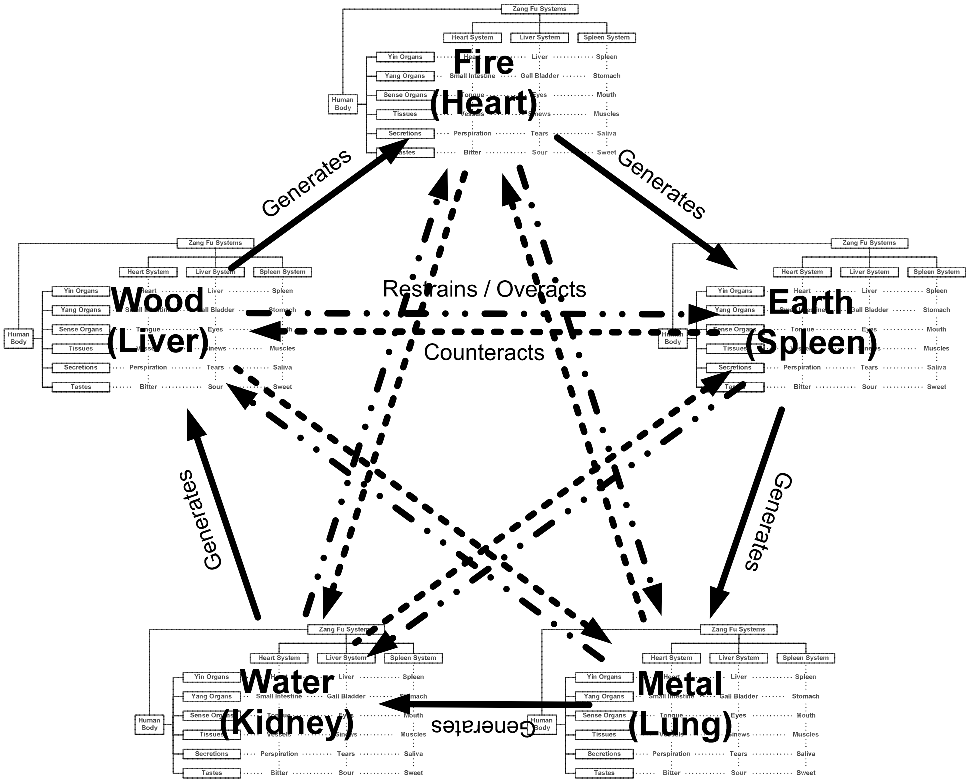


Figure 8-8. Human Body System Structure

Zang Fu Systems

Zang fu is not only about the function of *zang* or *fu*, it's about the relationships between *zang* (five yang organs) and *fu* (the five yin organs) and different zang's and different *fu*'s, more importantly, their relationships with the flow and circulation of the vital substances. (Zhou 2004 p.47) We are not interested in the physical structure of such as the kidneys in anatomy; we are interested, in TCM, with the functionality that includes the actual organ of kidneys. (Tang 2004 p.66)

Lacking any way of actually looking inside the body, a basic concept of TCM is that everything inside the body is interconnected and dysfunctions would appear on the surface of the body. Exterior appearances connote interior syndromes. (Tang 2004 p.67)

Initially, TCM organizes relationships between *zang fu* entities using *wu xing*. Similar to *wu xing*, *zang fu* is interconnected and has generating/restraining cycles, similar to what System Dynamics says with regard to positive/negative feedback loops. (Tang 2004 p.27) This relationship between *zang fu* entities comprises the body as a whole. Subsystem failure of any one portion leads to chain effects on the entire system; once one aspect of dynamic balance is broken, the entire system fails. (Tang 2004 p.32)

Chapter 9. TCM Approaches to Healing

Chinese medicine is a unique medical system. In TCM, a human body is deemed as an organic unity in which the components of the body are inseparable in structure and supplement each other in physiology, and therefore affect each other in pathologic changes. TCM also believes that nature is an organic unity in which everything is interconnected and interrelated. As an inseparable part of nature, the human body depends on nature for its growth and has developed the ability to adapt itself to nature.

TCM provides a comprehensive way of exploring complex human body systems that we have explored already—through *yin yang* and *wu xing* concepts, complex phenomena are simplified and organized into an interrelated unity. And, as discussed, an in-depth understanding of the theoretical framework of the Chinese medical system including its philosophical underpinnings is essential in order for TCM to be practiced effectively. In order to arrive at a diagnosis, the practitioner must be able to systematically collect and analyze the symptoms and signs according to TCM theories. In this system, these symptoms and signs do not just connote, but rather express underlying conditions of the body/system (Kuriyama 1999 p.271) These theories provide a framework in which to understand the origin of disease (etiology) and what happens in the body during the course of the disease (pathology), and are used to guide treatment.

9-1. Foundations of Diagnostics in TCM

Rather than a Western paradigm of systems and bodies that sees health as simply the absence of symptoms and disease, in TCM and our account of systems, health is a state of dynamic equilibrium. We are not interested in a precise epistemological system that reduces risks and consequences down to their finest details; rather, the approach is practical, moving from perception and study of disharmony to an "understanding of harmony." (Kaptchuk 2000 p.75-76)

9-1-1. Etiology: Origins of Disease

Etiology, or the causation of a disease or system failure, is traditionally diagnosed in a matter that treats symptoms, and not underlying causation, as a result of the traditional focus on particular accidents or diseases, rather than on whole-system function. Our account of system etiology will first set forth the notions of *ben/biao* (root/manifestation) dichotomy, then move to a general consideration of the origins of disorders and functional deterioration in bodies and systems.

The Root (Ben) and the Manifestation (Biao)

The *root* and *manifestation* metaphor can be compared to a tree, its root being the *root* (*ben*) and its branches the *manifestation* (*biao*) as shown in Figure 9-1. Maciocia (2005 p.1116) observes that *root* and *manifestation* acquire different meanings in different contexts:

- In the context of anti-pathogenic qi and pathogenic evils: the root is the anti-pathogenic qi and the manifestation is the pathogenic evils.
- In the context of pathology: the root is the functional disorders and manifestation is the symptoms and clinical manifestations.
- In the context of patterns: the original pattern is the root and the one originating from it is the manifestation.
- In the context of onset of disease: the root is the initial condition and the manifestation is the later condition.
- In the context of duration of the disease: the root is a chronic disease and the manifestation is an acute disease.

Maciocia (2005 p.1116-1118) further explains the *root* and *manifestation* and emphasizes the importance of the connection between the two. He wrote, “They are not separate entities, but two aspects of a contradiction [similar to the relationship between *yin* (*root*) and *yang* (*manifestation*)]. As their names suggest, they are related to one another, just as the roots of a tree are connected to its branches, the former under the ground and invisible, and the latter above the ground and visible. The same relationship exists between the root of a disease and its clinical manifestations: they are indissolubly related and they form two aspects of the same entity. There is no separation between the two. For this reason, it is not entirely correct to translate the *root* as ‘causes’ of the branches, but the two together forms the entity of a tree (i.e. the disease or the accident when considering complex engineered systems).” The art of diagnosis consists precisely in identifying the *root* by looking at the *manifestation*. It is only when we master the art of pattern differentiation that we can identify the *root* by looking at the pattern which is woven by the *manifestation*, much as a botanist can identify a tree by looking at its leaves.

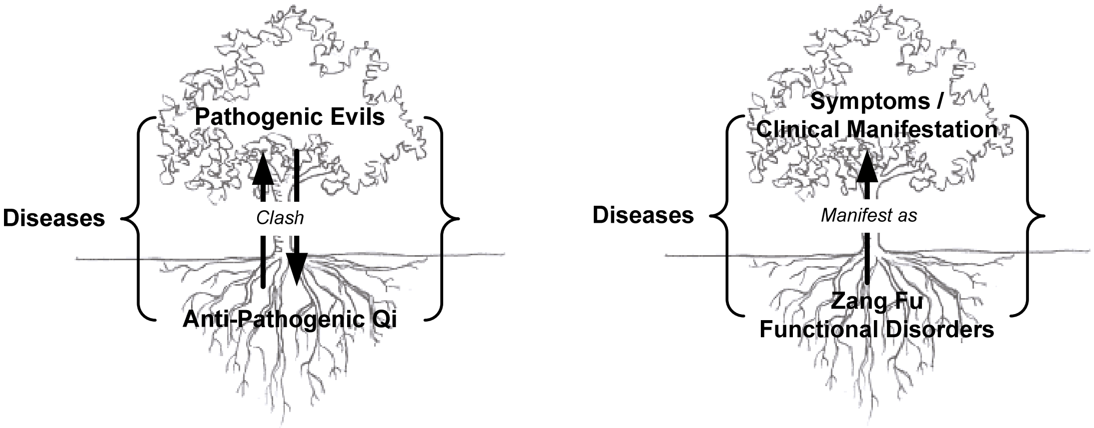


Figure 9-1. Different Meanings of Root and Manifestation

Origins of Disorder

Concepts of TCM represent a different way of detecting and organizing *ben/biao* information about disease. In TCM and Chinese philosophy, the relationships or the pattern of events are of greater concern than “cause and effect” is. The idea of how a disease begins is very different from the TCM point of view. In fact, pathological factors that could be described in the Western vocabulary as “causes” are not conceived as causes[9] by the Chinese people. (Kaptchuk 2000 p.143-144) In Chinese thinking about patterns, these factors are part of the bigger picture of a disease – the pattern, which organizes symptoms and clinical manifestations to arrive at an accurate perception of “what is going on” – the *origins* , *locations*, *characters*, and *trends* of the disorders[10].

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[9] In this research, they are called ‘*origins* of disorder.’

[10] *Locations, characters, and trends* will be discussed in Section 9-1-2.

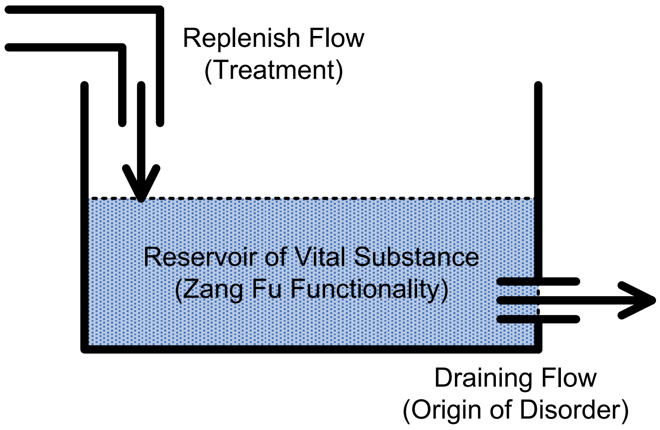

Figure 9-2. Concept of Functional Disorder

Identifying the origins of disorder is important because only by doing that can we advise the patient on how to avoid them, minimize them or prevent their reoccurrence. Similar to the hydraulic metaphor discussed in Section 6-3-2, if we give a treatment without addressing the origins of disorders, it would be like pouring water into the reservoir with a leak at the bottom as shown in Figure 9-2 (Maciocia 2005 p.237), so too with vital substances and sub-systems. Each *zang fu* sub-systems constitute a reservoir of vital substances. Deficiency of vital substance affects this reservoir functionality.

For the purposes of system diagnosis and treatment, there are two sets of systems which chiefly concern us: 1) Defense systems responsible for prevention and palliation of external attacks, such as bodily immune systems; 2) Organizational ideologies, engineered system reflex arcs and adjustment systems, which coordinate internal system operations. (Tang 2004 p.37-40) Together, these constitute the manifestation of *anti-pathogenic qi*, maintaining the internal balance of the system or body. When this *qi* circulates normally, this is a necessary but not sufficient condition for the system to be healthy, the other half of the sufficiency consideration being *pathogenic evils*.

Those factors that cause internal imbalance of the body are referred to as *pathogenic evils* in TCM. Both *anti-pathogenic qi* and *pathogenic evils* are forces that cause changes to systems and bodies. That means the occurrence of any disease depends largely on the relative strength between *anti-pathogenic qi* and *pathogenic evils*. If the *anti-pathogenic qi* is stronger than *pathogenic evils*, disease does not result; if the *pathogenic evils* are stronger than *anti-pathogenic qi*, disease results. There are two common situations when *pathogenic evils* are stronger than *anti-pathogenic qi*: 1) an excess of *pathogenic evils* exceeding the defense and adjustment abilities that normal *anti-pathogenic qi* can provide; 2) a deficiency of *anti-pathogenic qi* for withstanding the attacks of *pathogenic evils*. (Tang 2004 p.37-40)

Pathogenic evils are classified into two broad categories as shown in Figure 9-3: 1) *External evils*, which include influences to the human body from various climate factors, weather changes, pernicious microorganisms and *miscellaneous causes*, such as trauma, parasites, toxication; 2) *Internal evils*, which include effects to the internal balance from various emotional changes, lifestyles and diet patterns, and hyper- or hypo-functional failures of *zang fu* systems. One special category within the *internal evils* is the *intermediary causes* such as *qi* stagnation, *blood* stasis and body fluids accumulation. They are characterized as "intermediary" because these evils are a result of certain functional disorders and may cause further damages to the body. (Tang 2004 p.37-40) A simplified etiological chart is shown in Figure 9-3:

When the strength of those *pathogenic evils* exceeds the defense and adjustment capabilities of a normal body, the dynamic balance within the body is broken and the result is various diseases. For example, although we are safe from the exposure to microorganisms most of the time, some of them are more harmful and pernicious; they are able to infect a person with normal health condition and cause various diseases. Another example is that usually normal seasonal changes are not an impact to the human body, but the abnormal weather or temperature fluctuation may cause diseases. A normal and regular diet can provide necessary nutrients to our body, but if we over drink or eat, the overly ingested food will damage our digestive function and lead to diseases. They are all because the excess *pathogenic evils* exceed the defense and adjustment capabilities of the *anti-pathogenic qi*. On the contrary, we get sick because of some less harmful bacteria, viruses to which we are exposed all the time when we are weak/fatigued or catch a cold. Indeed, the decline of our own defense and adjustment abilities, which is the consumption of *anti-pathogenic qi*, is also an important pathological factor. (Tang 2004 p.37-40)

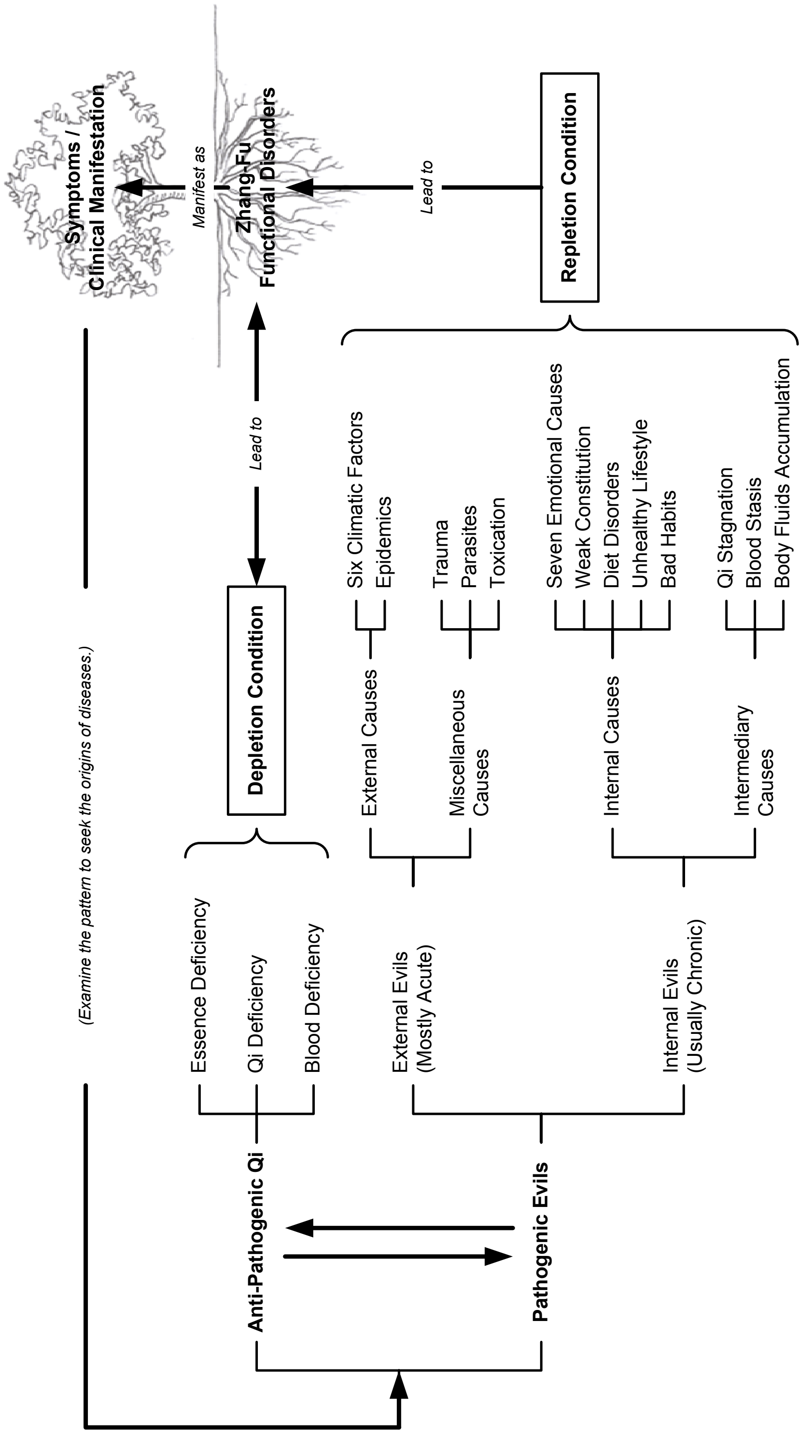

Figure 9-3. Origins of Disorder in TCM
Adapted from (Maciocia 2005)

With the unique perception on how diseases are developed, TCM defines the nature of disease as the broken dynamic balance of the body. And through the study of the symptoms and clinical manifestations that appear in our body after the attack of various *pathogenic evils*, TCM is able to infer the extent and degree of damage to the balance of our body and based on such inference to formulate effective means of treatment, i.e., to restore the broken dynamic balance of the body, without having to know the type and attack pattern of the micro-organisms. (Tang 2004 p.50)

When used as a diagnostic methodology, the TCM practitioner classifies the disorder according to the type of dysfunction, classifies these symptoms into patterns, and then issues appropriate treatment for the pattern, tailored to the patient’s individual constitution and life circumstances.

9-1-2. Pathology: Pattern Differentiation

Where Western traditions have well-established studies of particular diseases and accidents, TCM and the alternative risk-analytical approach we propose are concerned primarily with *patterns*.

The concept of “Bianzheng Lunzhi”

Bianzheng Lunzhi, or *pattern differentiation*, is one of the fundamental characteristics of the theoretical system of Chinese medicine. It is “a fundamental principle of discriminating and treating disease,” that constitutes a “special method of researching into and engaging with disease.” (Scheid 2002 p.202) Patterns exist at the boundary between disease/accident and patient/system. Thus, we are interested in “the unfolding of process rather than the manipulation of bounded structures.” (Scheid 2002 p.201)

As described in Section 3-3-4, *patterns* (*zheng*) are the pivot of Chinese medical practice and *the Eight Principles* (*ba gang*) is the basic matrix of Chinese medical diagnostics. “This was intended to mean that the principles they embody can be found in various manifestations in all the specific methods of pattern differentiation and treatment determination… [The Eight Principles] are the epitomization of the diverse principles of pattern differentiation with regard to which the other principles of pattern differentiation assume a subordinate relationship. In clinical practice, however, all the methods of pattern differentiation…can be used individually or in combination with one another without needing to reduce them to the [Eight Principles].” (Scheid 2002 p.277)

Holland (1995 p.37) gives a good example when explaining mechanism of complex systems, which we believe to pertain to TCM’s concept of differentiating patterns of disharmony rather than causes of disease. As he puts it, “If I encounter ‘a flat tire while driving a red Saab on the expressway,’ I immediately come up with a set of plausible actions even though I have never encountered this situation before. I cannot have a prepared list of rules for all possible situations for the same reason that the immune system cannot keep a list of all possible invaders. So I decompose the situation, evoking rules that deal with ‘expressways,’ ‘cars,’ ‘tires’ and so on, from my repertoire of everyday building blocks. By now each of these building blocks has been practiced and refined in dozens or hundreds of situations. When a new situation is encountered, I combine relevant, tested building block to model the situation in a way that suggests appropriate actions and consequences.”

From this synthetic process emerges the concept of the *model*. “Understanding the origin of these regularities [patterns], and relating them to one another, offers our best hope of comprehending emergent phenomena [such as a catastrophe or functional deterioration] in complex systems. The crucial step is to extract the regularities [patterns] from incidental and irrelevant details [symptoms, manifestations, warning signs, events, etc.]. For example, we may use an idealized form of billiards to gain insights into the way colliding molecules in a gas give rise to measurable regularities such as temperature and pressure [in our case, Newton’s Laws of Motion and System Dynamics modeling]. Or we may use a mathematical description of poker to discern the complexities of political negotiations. This process is called *modeling*.” (Holland 1998 p.4) We believe that TCM’s pattern differentiation is a process of mapping observed symptoms and manifestations onto its established human body model and from which, trying to understand the underlying disorders in the actual body.

Systems of Pattern Differentiation

In TCM, pattern differentiation indicates the process of gaining “a complex, subtle perception that leads to an understanding of the physiological events taking place in the patient’s body.” (Kaptchuk 2000 p.216) During the course of diagnosis, the physician simultaneously collects, interprets, and organizes available symptoms and clinical manifestations in order to understand how they arise and how they interact with each other and identify the prevailing functional disorder. This is the essence of TCM diagnosis and pathology. Since the pattern itself, the character and nature of the functional disorder, gives an indication as to the principle and strategy of remedy. Differentiating a pattern as it is developing with only a few symptoms and clinical manifestations releases the full potential of TCM in the treatment and prevention of disease. (Maciocia 2005 p.417,458-459)

The Eight Principles are the foundation for all the methods of pattern differentiation. The construct of the Eight Principles allows the physician to recognize the *origins*, *locations*, *characters* and *trends* of the patient's functional disorders that may affect their health conditions. It enables the physician to differentiate patterns of the broadest, most general type. "Occasionally, these are all that are needed to proceed with treatment. In most cases, however, further refinement of the pattern is required in order to discover the unique features of a particular disorder and so determine an appropriate treatment." (Kaptchuk 2000 p.217) This refinement is achieved by using the Eight Principles as a basic matrix and also emphasizing signs that relate to the vital substances, the *pathogenic evils*, or the *zang fu* sub-systems.

Figure 9-4 shows various pattern differentiation methods and their relationships with the Eight Principles. Specifically, the Eight Principals are composed of four pairs of opposite qualities: *yin/yang*, *interior/exterior*, *cold/hot*, and *depletion/repletion*. The structure of the Eight Principles is actually a subdivision of *yin* and *yang* into six subcategories. This division allows a clearer, more systematic approach to the practice of *yin yang* theory in TCM. Here, *yin* and *yang* retain their primacy because of their broad, all-encompassing nature, while the other six patterns are finally subsumed in *yin yang* patterns. (Kaptchuk 2000 p.218)

Although TCM's medical tradition is rich with patterns for use in diagnosing system health, for reasons of brevity and simplicity we will examine only *yin/yang* and *depletion/repletion* patterns in this work.

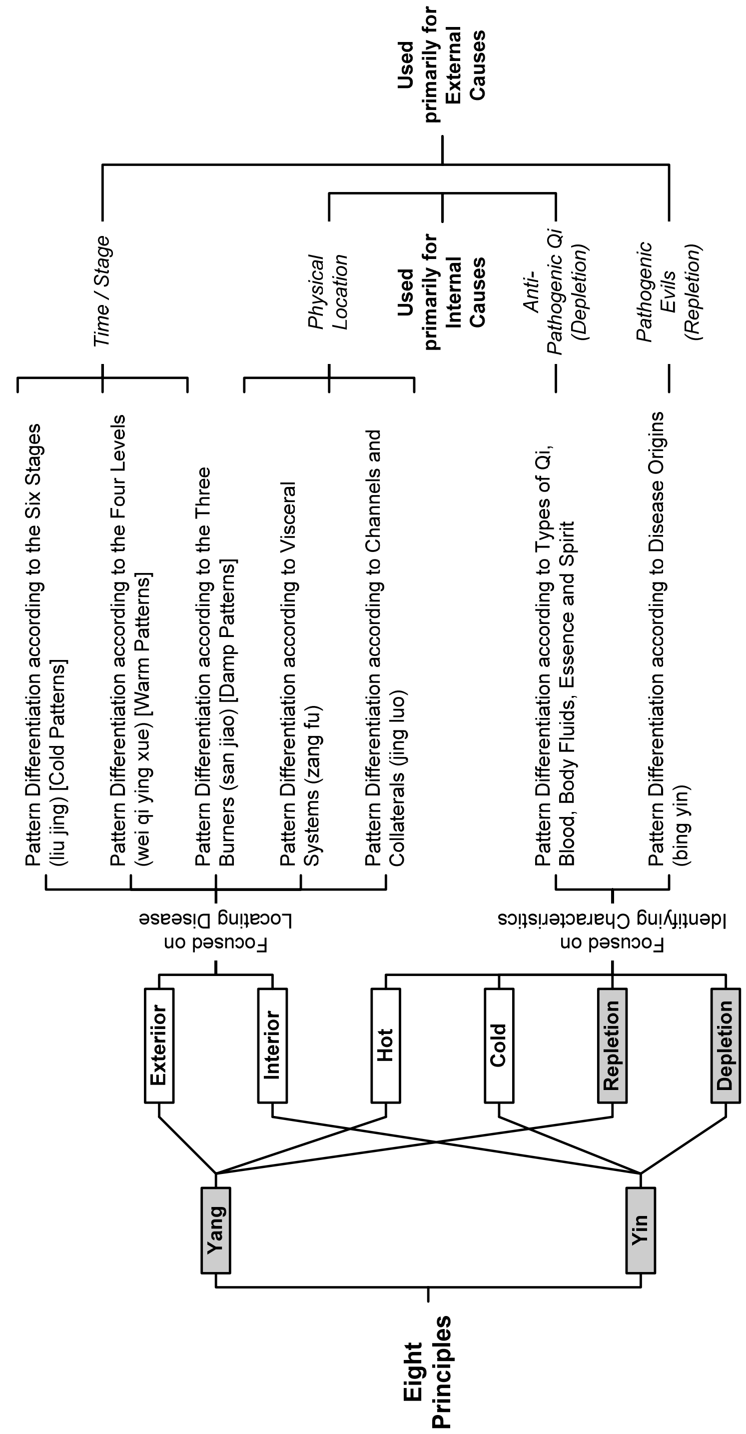

Figure 9-4. Systems of Pattern Differentiation
Adapted from (Chen 2004)

TCM defines patterns with four distinct characteristics of functional disorder—*origins*, *locations*, *characters*, and *trends*. *Origins* have been discussed in Section 9-1-1. *Locations* specify the regions within the human body where pathological changes are presented and defined via *zang fu* functional subsystems and vital substances. *Characters* refer both to the key symptoms and clinical manifestation that define a given pattern and to the nature of the pathology they represent. *Trends* indicate the developing timeline and stages of the patient's health condition, as well as the analysis of pathomechanism and potential pathological changes according to *wu xing* interrelationships. Various pattern differentiation methods are proposed over the history of TCM trying to characterize the four characteristics of a pattern and help physicians understand the underlying functional disorders of their patients.

Yin/Yang Imbalance Patterns

In TCM, health is achieved, and disease prevented, by maintaining the body in a "balanced state." This idea was applied to both individuals and society at large. The concept behind such idea represents a radically different approach to health and disease. TCM was also one of the first to grasp the potential within the broader field of preventative medicine.

The state of the body is determined by the balance of *yin* and *yang* within it. Each of the *zang fu* organs of the body has an element of *yin* and *yang*, although one organ may be more *yang* in its nature, while the other is more *yin*. When the healthy body is examined as a complete functioning system the *yin* and *yang* properties within it are in a dynamic balance. The balance of *yin* and *yang* is not always exact; a person's mood may be more fiery, or *yang*, whilst at other times he may be quieter and therefore more *yin*. Normally the balance changes from time to time, but if the balance is permanently disordered, for instance if *yin* consistently outweighs *yang*, then we may state that the patient or system is unhealthy and disease may occur.

According to *yin yang* theory, *yin* and *yang* stand for two opposite states in the process of change and transformation of all things in the universe. When everything goes through phases of a cycle and, in doing so, its form also changes. For example, the water in lakes and seas heats up during the day and is transformed into vapor. As the air cools down in the evening, vapor condenses into water again. Matter can acquire different states of density. For example, a table is a dense form of matter and if it is burned this matter changes into heat and light, less dense forms of matter. From this point of view, yang symbolizes the more immaterial, rarefied states of matter, whereas yin symbolizes the more material, dense states of matter. (Maciocia 2005 p.6)

Consider the vital substances and the functional activities in complex engineered systems. *Yin* and *yang* represent each of them respectively. In order to accomplish all functional activities that sustain the system development, vital substances are necessary to serve as the material basis for the functional activities; in turn, various functional activities results in the continuous creation of vital substances. Thus, although the vital substances (*yin*) and the functional activities (*yang*) are opposite states of matter aggregation as explained in the previous paragraph, they are also interdependent: one cannot exist without the other. They are in a constant state of dynamic balance, which is maintained by a continuous adjustment of their relative levels. When either the vital substances or the functional activities are out of balance, each necessarily affects the other and by changing their proportion they achieve a new balance. Under certain circumstances, they actually transform into each other during the process of system operation. (Zhou 2004 p.26)

Besides the normal state of balance of *yin* and *yang*, pathologically, there are four possible state of imbalance:

1. When *yin* is preponderant, it induces a decrease of *yang* (i.e. the excess of *yin* consumes *yang*).
2. When *yang* is preponderant, it induces a decrease of *yin* (i.e. the excess of *yang* consumes *yin*).
3. When *yin* is weak, *yang* is in apparent excess,
4. When *yang* is weak, *yin* is in apparent excess.

These are a matter of appearance, as excess occurs only in relation to the deficient quality, not as an absolute. These four situations can be represented by the diagrams in figure 9-5. Although the diagram of a normal, balanced state of *yin* and *yang* shows equal proportion of the two qualities, this should not be interpreted literally: the balance is achieved with different dynamic proportions of *yin* and *yang*.

It is important to see the difference between excess of *yin* and deficiency of *yang*; these may appear the same, but they are not. It is a question of what is primary and what is secondary. In case of excess of *yin*, this is primary and, as a consequence, the excess of *yin* consumes the *yang*. In case of deficiency of *yang*, this is primary and, as a consequence, *yin* is in apparent excess. It looks as if it is in excess, but it appears so only relative to the weakness of *yang*. The same applies to excess of *yang* and deficiency of *yin*. (Maciocia 2005 p.7-8)

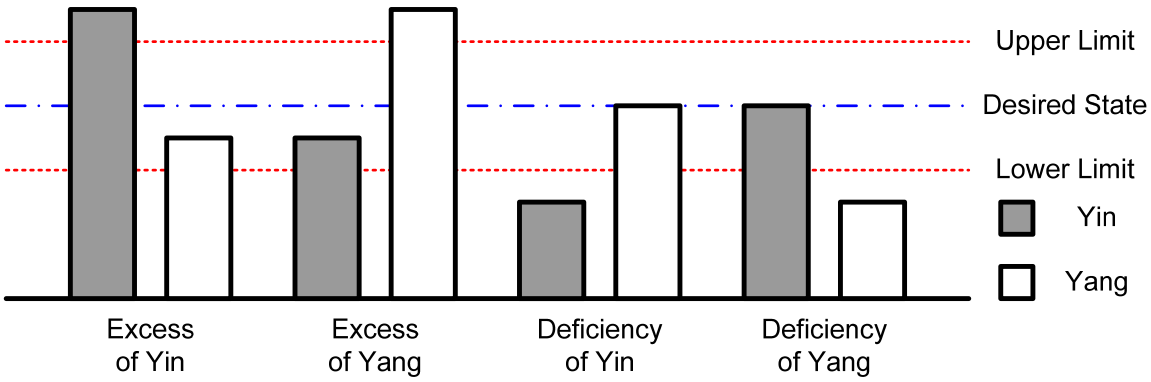

Figure 9-5. Yin / Yang Imbalance Patterns

Depletion and Repletion Patterns

As previously explained, dynamic balance is often based on two factors: vital substances and the functional condition of *zang fu* sub-systems. Vital substances are those such as *essence*, *qi*, or *blood* which are the energy and power sources of all sorts of life activities. If vital substances are sufficient, the function of *zang fu* sub-systems should be strong, and life activities will be ensured. Moreover, the functional condition of *zang fu* sub-systems is important. When *zang fu* functions are strong and coordinate well between each other, the production of vital substances and the operation of the human body should be sustained. However, when vital substances are deficient or the functioning of *zang fu* is disturbed, dynamic balance within the body is broken and various diseases emerge.

Using vital substance flows as a basis, we can divide the nature of diseases into two broad categories: 1) diseases with a *depletion* pattern which are caused by the deficiency of vital substances; 2) diseases with a *repletion* pattern (because the vital substances are sufficient in this case) which are caused by excess *pathogenic evils* that induce *zang fu* functional disorders. These two categories of diseases are formed with distinct causes and result in different effects to internal dynamic balance. For example, diseases with a *depletion* pattern are often chronic while diseases with a *repletion* pattern are often acute.

They manifest diverse symptoms as well. As a result, the nature of the disease should be clear if the *depletion* or *repletion* patterns of the disease are clarified. (Leung et al. 2003 p.75-78; Tang 2004 p.191-192)

There are two types of depletion in TCM relevant for our purposes: temporary and accumulative. A temporary state of depletion is a *state* of low adaptability, meaning that the body or system is temporarily low on anti-pathogenic influence or *qi*, limiting its ability to change in response to circumstances. A state of low adaptability does not necessarily result in a drain of vital substances; levels of *anti-pathogenic qi* within the system may recover.

In an accumulative depletion, the system experiences a *trait* of low adaptability, indicating a permanently low level of ability to adapt to change. In bodies, this may be caused by patterns of overwork, exhaustion, or climate; in systems, this may be from inflexible dominant logic, or persistent insufficiencies in raw materials, resulting in a drain in vital substances. This is the usual pattern of depletion that TCM typically focuses on.

In the *depletion/repletion* pattern, diseases are *depletion/repletion* conditions that pertain to *pathogenic evils* and *anti-pathogenic qi*. TCM acknowledges that one must consider both sides, since treatments differ for each type and symptoms for each may be similar. For instance, fever may indicate a viral infection, or it may indicate bodily stress, which require different treatments (either medications, or in the latter case "tonifying" or improving the tone of bodily systems). One treatment does not necessarily solve the other, and treatments that fix the wrong problem may worsen the problem. (Tang 2004 p.37-40) For instance, consider iron in the body; while it is vital to hemoglobin function, it is also important for tuberculosis reproduction. So, while it makes sense to suggest a treatment for common iron-deficiency anemia by increasing iron supply, in the case of tuberculosis, this may in fact assist the tuberculosis virus and may worsen the *root* problem. The medically correct response for anemia – in this case, simply a *manifestation* of body's defensive reaction to tuberculosis – requires the same type of dynamic balance judgement and adjustment that we argue is necessary for complex engineered systems. (Nesse and Williams 1994 p.49)

9-2. Prevention and Treatment Principles in TCM

9-2-1. Prevention Principles

Resilience has three major meanings: the ability to prevent something bad from happening, the ability to prevent something bad from becoming worse, and the ability to recover from something bad once it has happened. (Hollnagel et al. 2006 p.59) There is a nearly exact isomorphy with the three parts of TCM's paradigm of prevention: treating the "undiseased," preventing transformation and transmission, and promoting self-healing of bodily systems. We will discuss each in turn.

Treating the "Undiseased"

This concept is widely acknowledged to have two foci (— 1994; Chen 2004; Maciocia 2005; Song 1988; Zhou 2004):

- Promoting anti-pathogenic qi
- Preventing the invasion and attack from pathogenic evils

This is in contrast to the traditional school of thought with regard to prevention that focuses mainly on early symptom identification and inoculation; for TCM, prevention goes further and includes the efforts of *making no disease to be detected*. (— 1994 p.98; Liang 2006; Tang 2004; Zhou 2004) Diagnosing chronic diseases requires identifying functional change in the system, thus increasing reserve power and adapting to change should be how we prevent occurrence of the disease, on TCM's account. (Liang 2006 p.11,43)

Preventing Transformation and Transmission

However, diseases do occur. While early detection is also important in TCM, preventing transformation and transmission is seen as its primary component when diseases have formed. *Transformation*, as the term is used here, means for example the change of a disorder or disease from depletion to repletion or vice versa. *Transmission* is spread of the disorder or disease across bodily subsystems, much like the concept of metastasis in oncology (— 1994; Chen 2004; Maciocia 2005; Song 1988; Zhou 2004).

The differences between the traditional and new account of prevention that we propose are most apparent in chronic disorders such as diabetes. Diabetes may hit at different life stages, and as a developmental disease, there exists a chance to prevent diabetes from even occurring. Life changes like quitting high-sugar drinks alters the *anti-pathogenic qi* vs. *pathogenic evils* imbalance that cause diabetes, preventing its causation. Indeed, modern public health recognizes similar progression patterns (*transformation*) of diabetes over time, which the initial bad diet or lifestyle (*repletion* pattern) transforms into bodily functional deterioration such as kidney failure (*repletion* pattern) and eventually into *depletion* condition (deficient in overall *anti-pathogenic qi*). To prevent *transmission*, one would examine the spreading effects of diabetes, starting at kidney functional deterioration, with downstream effects like heart disease, blood problems, poor circulation and lymphatic problems can occur, even to the point of necessitating medical amputation. Thus, the important preventive goal in diabetes should be 1) to promote healthier life and diet to prevent it from happening, and 2) when it has developed, to prevent symptoms from progressing to that point by stopping the pattern of disorder from spreading outside the kidney functional failure. (Liang 2006 p.89-90)

Promoting Self-Healing of Bodily Systems

This may be seen as having two core components: *self-healing ability*, what we term resilience, positive momentum or system inertia, and *health*, defined as healthy functioning, not simply the absence of disease.

The conventional engineering and medical concept of risk focuses on particular diseases and failures, developing curatives and detective measures aimed at the particular causes identified. While these may be effective for repetitive, unchallenging problems, they also only passively reduce harm, in doing so failing to promote health. Roughly 25% of identified diseases are detectable and treatable through medical measures; the remaining 75% are only curable through self-healing, which requires healthy balance that must be promoted, thus necessitating “tonifying.” For the vast majority of the time – and, as we argue, essentially – health is the healthy operation of the system, not merely the absence of symptom or disease. (Liang 2006 p.105-107)

9-2-2. Treatment Principles

Put succinctly, restoring dynamic balance is the essential nomothetic principle of TCM treatment; how balance is restored is an idiopathic concern. Interestingly, the ancient Western theory of *humors* (Vick 2002 p.25) strongly resembles, in structure and overall aim, the *wu xing* theories of organ systems which we have mentioned in Chapter 8. Thus, treatment ultimately aims at restoring the balance of *yin* and *yang*, restoring the functions of the *zang fu* organs or sub-systems and regulating the circulation of vital substances while taking into account individual constitutional factors.

TCM recognizes, and adopt, three types of forces in the consideration of treatment:

1. *Temporal or "Heaven" based forces* focused on manipulating diurnal, circadian, seasonal rhythms;
2. *Geographical or "Earth" based forces* focused on the effects of persistent background phenomena such as local climate, the social effects of place and culture;
3. *Personal or human based forces* that focus on individual differences such as gender, constitution, age, habits, and occupation.

Disease is disorder between or within these forces; treatment is aimed to bring them back into balance. An important aspect of the system we are describing is that the concept of dynamic balance is based on adaptability, not maintaining a single state of system operation. There is no fictive "original" balance of the body or system that must be hewed to, but rather the constant necessity to achieve a balance adaptive to the environment. After all, different imbalances require different treatments, and imbalances cannot be anticipated. Thus, the goal of a wise system manager should be the same as for a doctor: adaptive health control that masters the changes necessary to adapt to a changing environment. (Tang 2004 p.248-249)

Treatment Principle according to Root and Manifestation

Generally speaking, the *root* is primary and needs to be treated first. However, under certain circumstances, the *manifestation* can become primary and needs to be treated first, even though the ultimate goal is always to treat the *root*. The decision to treat the *root* or the *manifestation* depends on the severity and urgency of the clinical manifestations. There are three possible courses of action: (Maciocia 2005 p.1119)

1. Treat the *root* only;
2. Treat both the *root* and the *manifestation*;
3. Treat the *manifestation* first, and the *root* later.

In effect, we expand the set of *manifestations* that we should be watching out for to more intangible, subtle warning signs and events, such as complaints, chaotic job sites, administrative inconveniences etc., rather than focusing solely on physical evidence for random failures. Facing those warning signs and events, the objective is never simple, direct elimination of them, but instead to analyze those available manifestations in order to identify the origins of functional disorders that underlie them. The ultimate goal is to treat the *root*, i.e., the functional disorder, and restore the necessary dynamic balance of the system. (Wu 2005 p.130)

Treatment Principle according to Yin and Yang Patterns

An understanding of the pathology of imbalances between *yin* and *yang* is crucial to determine the correct treatment principle and method. The treatment principle is intimately related not only to the imbalance of *yin yang* but also to the *cold/hot* and *depletion/repletion* nature of the pathology. Put simply, there are only four basic treatment principles:

1. In excess of *yang*, clear *heat*;
2. In deficiency of *yang*, tonify *yang*;
3. In excess of *yin*, expel *cold*;
4. In deficiency of *yin*, nourish *yin*.

In excess of *yang* and excess of *yin*, the emphasis is on “clearing” and “expelling” *pathogenic evils*, while in deficiency of *yang* and deficiency of *yin*, the emphasis is on “tonifying”’ and “nourishing” the *anti-pathogenic qi*. (Maciocia 2005 p.401)

Treatment Principle according to Depletion and Repletion Patterns

The pathology of *depletion* and *repletion* patterns depends on the relative strength of *anti-pathogenic qi* and *pathogenic evils*. With the understanding of their relationships with the development of accidents, we are able to distinguish the system health condition into *depletion*, *repletion* or *mixed* (*depletion/repletion*) pattern. Such diagnosis influences the principle of treatment and the therapeutic results. (Tang 2004 p.37-40)

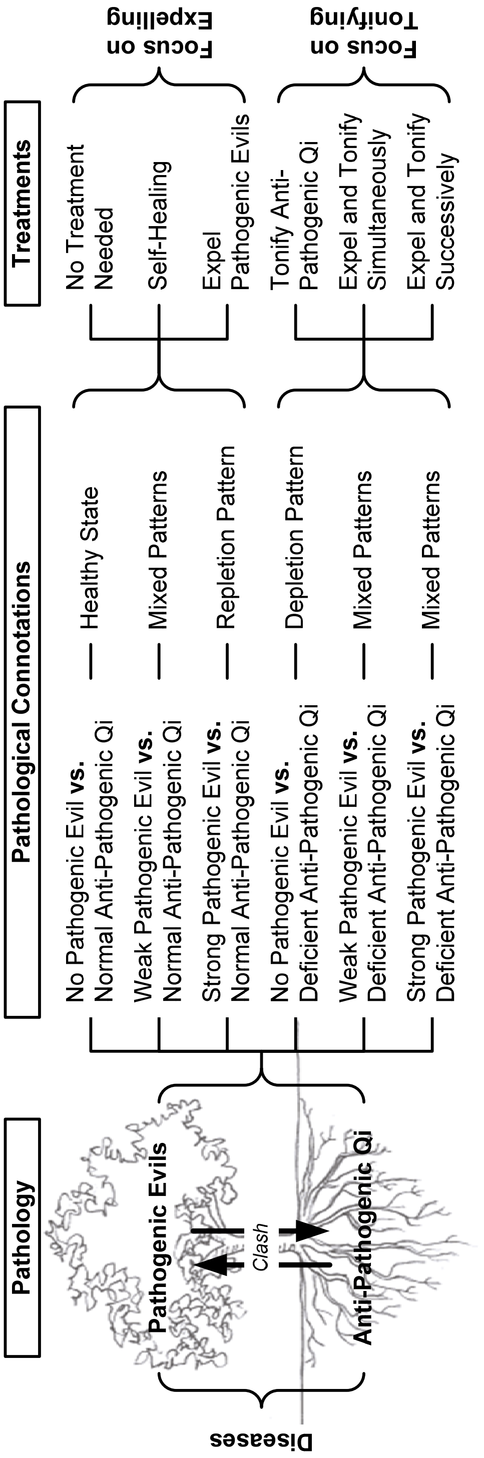

Figure 9-6. Treatment Principles for Depletion / Repletion Patterns

Figure 9-6 shows possible pathological connotations and their corresponding treatments. It would be completely wrong to tonify the *anti-pathogenic qi* in a *repletion* pattern or to expel *pathogenic evils* in a *depletion* pattern. In *mixed* patterns, diagnosing the relative balance of *anti-pathogenic qi* and *pathogenic evils* is still very important. In such conditions it is not simply a matter of simultaneously expelling *pathogenic evils* and tonifying the *anti-pathogenic qi*: the treatment principle must be based on a careful assessment of the relative strength of *anti-pathogenic qi* and *pathogenic evils* and of the pathology of each individual case. Although balanced between expelling *pathogenic evils* and tonifying the *anti-pathogenic qi*, the treatment will nevertheless always place the emphasis on one or the other. (Maciocia 2005 p.383)

Treatment Principles according to Wu Xing Interrelationships

When considering the treatment principles of a system, we should keep in mind the various relationships of the disordered subsystem with the others along the *generating*, *restraining*, *over-acting* and *counteracting cycles*. Maciocia (2005 p.37-38) provides two great examples explaining the consideration according to *wu xing* interrelationships:

> *If there is a [Liver] disharmony, one must consider first of all if this disharmony may be affected by another [subsystem], and secondly, whether it is affecting another [subsystem. As shown in Figure 9-7a, for example], if the Liver [sic: for differentiating the zhang fu organs in TCM from the physical organs in Western medicine] is deficient and the patient has several signs and symptoms of Liver-Blood deficiency, one should always consider and check whether the [parent subsystem (the Kidney)] is at fault, failing to nourish [the Liver]. On the other hand, we must consider and check whether [the Liver] is deficient from being over-acted upon by [the Lung,] or because [the Heart (the child)] is drawing too much from [the Liver (the parent)], or even because it is being [counteracted by the Spleen. As shown in Figure 9-7b, One] should also consider and check whether the Liver deficiency is [failing to nourish the child (the Heart), or failing to restrain the Spleen to prevent complications from arising.]*
>
> *It is necessary to keep all these relationships in mind when determining the treatment. Thus, if the Liver is deficient because it is not nourished by its [parent subsystem, the Kidney], both the Kidney as well as the Liver must be*

tonified [sic]. If the Liver is deficient because it is being over-acted on by [the Lung], the correct course of action would be to sedate the Lung. If the Liver is deficient because the Heart (the child) is drawing too much from it, one would have to sedate the Heart. If the Liver is deficient because it is being [counteracted] by the Spleen, treatment demands sedation of the Spleen. If the Liver deficiency is affecting its [child subsystem], one would tonify the Heart as well as the Liver.

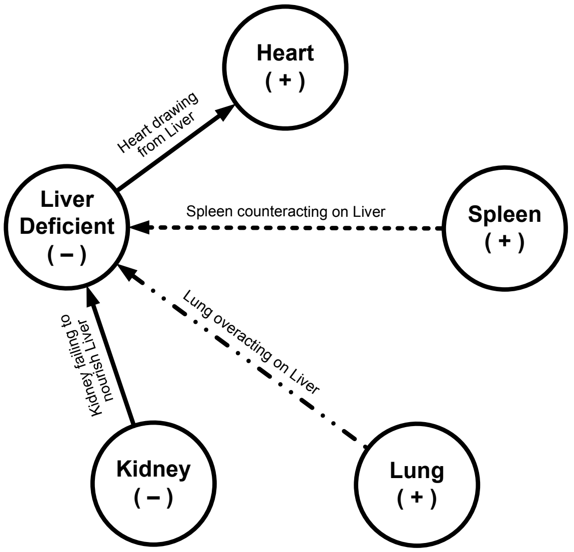

Figure 9-7a. Pathological Precursors
(Maciocia 2005)

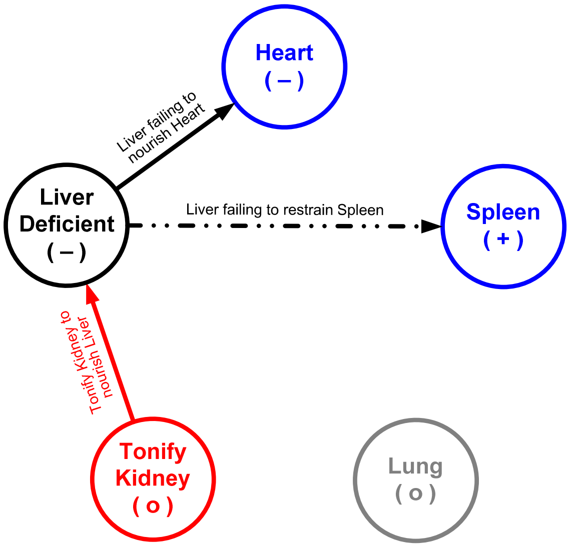

Figure 9-7b. Pathological Developments
(Maciocia 2005)

[As shown in Figure 9-8a], if the Liver [sic: for differentiating the zhang fu organs in TCM from the physical organs in Western medicine] is in excess and the patient for example, has symptoms and signs of Liver-Qi stagnation or Liver-Fire, we must check whether this excess is due to deficient [Lung] failing to control [Liver]. This often happens in chronic constitutional weakness of the Lung. On the other hand, [as shown in Figure 9-8b], one must check whether the excess in [the Liver] has begun to affect other [subsystems]. For example, when [the Liver] is in excess, it can easily over-act on [the Spleen]. This is called "Wood invading Earth" and is very common in practice. If [the Liver] is in excess, it could also make too much demand on the parent (the Kidney), or even counteracts on Lung].

> *If the Liver is in excess because [the Lung] is not controlling it, one must tonify [sic] the Lung, as well as sedating the Liver. If the Liver excess is affecting and depressing [the Spleen], in this case the Spleen requires tonification [sic]. If the Liver is in excess and is drawing too much from the [parent subsystem], one must also tonify [sic] the Kidney.*

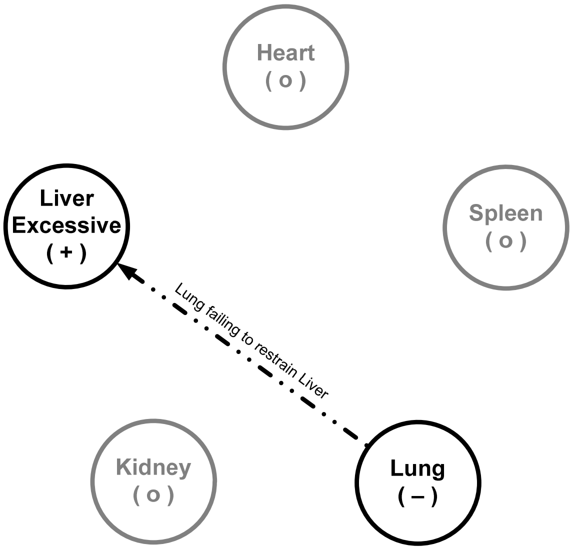

Figure 9-8a. Pathological Precursors
(Maciocia 2005)

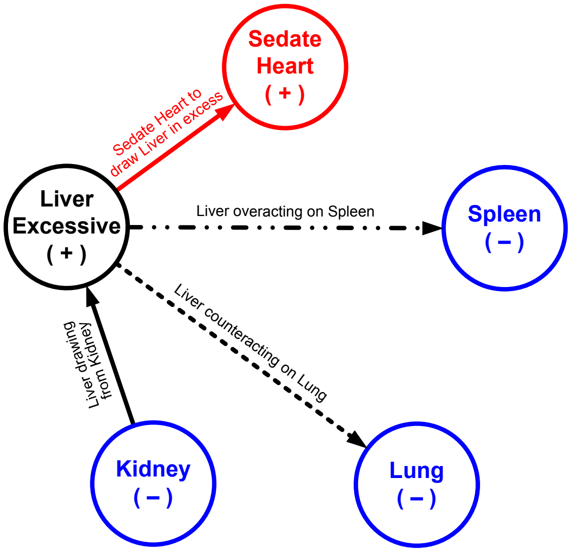

Figure 9-8b. Pathological Developments
(Maciocia 2005)

9-3. TCM Diagnostics and Treatment Framework

9-3-1. Process of Medical Diagnosis

Comparing the two medical paradigms of diagnosis process, we can find the following key points:

- The Western approach is retrospective; the TCM approach is prospective. It may not be fair to say that TCM is more holistic while Western approach is strictly reductive. It is clear that TCM approaches problems from a macrocosmic perspective while Western approach does it from a microcosmic perspective.

- They both use past medical cases as a reference for current diagnosis. However, the Western approach uses them to establish the correlations between symptoms and diseases. In contrast, TCM analyzes pathomechanisms from medical cases, uses them to establish causal effects between zang fu sub-systems and further perfect the functional model of the human body and diagnose the disharmony of the patient in the context of the established model.
- In the Western approach, diagnosis is mainly for identifying the disease proceeding from symptoms; the treatment of the disease is mostly irrelevant to the diagnosis after confirming the identity of it. In contrast, TCM's diagnosis advises on treatment strategies for disharmony. Treatment is simply correction of the imbalance found in the process of diagnosis.

In order to understand the differing systemic bases of each and their impact on engineered systems, we will examine each in depth.

Western Medicine Approach

In traditional Western medical systems, given the patient's symptoms, medical history, and laboratory or other test results, the causative disease must be identified. This is purely an inductive process, generalized specific patient information to the disease identified. In reviewing some 50 diagnostic exercises published over a period of years in the *New England Journal of Medicine*, Eddy and Clanton (Vick 2002 p.192-193) found that physicians use a diagnostic strategy consisting of the following six steps:

> ***1. Aggregation of information about the case.*** *The first step involves learning about the patient's presenting symptoms and history of the illness. Because there is often a large amount of information, it is summarized by aggregating it into more limited sets of correlated symptoms.*
>
> ***2. Selection of a "pivot" finding from this information.*** *Perhaps one or two of these aggregated symptoms called "pivot findings" are then identified as particularly significant, while the rest are temporarily put aside. This pivotal finding is often something known to be a generally important diagnostic indicator and emphasized in medical education as suggestive of a certain disease or class of diseases. As a cognitive expedient, the selection of a pivot*

finding reduces information-processing demands by emphasizing a select few aggregated symptoms felt to be most significant.

3. Use of the pivot finding to generate a cause list of possible diseases. *This involves generating a cause list of diseases that could be responsible for the pivotal symptom. Note here that the direction of reasoning is changing. Before, it was forward from symptom to disease; from here on it will be backward from disease to symptom. At this point, the process shifts from hypothesis forming to hypothesis testing.*

4. Pruning of the disease list. *Here the cause list is pruned or screened by comparing each disease with all of the aggregated symptoms. Each incompatibility reduces the plausibility of the candidate disease as the cause of the illness. This continues until some minimum threshold of plausibility results in a hypothesis being culled from the list.*

5. Selection of the diagnosis. *Now the actual diagnosis is formulated from the remaining hypotheses. If multiple candidate diseases survived the pruning process, these are compared to see which best matches the symptoms.*

6. Confirmation of the diagnosis. *In the final step the diagnosis is reviewed to determine its adequacy in a larger context. This involves evaluating the extent to which the selected diagnosis could comfortably fit all the symptoms, a retrospective reassessment of the fourth step. Any insufficiency here results in repeating the entire process using the unexplained symptoms as the new pivot finding.*

The emphasis of this process is on hypothesis testing, i.e., making sure the developed “feeling,” through the observation of the symptoms, for the patient’s problem “makes sense.” The patient is viewed as “a unique, single-event occurrence” and compared to the statistical data collected from many other patients who exhibit similar symptoms in order to establish the causal relationship between the symptoms and a particular disease. Note here that the critical step of hypothesis forming (in other words, asking the question of what is going on beneath the observed symptoms) in the process is simply developed from “feelings” and by way of “trial and error”. No wonder it is often seen as a “black art” in Vick’s (2002 p.192) account.

TCM Approach

In contrast with Western approach, TCM approach to diagnosis places an emphasis on "hypothesis forming," in our view, designed to understand the underlying disorders through adequate pattern differentiation and treatment prescribed accordingly. Although critical in TCM practice, no attempt at systematizing the pattern differentiation and treatment determination was made until the mid-19th century. (Scheid 2002 p.203) Among those attempts, the TCM theorist Fang Yaozhong summed up a seven-step process for clinical practice in his book, *Seven Lectures on Pattern Differentiation and Treatment Determination Research*, excerpted at length in Scheid (2002 p.285-289):

> ***Step 1.*** *Determining the Location [of the Illness] in the Visceral Systems (zang fu) and/or Channels and Network Vessels (meridians)*
> *On the basis of presenting symptoms and signs*
> *On the basis of visceral functions*
> *On the basis of evidence from characteristic reflections of visceral functioning*
> *On the basis of the interrelation of visceral systems, seasons, climates, etc.*
> *On the basis of the interrelation of visceral systems and particular disease causes*
> *On the basis of taking into account constitutional factors, body types, age, sex, etc.*
> *On the basis of illness development and treatment response*
> ***Step 2.*** *Determining the Nature [of the Illness Process] in terms of yin/yang, qi/blood, interior/exterior, depletion/repletion, wind, fire, damp, dryness, cold, and toxicity*
> *On the basis of the characteristics of clinical symptoms and signs*
> *On the basis of the onset and development of an illness*
> ***Step 3.*** *Determining both Location and Character [of the Illness Process]*
> *Referring to a more precise differentiation of the illness process by jointly considering visceral system function and physiology/pathology and of the illness process as described by the categories wind, fire, damp, dryness, and cold*
> ***Step 4.*** *Giving Priority to Earlier [Phases of the Illness Process] in terms of the [Wu Xing Theory]*

Referring to reflecting on the illness process in terms of five-phases visceral system relationships (wu xing theory)

Step 5. *To Sort Each into Its Category*

While referring in a wider sense to all the above processes, the [step] is used here to [align] therapeutic strategies with previously diagnosed illness processes.

Step 6. *To Treat the Illness, Seek the Root*

Treating not only the illness as determined in steps 1-3, but also its cause as determined in step 4

Step 7. *Develop Treatment ahead of the Dynamic of the Disorder*

Considering physiological visceral system interrelations even where they are not actively implicated in the presenting illness

As discussed in the previous section, this diagnostic process identifies patterns of disorders which express four core aspects of disease development: its *origins*, *locations*, *characters* and *trends*. We will develop and deploy Fang's approach in our proposed risk analysis framework to proceed in Chapter 10.

9-3-2. Problems in Applying TCM Concepts

The theories of *yin yang* and *wu xing* were a fundamental concept in the development of TCM. In the early stage of TCM development, ancient Chinese successfully applied those concepts to help organize medical cases and experiences into theories. However, the over-simplified ontological assumptions of these theories, on the other hand, have hindered the later development of TCM and create barriers for our application to risk analysis. In their inspiring article *The Functional-Analogical Explanation and Culture Of Science and Technology—A Case Study of the Theory of Yin-Yang and Five Elements*, Chinese science philosopher, Huaxia Zhang and Zhilin Zhang (2007), point out several key problems of *yin yang* and *wu xing*:

- Zhang and Zhang (2007 p.254) conclude that yin yang and wu xing provide what they termed "functional-analogical" explanations to the world, which essentially put "a phenomenon into a certain class, and then using the universal characters of the class to explain or predict characters of the phenomenon." Although common in early human history and very helpful for systematize experiences and knowledge, this way of understanding the world, as Zhang and Zhang (2007 p.254) put it, “is intuitive and not experimental, synthetical and not analytical, conjectural and not logical.”

- As Leung et al. (2003 p.54) point out the yin yang relationship works only when considering “two objects that are mutually related or two opposite aspects of the one phenomenon.” The task of matching two objects or identifying two opposite aspects of a phenomenon is not easy and criteria for such judgement are rather vague (based on qualitative descriptions).
- There are two key points in the wu xing theory: 1) everything in the world and its nature is classified into one of the “five” basic elements; 2) the strict one-to-one interrelationship between each element. Zhang and Zhang (2007 p.254) argue that “the value of this kind of explanation depends on whether the classifications are proper, and whether the supposed universal characters of a class are applicable to all the individuals.” There does not seem to be a proper explanation for why there are five categories or whether classification is absolute and unique. Also, its over-simplified interrelationship model, although complete, is not perfect for explaining many of the existing complex phenomena in the world.

TCM theorists are aware the constraints of *wu xing* model and many of them propose amendments to the theory and some suggest upgrading it with *zang fu* related theories. (Deng and Zheng 2008) Our attempts to apply *yin yang* and *wu xing* theories to complex engineered system will face the same problems. Among those, we find the following key concepts that are applicable:

- Functionally, the correspondences and interrelationships of wu xing connect elements of a human body into an organic unity. Both yin yang and wu xing emphasize holism and that systems are interconnected not only with internal subsystems but also with the environment.
- The generating and restraining cycles resemble the positive and negative feedbacks in System Dynamics, which are critical features of a self-organizing system. Components of real complex systems may not bear perfect one-to-one relationships as wu xing model does. We believe there exists relationships of facilitating, constraining, coordination (Deng and Zheng 2008)
- Counteracting and overacting cycles reveal excess and deficient states of certain subsystems. The concept of hyper- or hypo-functionality is potentionally useful for judging system health conditions.

- The relationships between zang fu subsystems are defined through the flow of vital substances. In a sense, the zang fu subsystems resemble the concept of “stocks” and the vital substances in them correspond to the concept of “flows” in System Dynamics; the concept is potentially useful for our modeling purpose.

Chapter 10. A New Approach to Risk Analysis—The Framework

Although the metaphor of health for safety concerns is not original, our specific casting in terms of system dynamics and TCM is. Reason (1990) applied it for considering the causes of failure; Elms, on the other hand, uses it as a critical framework for assessing structural system health. In Elms' (1998 p.272) view, symptoms of disorders in a complex human system may not present an immediately clear pattern of deterioration; "however, with a further deterioration, symptoms become clearer. It is apparent that something is wrong. Functionality becomes impaired. With further deterioration, death ensues." We argue that the difficulty presented with the current metaphor of system health is its insufficient dynamism. Only by including the elements of time and change is it possible to develop a meaningful picture of a dynamic complex system, which the TCM paradigm develops through its concepts of interaction of flows (*wu xing* structure) and mutually reconciling opposites (*ying/yang* concept).

In 1859, Darwin brought together a wealth of evidence to elucidate the process of natural selection in On the *Origin of Species*. Over time, this process can result in adaptation that transforms populations for particular ecological niches and may eventually result in the emergence of new species. Adaptability, or responsiveness to change as a quantity, is more valuable to an individual than any particular trait; as he notes, "it is not the strongest of the species that survive, nor the most intelligent, but the one most responsive to change." System optimization is not necessarily a solution to change; systems that survive are those which adapt to change and have the ability to maintain their ordinary day-to-day operating behaviors under developing challenges without resorting to anomalous, crisis-management behavior.

This approach is, of necessity, somewhat subjective. It is similar to the manner in which Elms (1998 p.272) describes the system health, "It is a way of framing one's view of a system, rather than an objective technique or tool existing independently of the user." However, this subjectivity should not be seen as a flaw, but rather as a consequence of the essentially subjective nature of all technical judgment. On Vick's account – corroborated by modern psychological research – there is no perfectly objective mathematical decision-maker; the “reasonable man” is a fiction, and we must plan for imperfect people, with imperfect information, attempting to make the best of the day-to-day normal operation of their imperfect systems. Subjective information incorporates a wide range of conscious and unconsciously held views and beliefs. Its richness is simultaneously a flaw and also its greatest strength, since subjective measures, although often conflicting and diverse, are also summaries of a range of information. Managerial opinions are often phrased subjectively, and their value can easily be discounted in a quantitatively-biased decision-making environment. Furthermore, health is, of necessity, a subjective concept, and to the extent we agree that the concept of health is the best means of looking at the situation, as decision-makers we are compelled to admit subjectivity as simply a potential disadvantage to an otherwise powerfully explanatory model.

The value that TCM provides to the system health approach is an intrinsically dynamic view which is missing from the Western hypothesis-testing approach. Although proponents of Chinese medicine will be the last to admit it, Western medicine simply has a more sophisticated philosophy of science than the Chinese tradition; the concept of the null hypothesis, a peer-review culture and a critique-oriented Popperian tradition are notably missing from the model-driven TCM paradigm. However, the Chinese system does have a tremendously sophisticated taxonomical understanding of systems in operation developed through literally eons of clinical observation. Since *wu xing* and *zang fu* models deal with the constant interchange and flows between a limited number of functional parts – functional structures in the human body, and functional sub-systems in the engineered system – we are able to develop easy-to-understand diagnostic schemata for system managers based on a powerfully reductive representational system that nonetheless retains a holistic, dynamic character due to its allegorical nature. Rather than casting health in terms of a set of static metaphors, in the TCM paradigm as we present it, health is a balanced state of operating flows, changes and interrelationships inside a system and its environment. Since flows and changes are necessarily time-oriented concepts, a concept of time is incorporated, or “baked in” to the measures that we present.

Rather than concentrating on static *hypotheses*, the TCM paradigm constructs *models*. The primary difference is that TCM models are representations of flows and change in operation. Rather than arriving at a falsifiable theory that can no longer be criticized meaningfully (the Western approach), the change-oriented system model that we set forth here constitutes an inductively based diagnostic guide to understanding change, and its attendant risk, in constantly changing engineered systems.

The results we obtain from using the TCM paradigm may not correspond exactly to the deterministic models of human health processes we have today, but it is not their metaphorical value we are after. Rather, we argue for an allegorical understanding, based on the interaction of moving parts within the system. It is trivial and potentially inaccurate to argue that an engineered system is anything like a human body (a metaphorical view). The strength of TCM is that, similar to the Western tradition, it constructs, tests, and revises allegorical models in accordance with inductive observation, without attempting to put these inductively observed facts into a theoretical model. In engineered systems, symptoms may simply present themselves without necessarily conforming to an abstract theory (or, on the deterministic account, they may conform to a theory that we have simply not developed yet). Just as we argue risk managers should, the TCM practitioner attempts to develop and constantly revise a sophisticated mental model of internal bodily processes, monitored through subjective, summary diagnostic procedures like pulse, smell, observation and interrogation that incorporate a wide range of objective data into a single readily available subjective pattern. In this regard, there is a clear isomorphism between the TCM practice of diagnosis and prognosis and the dynamic, change-oriented approach that we argue risk analysis should take.

10-1. Adaptive System-Health Control Framework

Here we will outline the concept and process of system health control for management of risk in complex engineered system through analysis of change and restoration of balance. In this approach, we conceive of complex systems as analogous to living organisms, providing an account of the fluctuating risks in a system by applying the analysis of the risk of change and concepts of healing derived from TCM. We will begin with a brief review of TCM concepts applicable to complex engineered systems and a concise process overview.

10-1-1. Overview of TCM Concepts

Table 10-1 summarizes the selected concepts of TCM we discussed in Chapter 3, 8 and 9. For each concept, we provide our thoughts or related ideas about its application to complex engineered systems.

Table 10-1. Critical TCM Concepts in the Application of System Health Control

Topics	TCM Concepts	Engineered System Applications
Concept of Health	The human body as a homeostatic system is in balance with itself as a whole and with the Nature and the passage of time, conceptualized as continual seasonal and day/night cycles (— 1994; Tang 2004; Zhou 2004)	A system has dynamic balance based on the relationships between its subsystems, among its related systems and with its environment. (Kauffman 1980)
Concept of Disease/Accident	Diseases are disorders of human organismal internal structure or function, resulting from a loss of equilibrium in and/or between internal and external environments. (— 1994; Maciocia 2005; Song 1988; Tang 2004; Zhou 2004)	Accidents are the result of internal function degradation in excess of system constraints for adjustment. The process leading to an accident may arise from challenges of external variation or internal dysfunctions among various subsystems and components.
Definition of Risk	Undefined in TCM; prevailing paradigms of *the risk of chance* govern risk thinking, using the traditional formula of risk = consequence × probability	Defined as *the risk of change*, derived from the momentum of change; a new formula, risk = consequence (inertia) × speed of change. Patterns, processes and habits are the action of strong/weak forces over time, producing a cumulative effect over time: change in risk = force × time.
Systems Theory	Through *yin yang* theory and *wu xing* correspondence, TCM simplifies complex interrelationships within and without a human body in Nature and simulates its operation with a theoretical model of body functionality as an organic whole. (Tang 2004; Wang 2007; Wu 2005; Wu 2008)	Through System Dynamics, complex engineered systems can be modeled based on their behaviors and relationship patterns between each of their elements and subsystems. (Forrester 2002; Kauffman 1980; Sterman 2000) The notions of mutually reconciling dichotomies and orderly circulation of flows correspond to yin/yang and *wu xing* respectively.
Subsystem Interrelationships	*Wu xing* theory maps functional and dysfunctional interactions amongst organs as functional structures. The four most common ones are the *generating cycle*, *restraining cycle*,	Feedback loops in system dynamics define relationships within a system. For instance, a positive feedback loop is isomorphic to the *generating cycle* that supports the growth of a system, while a

	overacting cycle and *counteracting cycle*. (— 1994; Maciocia 2005; Sheikh and Sheikh 1989; Zhang and Zhang 2007; Zhou 2004)	negative feedback loop is isomorphic to the *restraining cycle* that controls organismal growth. (Senge 1994b; Senge 2006; Sterman 2000)
Roots of Health Deterioration	In Chinese medicine, the *roots* of health deterioration are usually found in day-to-day operation of the human system – habits, lifestyle, exercise, etc. Treatments given without addressing root causes fail similarly to pouring water into a container with a leak at the bottom. (Leung et al. 2003; Liang 2006; Maciocia 2005; Tang 2004)	In system dynamics, complex systems are described as interlocking structures of feedback loops. All man-made and natural rules and processes fall within this structure, from which the behavior of a system arises. (Senge 1994b; Senge 1999; Senge 2006; Sterman 2000)
Diagnosis	TCM practice depends heavily on differentiation of patterns, making for a medical practice organized around the unfolding of process rather than the manipulation of bounded structures. A pattern expresses four core aspects of disease development: *origins*, *locations*, *characters* and *trends.* Each of these patterns is composed of discrete, particular manifestations reflecting the root of the dis-harmony. (Maciocia 2005; Scheid 2002; Song 1988)	The same four aspects of accident development are analyzed: *origins*, determined through etiological analysis; *locations*, which are then determined at the subsystem level and associated with the relative health condition of each subsystem by applying the risk of change analysis; *characters*, determined by differentiating between *yin/yang* and *depletion/repletion* conditions; and *trends*, investigated in order to understand etiology and prognosis through system dynamics and *wu xing* theory.
System Vitality	Health for TCM is positive vitality resulting from dynamic balance between the vital substance (*yin* aspects) and functional activities (*yang* aspects) of the body. The working of the body and mind are a result of the interaction of vital substances, including *essence*, *qi*, *blood* and bodily fluids. (— 1994; Leung et al. 2003; Maciocia 2005; Sheikh and Sheikh 1989; Tang 2004; Zhou 2004)	Since the health of engineered systems is not merely the absence of accidents, in contrast to a traditional focus on events and accidents, we argue that a healthy system should be well-balanced in its functional activities and the usage of its corresponding vital substances such as capital (*essence*), information (*qi*), value (*blood*), and "food" or metabolism (its processing of raw materials and human resources).
Reservoirs of vital substances	*Zang fu* theory is used to explain functional relationships between human organ systems, casting the *zang fu* system as a reservoir of human vitality, which, when healthy, adjusts vital substances to optimally support human life. (— 1994; Leung et al. 2003; Maciocia 2005; Sheikh and Sheikh 1989; Tang 2004; Zhou 2004)	The concept of stocks and flows in system dynamics is seen through the lens of zang fu theory. Sub-system stocks in a dynamic system may be seen as operating similarly to human body systems, while flows are the movement of certain vital substances that affect the amount of their stock reserves. (Forrester 2002; Senge 1994b; Senge 2006; Sterman 2000)

Etiology (Origins of Disorders)	Identifying the root of a patient's illness is crucial. The presenting illness is not the cause of disease; merely palliative treatment aiming at eliminating the discomforts is disfavored. Balance is the key to health: balance between rest and exercise, in diet, in lifestyle, and in climate. Any long-term, even minor, imbalance can become a cause of disease. Relating the cause with the patient's living patterns allows TCM to advise patients on how to minimize, prevent the re-occurrence of and avoid causing the disorder. (— 1994; Chen 2004; Maciocia 2005; Song 1988; Tang 2004; Zhou 2004)	Rather than the conventional risk analysis approach putting emphasis on incidents and accidents that involve potential consequences, (Apostolakis 2000; Apostolakis 2004; Ayyub 2003; Kaplan 1997; Kaplan and Garrick 1981) signs and events without adverse or unknowable implications are mostly ignored until something bad and serious happens. Environmental causation, seen as *external pathogenic factors*, is only a small part of the potential cause of accidents. Well-managed, balanced patterns of human and organizational factors and the smooth circulation of vital substances (capital, information, value) are also critical to system health.
Pathology (Pattern Differentiation)	Pathology explains how a disease process arises, how its manifestations change and how they are resolved. The concept of pathomechanism in TCM does not depend on pathological analysis of changes at a microscopic level, nor does it take into account the changes taking place in the tissues and chemistry of the body, but rather draws from a broad understanding of general disease processes and changes in light of general, broad factors such balance between *pathogenic evils* and *anti-pathogenic qi* and between *yin* (vital substances) and *yang* (functional activities). (Chen 2004; Maciocia 2005; Song 1988; Tang 2004; Zhou 2004)	Accidents are the negative results of the competition of forces that produce system changes. Accident pathology is assessing the relative strength between *pathogenic evils* (negative forces) and *anti-pathogenic qi* (positive forces) and actively preventing developing accidents from occurring. This approach incorporates conventional accident models that perceive accidents as the results of a series of failure events through intensive and thorough forensic investigation after system breakdown.
System Health Stages	Pattern differentiation according to the Four Levels (*wei*, *qi*, *ying*, and *xue*), as set forth in the 1746 book *A Discussion on Warm Diseases* (*Wen Bing Lun*): *wei* (*defensive qi*), *qi*, *ying* (*nutritive qi*) and *xue* (*Blood*) are extended in meaning to describe the invasive progress and development (location, depth, seriousness and priority) of so-called "Warm Diseases." (— 1994; Chen 2004; Maciocia 2005; Tang 2004)	Besides the understanding of how accidents happen through etiological and pathological reasoning, our approach also considers the importance of assessing the health condition of the deteriorating system. The system dynamics model and *the risk of change analysis* identify the seriousness of the degrading health condition and possible problematic sub-systems. (Forrester 2002; Senge 1994b; Senge 1999; Senge 2006; Sterman 2000)
Treatment	Clinical manifestations are collected through observation, interrogation, palpation, and hearing and smelling forming patterns of imbalance in	A careful diagnosis revealing the *origins*, *locations*, *characters* and *trends* of a developing accident or health condition is conducted. Treatment is given aimed at

	unhealthy patients. *Root* and *manifestation* are carefully evaluated to distinguish between repletion and depletion conditions. A detailed diagnosis entails a treatment strategy for restoring balance. (— 1994; Chen 2004; Maciocia 2005; Tang 2004)	restoring broken balance, holistically considering all available manifestations, thus determining the correct treatment – whether to eliminate *pathogenic evils* or tonify the *anti-pathogenic qi*.

10-1-2. Dynamic Balance in a Holistic View

As we discussed in our truck example, when considering a moving system, the safest state is when the system is in a state of constantly changing adaptive or dynamic balance and in control at all times. The concept of balance is used very often but vaguely in colloquial language:

- The American Heritage Dictionary of the English Language (4th Edition 2000) defines it as “a state of equilibrium or parity characterized by cancellation of all forces by equal opposing forces.”
- Collins Essential English Dictionary (2nd Edition 2006) defines it as “Harmonious arrangement or relation of parts or elements within a whole,” and also “the power to influence or control.”
- Cambridge Dictionary of American English (2008), however, defines it as “the condition of someone or something in which its weight is equally divided so that it can stay in one position or be under control while moving.”

Despite small variations, the sense that all definitions give us is that of a holistic state, or in other words, balance as an emergent quality of a whole. For our account, then, the concept of balance is, of necessity, a synthetic concept that integrates at least two different quantities, and casts them within mutually reconciling terms – in other words, in terms of a *yin yang* balance. However, the conventional notion of balance is essentially an atemporal state; although the concept of balance may be necessarily incorporative of the concept of a whole, it does not of itself incorporate the notion of time. The qualification that we add, *being under control while moving*, on the other hand, provides insights into how balance can be achieved in a dynamic, time-oriented setting. Balance, in our account, is more than simply a temporary state of equality between forces which may or not exist in a perfect state like Vick’s perfect 50-50 coin. Balance is a dynamic concept, constantly shifting and being maintained. Perfect balance may never be attained because perfection is not a prerequisite of dynamic balance as we discuss it. In Part II, we discussed how interacting forces may evolve to create the system state as we see it in the moment.

For example, consider a hypothetical simple floodwater control system. A conventional approach might attempt to derive the necessary size of drains, levies and ditches to allow water to flow at sufficient speed to avoid flooding and construct these control measures accordingly. Such an approach would reduce the risk of a catastrophic event from natural events by decreasing the levels of water flow into the city through diverting it elsewhere. If a relationship between amount of water and risk of flood is known and safety margins are a given, engineering an adequately safe system is a simple matter of building an adequately high levy to meet safety requirements.

Such a traditional approach, however, has significant difficulties. Unpredictable consequences result from imbalanced solutions that attempt to control only one force – in this case, the level of water in the city – instead of attempting to seek a long-term tenable balance between the city and the forces of nature. In this case, traditional surface channels called for by conventional planning tends to reduce natural absorption of water into the ground, reducing water absorption into underground aquifers and resulting in unpredictable flood and drought conditions. If taken in isolation, attempts to optimize any single control measure always result in imbalance, a phenomenon known in policy terms as “blowback.”

Long-term solutions, we argue, require different thinking. Although a traditional barrier-and-reservoir based flood control system may be acceptable against most normal storms, a sufficiently large natural event outside of expectation, like a once-in-a-millennium tsunami, would still destroy the system. Even though the safety margin by the flood management system may be, on first face, a satisfactory quantity – safe for, let us say, two hundred years of floods – such safety assurance is, in fact, quite a brittle and easily lost, especially considering that there is no guarantee that the once-in-a-millennium tsunami will not occur, say, tomorrow. There are always events outside of expectation; definitionally, the time and place of their incidence cannot be predicted.

A holistic, dynamic approach like the one we advocate would first model the relevant natural and man-made systems, and then attempt to find adequately resilient means of controlling a constantly changing volume of floodwater which is acknowledged to be probabilistic and thus incalculable in detail. Rather than creating an artificial state of separation, a more organic system like the Amsterdam model we discussed in Chapter 7 attempts to create a dynamic balance between the inhabitants of the city and its natural conditions, where the flood is acknowledged to have a dimension of unexpectability and potential to exceed expected bounds. Rather than attempting to create an unnatural separation of land and water with a certain "safe" determinate level of safety against the unknowable and the unknown, our approach advises discovering how water flows naturally within natural lakes and rivers in the environment and attempting to discover control mechanisms by which a dynamic balance can be maintained between the destructive external force of the water and the constructive internal forces of the flood control system. (Tang 2004 p.313-314) Flood events in this sense are an imbalance between the pressure of the natural flow of water, seen as pathogenic evil, and flood control architecture as anti-pathogenic *qi*. Balance is dynamic, achieved not through a temporary act of balancing, but rather by laying in place a framework for the constant, controlled interaction of forces.

10-1-3. Outline of the Framework

Conventionally, risk analysis suggests we focus on the worst possible accident scenarios and tend to ignore signs that have no immediate failure concern. Attention is mostly invested in looking for cues of failure. Under such a mentality, however, once the cues are identified, that means the system is very close to failure. In this new approach, we suggest that we pay attention a step earlier and look for cues that show a tendency of system degradation through pattern differentiation. A problematic pattern is simply one that is likely to cause failure if the system continues it, unless proper actions are taken. With constant system health diagnosis and control, we can restore broken dynamic balance and avoid deterioration of system functionality. Figure 10-1 shows our proposed framework for system health control.

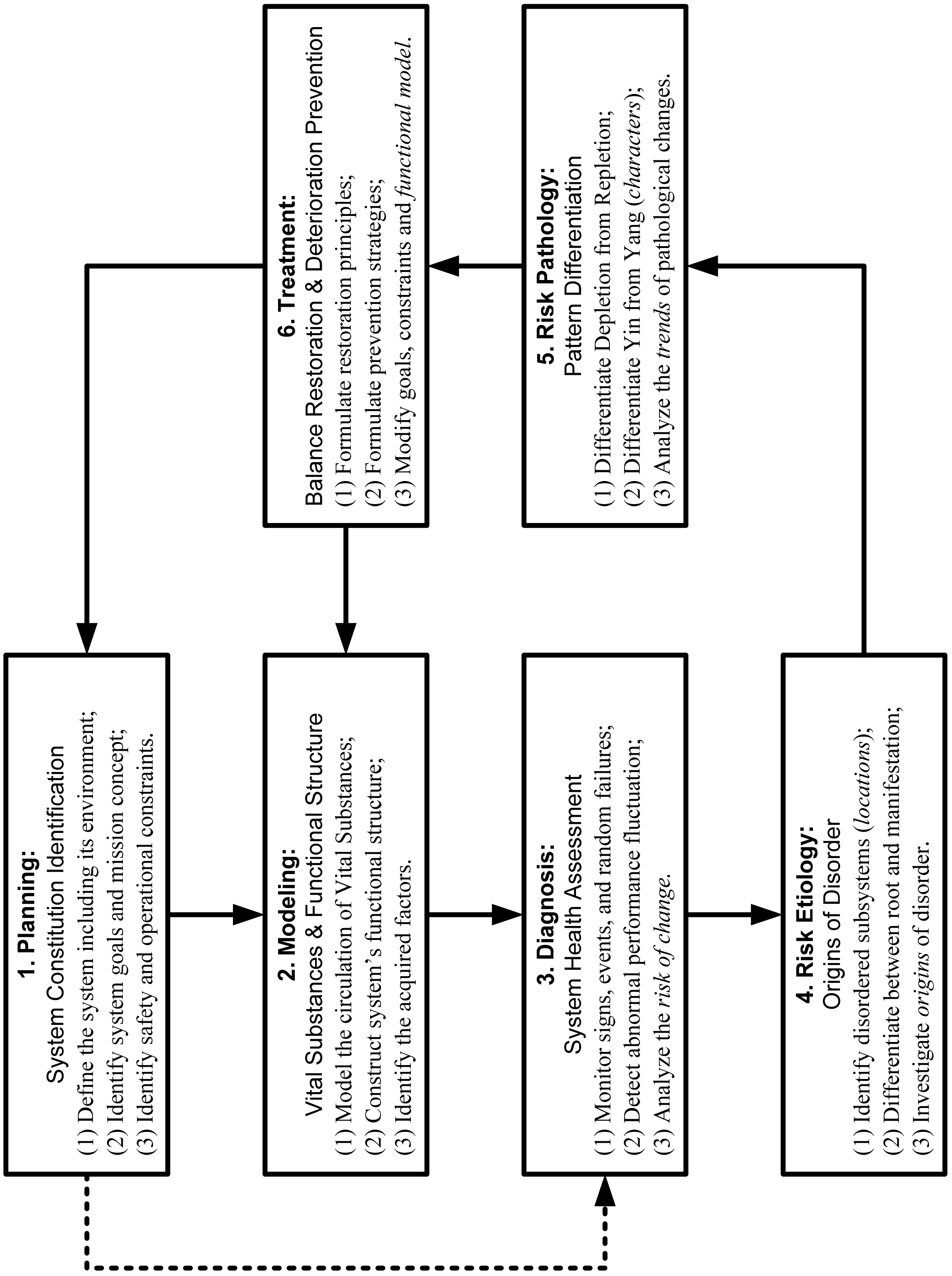

Figure 10-1. Adaptive System-Health Control Process

Table 10-2. Adaptive System-Health Control Process

Step Description	How the Step Is Performed	Why It Is Performed	References
1. Planning: System Constitution Identification	(1) Define the system including its environment; (2) Identify system goals, assumption and mission concept; (3) Identify the related safety and operational constraints that keep the system in health.	To understand the innate factors that set the basis for the system constitution	§ 4-3-1 § 7-1-2 § 7-2-2 § 8-3-1
2. Modeling: Vital Substances & Functional Structure	(1) Model the circulation of system's vital substances; (2) Construct the functional structure with System Dynamics modeling techniques; (3) Identify the acquired factors that affect the system constitution and development.	To simulate the operation of complex engineered system in order to understand how system health evolves over time.	§ 5-2 § 6-1 § 6-2 § 8-3-1
3. Diagnosis: System Health Assessment	(1) Monitor signs, events and random failures; (2) Detect abnormal performance fluctuation in system's functional model based on the goals and constraints defined in Step 1; (3) Analyze *the Risk of Change* and determine the corresponding health condition.	To analyze the urgency and seriousness of health condition based on available signs, events, and random failures.	§ 3-3-3 § 5-1 § 6-3 § 7-1-3
4: Risk Etiology: Origins of Disorder	(1) Differentiate the *manifestation* from the *root* disorders; (2) Determine the functional disorders and their related subsystems; (3) Analyze the origins of disorder according to the available *manifestation*.	To identify the disorder *locations* within the functional structure and to analyze the *origins* of those disorders.	§ 3-3-2 § 4-3-2 § 9-1-1
5. Risk Pathology: Pattern Differentiation	(1) Differentiate between *depletion* and *repletion* patterns; (2) Differentiate between *yin* and *yang* patterns; (3) Analyze the pathomechanism and potential pathological changes according to *wu xing* interrelationships.	To determine the *characters* of the identified functional disorders and to analyze the *trends* of pathological changes.	§ 3-3-3 § 8-1 § 8-2 § 9-1-2
6. Treatment: Balance Restoration & Deterioration Prevention	(1) Formulate restoration principles; (2) Formulate prevention strategies; (3) Modify goals, constraints and functional model of the system.	To restore necessary balance for the system and prevent further functional deterioration.	§ 3-3-3 § 7-2 § 9-3

The adaptive system-health control we propose consists of the following steps as briefly described in Table 10-2 including planning, modeling, diagnosis, risk etiology, risk pathology and treatment. The "references" column in the table indicates chapters in this dissertation that relate to each step. Each step is discussed and demonstrated with an illustrative case study in a later section.

The basic idea of our system is that we extract and organize the way TCM tries to heal with the human body system and apply it to health control in complex engineered system. In TCM, diseases are not determined solely by the attacks of external factors (*pathogenic evils*), but also by the body's constitution (literally, how the body is constituted) and the condition of the body (*anti-pathogenic qi*) at the time. It is the reaction of the body to the attacks that defines a disease. We apply this basic idea to the risk analysis for complex engineered system: accidents are not determined solely by the attacks of external factors (*pathogenic evils*), but also by how the system constitutes itself – literally the way of its formal nature – and its health condition.

The first step, planning, is to develop an understanding of how the system is constituted, what forces are at work within it, and how these forces together "are" the system. System constitution affects how a system reacts to change, determines whether the change would lead to an accident or not, and also affects how the system responds to treatment we may apply. In a complex engineered system, systems are constituted largely of system structure, goals, and safety and operational constraints.

The second step, modeling, tries to simulate system behavior using the concepts of system dynamics we have covered. Using the conceptual vocabulary we have developed through our study of the dynamic, holistic nature of TCM, a complex engineered system consists of its functional structure (*yang*) and the circulation of several vital substances (*yin*) that sustain its functionality. Each component follows the *yin yang* relationships and acts as a whole. Each sub-functional system is modeled with reference to their functions and to their relationships with vital substances, other subsystems, and other parts of the system. Among subsystems, there exist interrelationships (facilitation, restraint and synergy) similar to the *wu xing* system that defines how the functionality of each subsystem is supported and constrained by the others and how they together govern the operation of the whole system.

The third step, diagnosis, seeks to diagnose the current situation of the system and assess its health condition. Warning signs, events and random failures are collected at this point for later analysis of system disorder. The risk of change analysis that draws on speed of change and system inertia we have developed is applied to assess the system's health. With the assistance of the computerized system dynamics model established in Step 2 and the goals and constraints defined in Step 1, we can identify problematic links in the functional structure of the system and assess the condition of each subsystem as either hyper-functional or hypo-functional.

The fourth step, risk etiology, resembles what hazard analysis tries to do in conventional risk analysis – namely, it seeks to identify all possible hazards that can cause losses to humans, property, and environment. However, in our proposed risk etiology, hazards are not just identified, but are also categorized according to the various forms of functional disorder (*root*). Each category is then connected with the collected signs, events and random failures (*manifestation*) that may result from the disorder. The *origins* and *locations* of disorder are identified.

The fifth step, risk pathology, tries to find out how a functional disorder arises and develops. By differentiating patterns shown in the collected signs, events and random failures, we characterize functional disorders into *depletion/repletion* and *yin/yang* patterns. Each pattern has its unique *character* that suggests ways of treatment. By applying the interrelationship of *wu xing*, we can examine the disordered subsystems hyper- or hypo-functionality together and obtain the *trend* of how such disorders are developed and will develop in the future—in other words, a system prognosis.

The sixth step, treatment, suggests treatment principles according to the *origins, locations, characters* and *trends* of the disorders. The basic concept of treatment is to restore broken balance and to prevent further deterioration. According to the identified treatment principles, we may at this point revise system goals, reduce system constraints (in Step 1) or modify the functional structure (in Step 2) to adapt to the changes that disturb the system.

The proposed system-health control framework is not about anticipating accidents and making preparations for events that are most likely to happen, but rather about understanding the capabilities of the system and the challenges that currently face it through "making sense" of the signs, events and random failures that are presented to us as system managers. The upside of this approach is that even if we do not know what accident is going to happen, we can still deal with the causative situation with careful diagnosis of the system conditions. The more we understand our system, the more we are likely to identify a problem early. The downside of this approach is that the remedy for known accidents may not be as accurate and take effect as quickly as the conventional approaches do.

10-2. Framework Demonstration and Evaluation

10-2-1. Change Orders in Construction Project Systems

Construction projects are extremely dynamic and complex. They consist of multiple interdependent component sub-systems, which have multiple interacting feedback processes, and non-linear relationships (Love et al. 2000, Bertelsen 2003). For instance, scheduling is a feedback process which interacts with budgeting and job progress; both of them also feedback processes. Surfeits or deficits in time have important chain effects; if a project schedule is unrealistically short, this has implications on budget and job process. Such effects are bi-directional – budget deficits or surpluses may affect job progress, which must be accounted for in scheduling. Similarly, budget and quality have a non-linear relationship; an increase in project spending does not necessarily connote an increase in project quality. Since these are all non-determinate factors which differ from case to case and differ substantially *within* cases, the state of the process is constantly changing and requires proper management to achieve project goals.

An important aspect of how a construction company deals with change is the *change order*. We are interested in the management of risk of change and cost involved in a *change order*, a form of change ordered by an owner on a project in progress. In the industry standard account of change orders, there are three basic components to a change order: 1) Scope, 2) Time and 3) Cost. (Civitello and Locher 2002 p.183)

Cost, which we have previously hinted is an important component in the system view which we have developed, is split out into three categories: *direct*, *indirect*, and *consequential* costs. *Direct costs* are those costs which are documentable and directly assignable to some event. Labor, material, shipping, scaffolding, and temporary heat, light and power are all examples of direct costs. *Indirect costs* are those costs which are related to the change order but cannot be directly assigned to any particular event. Home office expenses, the cost of off-site supervision, the cost of time delays and increases in the duration of the guaranty or warranty which the contractor must provide the owner are all examples of indirect costs. Finally, *consequential costs*, or damages, are costs which result from the impacts and effects of a change. For instance, if a schedule delay pushes construction from summer into winter, the costs of doing construction in the colder climate would be considered consequential costs. Lost profit, project delay costs, cash flow interruptions in the owner or contractor's businesses, lost opportunity cost for the owner or contractor due to the delay and the cost of interference or disruption caused by a change in the process are all examples of indirect costs. (Civitello and Locher 2002 p.184-188)

In the management of risk for construction projects, existing approaches to change management (see Figure 10-2) focus on the reaction to previously identified changes. Thus, owners of construction projects often draft complex systems of contracts written to exculpate owners from the costs and liabilities associated with even unreasonable changes. On the other hand, contractors try to avoid the potential for change orders by "prospecting," or carefully examining work once accepted for any areas that may require correction or change. In both cases, contractors and owners are dealing with the uncertainty of future behavior on each others parts by using previously acquired knowledge as to "what can go wrong" to examine and troubleshoot proposed plans. Owners, through contracts, attempt to prevent previously observed harmful behavior by contractors through specifically worded "exculpatory clauses." Contractors, on their part, do extensive pre-construction analyses after the work is accepted, testing for common problems such as difficulties with code compliance, zoning, schedule conflicts, adequacy of ceiling space, light fixture locations and other apparently minor but potentially project-threatening issues. (Civitello and Locher 2002 p.101-102; O'Brien 1998 p.107)

The conventional approach as we describe it, however, experiences critical difficulties because its view has important insufficiencies with regard to time and the interrelationship functional sub-systems. A classic example is the time delay in change order paperwork and job progress. Results-oriented, "macho" field managers with a disdain for paperwork often build work-in-place before the change orders have been processed for them. Since completed change order documentation is required in order to pay for work-in-place, the result is recurrent contractor and sub-contractor cash flow difficulties as work is performed before owners have adequate paperwork in place to pay for it. This often results in messy litigation or insurance claims by owners, contractors or subcontractors where differing arguments by all three parties are made. (Civitello and Locher 2002 p.201) We refer to this problem as "work-in-place before payment."

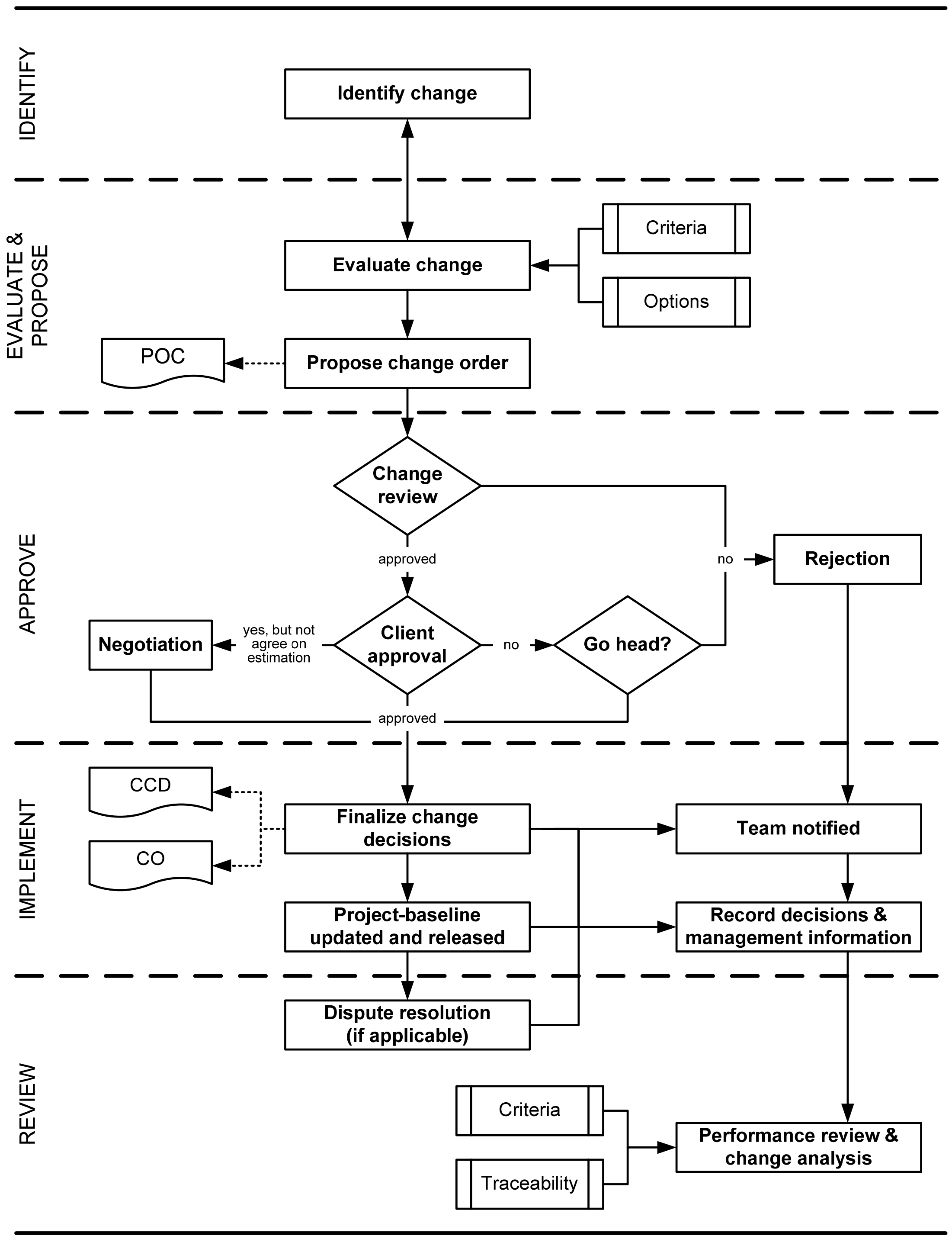

Figure 10-2. General Change Order Process
(Hao et al. 2008)

When faced with the problem of work-in-place before payment, a standard account advises that owners issue unilateral change orders, and that contractors carefully examine potential work with the awareness that "change and the change process must be managed." (Civitello and Locher 2002 p.201) However, unilateral change orders from the owner, the owner's assignee or the contractor is definitionally an un-balanced state (where one party's needs are balanced over another). For contractors, the awareness that "change must be managed" is trivial; contractors are more interested in *how change must be managed*. For such detail, the standard account is either silent or supplies only a series of preventative "prospecting" procedures based on a probabilistic judgment that costly measures must be taken to prevent uncertain failures which are judged more likely to occur simply because they occurred in some past project or are listed in an industry-standard text such as Civitello's.

The fundamental issue in the "work-in-place before payment" problem is a lack of synchronization between two feedback processes in the contractor: the *budgeting* process, specifically that part dealing with approval of new or changed work, and the *value creation* process that deals with the physical construction on-site.

When the pace of work-in-place exceeds the pace of budgetary recording and control, it connotes multiple dysfunctions of flow. First, it shows the primary problem: an insufficiency of the flow of information, or *stagnation of information flow*, in the form of approved change orders emanating from the owner and going through the general contractor down to the sub-contractor. In addition, the sub-contractor performing work before the arrival of sufficient information (in the form of budgetary approval) is in a *hyper-functional state*, where the outputs of the subcontractor's process are growing faster than the input. Another real risk in this context is the risk of "burnout" or an unsustainably accelerated *depletion cycle* of the sub-contractor's human resources. Finally, in addition, the lack of payment received by sub-contractors is a deficit of *vital substances* – in this case, money. Should this depletion cycle continue, the sub-system – here the sub-contractor – can be expected to fail. As we will demonstrate in our case study, these symptoms all occur even when the symptoms are different – the underlying causes of discord between owner and contractor produce systemic, trended changes in contractors in a manner compliant with the *Tao* or "way of doing business" of each party, contractor and owner.

The causes of the problem of "work-in-place before payment" occur at multiple levels: between the owner and their desired goals, between the general contractor and the owner, and between the sub-contractor and the general contractor. According to our notion of system constitution, any change or dysfunction affecting one system must also affect other levels. Thus, we see in the "work-in-place before payment" problem that although the difficulty is with the sub-contractor's payment, this has consequences on the general contractor's reputation and ability to employ other sub-contractors, and similarly affects the owner's faith in the professionalism of the general contractor.

In addition, the problem of "work-in-place before payment" has multiple etiologies. The primary problem, insufficient communication flow, stems from the interrelationships of functional structures in the construction project, not from any particular property of just one member. These relationships are often set at the beginning of the project and constantly revised; the problem we are dealing with may be a systemic problem embedded in the nature of the project (e.g. a contractual structure creating an underfunded budgeting department), or may have arisen over the course of the project (e.g. unforeseen changes in credit conditions raising the cost of unpaid work over an acceptable level for the sub-contractor).

The pathomechanism of the problem of "work-in-place before payment" occurs at multiple levels of system: first, between the owner and the system's goals; second, between the owner and the contractor; thirdly, between contractor and the sub-contractor; and finally, between the sub-contractor and the work performed.

For the owner and system's goals, once the constitution of the construction project is thus modeled, we must inspect whether or not the project time and budgetary constraints established by the owner are adequate to the task. For the owner and contractor, we would inspect the contractor's state of flows of time, money, and information, not only as conceived in a contract but also as practiced across time. This is in contrast to a standard view that advises adversarial, pre-emptive conduct by owners and contractors to prevent probabilistic difficulty. For the contractor and sub-contractor, we inspect whether or not the sub-contractor is a hyper- or hypo-functional sub-system in the contractor's activity as a system, and determine the effects of hyper- or hypo-functionality on other components; the case may be that the problem of "work-in-place before payment" is the least of our problems and may not warrant a direct solution. Finally, between the sub-contractor and the work performed, we must inspect whether there are limiting or over-expansive factors within the sub-systems of the sub-contractor which create blockages of flow (e.g., there may be inefficient transmission of change order documentation by sub-contractors or embezzlement by sub-contractors which is invisible to the contractor or owner).

As balance-restoration, then, we would recommend a set of measures to restore a proper balance between the different levels of the construction project system, as well as within the different sub-systems of the construction project.

For instance, for the relationship between the owner and the general contractor, we would advise a more communicative and open dialogue about time requirements *prior to the consideration of bids*. As O'Brien (1998 p.106-107) puts it, "In most cases, bidding contractors do not make a serious evaluation of the contractual time requirements unless the requirements are unusually and obviously stringent…The bid of the contractor who has questioned or conditioned the time frame of a contract usually must be rejected. Therefore, most contractors will not do so, but they may state their reservations about the projected dates after the award of the contract." Such impression management represents a malformation of flow between contractor and owner – in this case, a reciprocal flow of information with regard to expectation-setting.

What, then, does our system specifically recommend with regard to the problem of "work-in-place before payment?" Our proposed solution is:

1. Planning
2. Modeling
3. Diagnosis
4. Risk etiology
5. Risk pathology
6. Treatment

We will examine each step in depth. The overall goal is to promote a healthier overall construction project. Few studies have been devoted to promoting a healthier project operation and prevent accidental changes from happening, and even fewer have analyzed change orders in such a context. The core of the approach that we suggest with regard to change orders is that instead of waiting for the changes to happen, a better management of change should seek to identify the characteristics and constitution of a healthy operating project to plan preventive measures and coordinate changes across the entire project system.

The purpose of this case study is to test the risk analysis methodology we propose in a hypothetical context. In this situation, our system holds that the essential way at work is that risk comes from changes to the system. A fixed system would not incur any risk, but would also eliminate the opportunity for success; for the purposes of risk analysis, such a system would not be considered. Thus, most systems are, to a lesser or greater degree, unfixed and changing – at least the ones that would be considered by risk analysis. The effects of changes may accumulate over time and pose increasing risks to the system until the weakest link in the system breaks down and causes failure. To maintain a healthy system, all of the forces (factors) that cause change have to be maintained in a dynamic balance that moves the system towards its goals. Signs revealing imbalance may indicate an upcoming failure in the system.

From the standpoint of the construction company under consideration, this case study illustrates a new approach to change management and an opportunity to reexamine the interrelationships between different key subsystems and the environment of the construction company. In our view, these are *schedule*, *sustainability*, *budget*, *work efficiency*, *safety* and *quality*. It is emphasized in the case study that the primary circulating vital substance from which the system is constituted is information. The primary physical manifestation of the system is the *creation of value*. The case study shows how our system helps to clarify and potentially quantify the benefits and risks of change in complex engineered systems in operation—in other words, a dynamic view of a system as a whole and how it comes to terms with to change. We will now explain our framework step by step in detail in the following section.

10-2-2. Adaptive System-Health Control

Planning: System Constitution Identification (Step 1)

The company's plan is its blue print for system growth and a road map of its development. Planning involves goal setting on the basis of specific assumption and mission concept while keeping the system operation within its necessary constraints. For the purpose of system health control, this planning aims to understand the various innate factors that set the basis for the constitution of complex engineered systems. The foci of this step are:

- Define the system; to define a system is also to define its environment, which clarifies relevant influences outside the boundary of the system affecting or are affected by it;
- Identify system goals, assumption and mission concept;
- Determine the related safety and operational constraints that keep the system in a healthy state.

In defining the system of the Construction Project System Case, we can understand it as existing at two levels:

- The industry level
- The company level

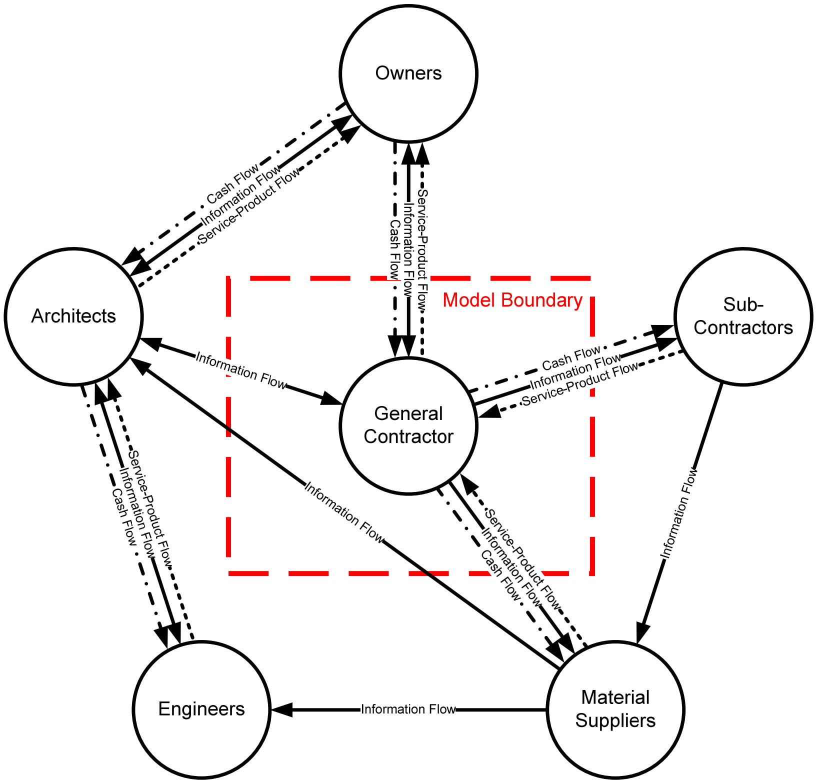

Figure 10-3. Model Boundary & External Relationships

At the industry level, the company participates in a contractually defined environment that exists in relationship to other components of the construction company sub-system (for instance, its suppliers, the architects that design its work, its sub-contractors, engineers and its clients or owners). At the company level, the system goals and mission concept are to maximize profitability (the rate at which the system obtains *money*) and productivity (the rate at which the system produces *value*). The primary constraints on the system's operation are the socio-cultural, technological, financial and regulatory forces affecting the industry at large (and potentially the company in particular).

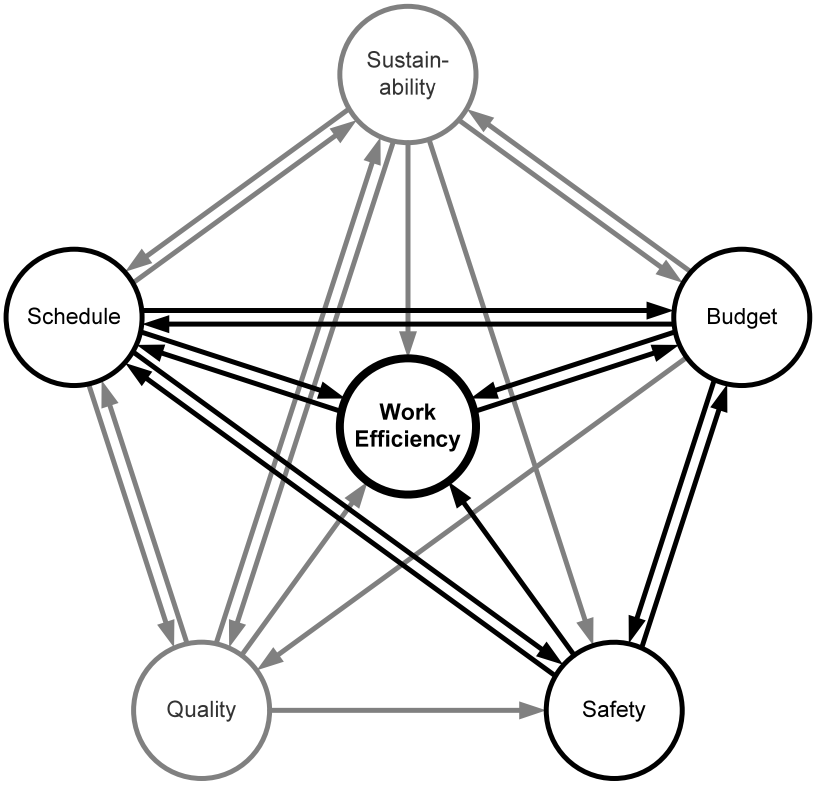

Figure 10-4. Subsystem Relationships

Modeling: Vital substances & Functional System Structure (Step 2)

The purpose of this modeling step is to understand the operation of construction project systems through simulation. Major influences, such as the functional structure of the system and the circulation of its vital substances – in this case, capital, information and value which are all required for the operation of the system's sub-systems – along with the effects of various forces on its constitution and growth (e.g., acquired factors in constitution, influencing forces, patterns of system operations) are at work. Together, these factors determine how the system's health changes over time.

Although we are able to form a mental model of the essential processes and relationships, the complexity of most real systems vastly exceeds our capacity to understand their implications. Formalizing qualitative models and testing them via quantitative simulation can lead to radical changes in the way we understand the system. The foci of this step are:

- To model the circulation of system’s vital substances;
- To construct the functional structure with system dynamics modeling techniques; and
- To identify the acquired factors that affect the system constitution and development.

The behavior of a system emerges from its structure. Per Sterman (2000 p.107), we concur that structure consists of the feedback loops, stocks and flows, and nonlinearities created by the interaction of physical and institutional structure of the system with the decision-making processes of the agents acting within it. Thus, the structure we are looking for in this example is one based on dynamic functional activities (budgeting, planning, building) rather than the fixed physical structures that perform the activities (offices, cranes, scaffolds). In such a structure, subsystems are discussed always with reference to their functions and to their relationships with the vital substances, other subsystems, and other parts of the system. It is only through these relationships that a subsystem can be defined. Absent the relationship between the budgeting and architecture departments, for instance, these terms lack meaning; they may as well be oddly small and disconnected accounting and engineering firms. Only their work together in defining the project’s budgetary and architectural constraints provide their definitions. Our system-health control framework proposes to organize all the known and observable system behaviors of these sub-systems into an integrated set of functions and relationship patterns. Understanding these patterns enables us to identify and treat disorders in them.

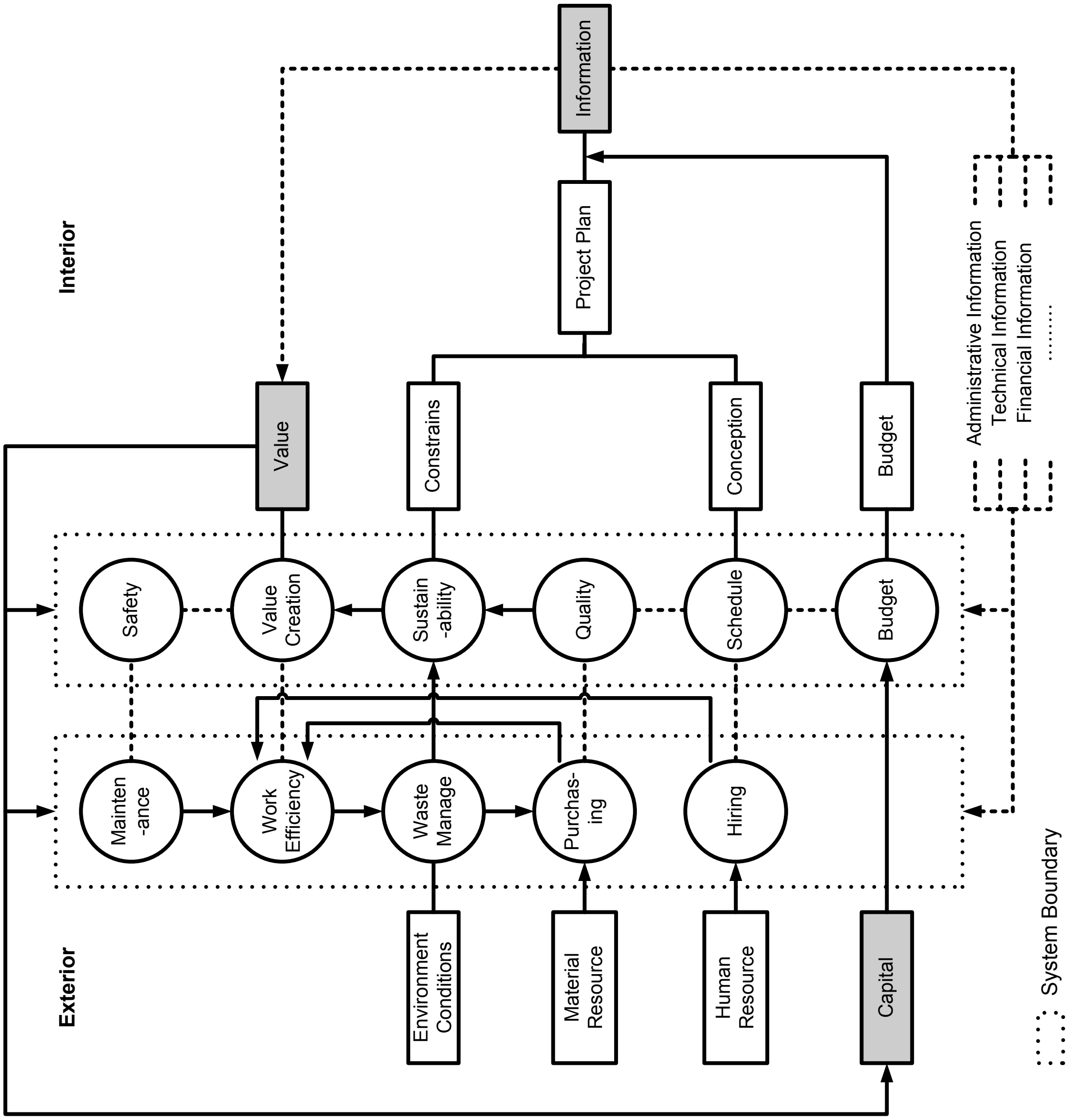

Figure 10-5. Vital substances in a Complex Engineered System

As discussed in the previous section, forces of change are essentially patterns that can take many forms in complex engineered systems. Examples of such forces in human systems are diet, habits, emotion, and age. In our construction project example, we are dealing with forces like constitution (the effect of the form that money and information take, for instance a credit memo or cash), long-term behavior patterns in organizations, and the unique effect of individual human behavior on a whole project. We may divide these into two types of factors: acquired factors and innate factors. *Acquired factors* are various factors that the development of a system depends on. For instance, a construction company that fosters a good organizational culture with coherent policies and procedures and employs high quality human and natural resources generally develops a strong and healthy constitution; what it "eats" literally determines what it is. Absent such strong constitutional factors, system constitution may become weak and the system may become more prone to failures. The system's *innate factors* will include details such as the nature of its formation, the goals initially set by the system (identified in Step 1), and the contractual relationship it enters into with its clients, sub-contractors, engineers and employees. Operational and safety constraints which apply to the entire industry are also innate factors in the construction project's operation.

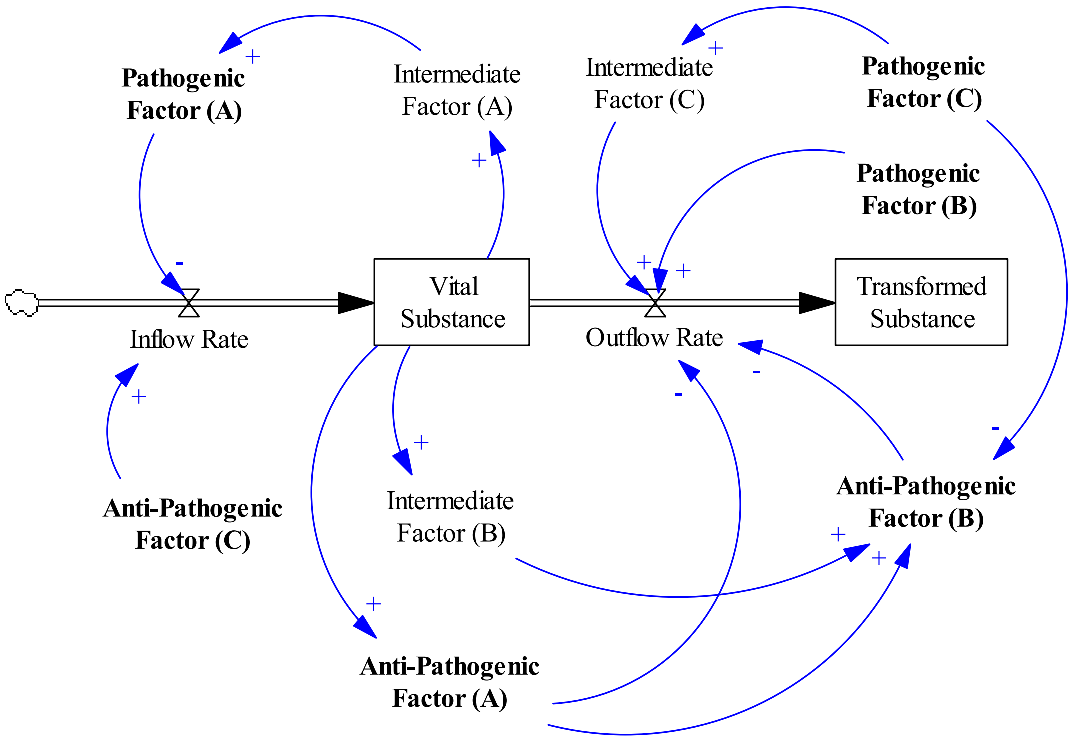

Figure 10-6. Functional Structure Diagram

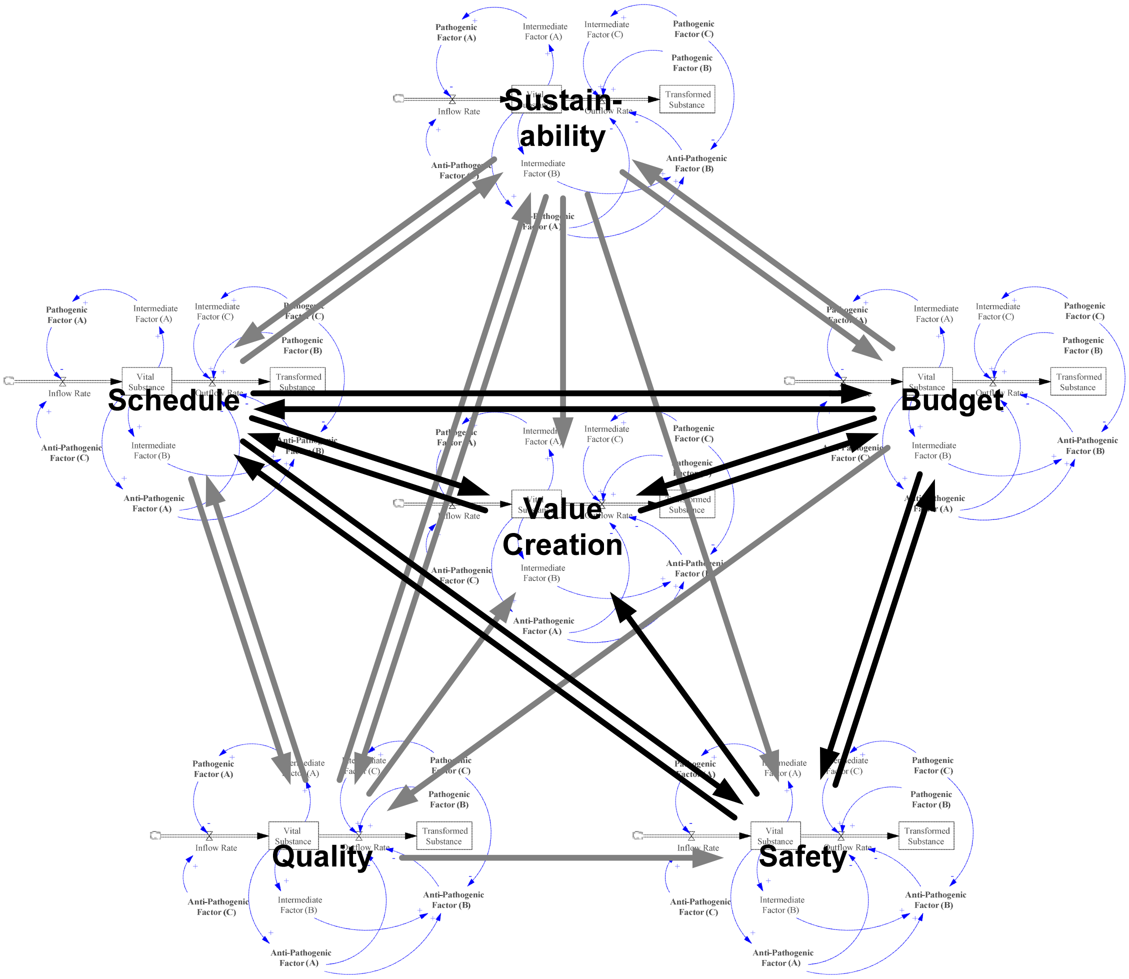

Figure 10-7. Complex Engineered System Structure

Diagnosis: System Health Assessment (Step 3)

The network of functional subsystems that are modeled in Step 1 and 2 sustain the system activities of storing and supplying, maintaining and creating, purchasing and recycling, preserving and transforming. When all these activities take place harmoniously, the system is healthy and in balance. The concept of system health is a simple sense of equilibrium, but is not easily quantifiable. Thus, the diagnosis in Step 3 is trying to establish quantifiable criteria for system health by analyzing the risk of change. The foci of this step are:

- To monitor signs, events and random failures;
- To detect abnormal performance fluctuation in system's functional model based on the goals and constraints defined in Step 1;
- To analyze the risk of change and determine the urgency and seriousness of its corresponding health condition.

Risk Etiology: Origins of Disorder (Step 4)

Risk etiology in our proposed system health control is similar to the hazard analysis in conventional risk analysis. In most cases, hazard analyses simply classify hazards into naturally occurring and artificially induced hazards, and try to identify all possible hazards that could cause losses to humans, environment, and property. (Ayyub 2003; Brebbia and Popov 2006; Henley and Kumamoto 1992; Kumamoto and Henley 1996; Modarres 2006) In our proposed risk etiology, we suggest that potential hazards have to be classified according to the various forms of functional disorder (root) after the system's exposure to the hazards, and each category should be connected with available signs, events and random failures (manifestation) that may result from it. Understanding the relationship between hazards and manifestation allows us to identify the locations and origins of functional disorders when corresponding manifestations appear during system operation. In addition, intermediary causes – problems that result from other problems and themselves cause further problems – are identified. The foci of this step are:

- To differentiate the Manifestation from the Root disorders;
- To determine the functional disorders and their related subsystems;
- To analyze the origins of disorders according to the available Manifestation.

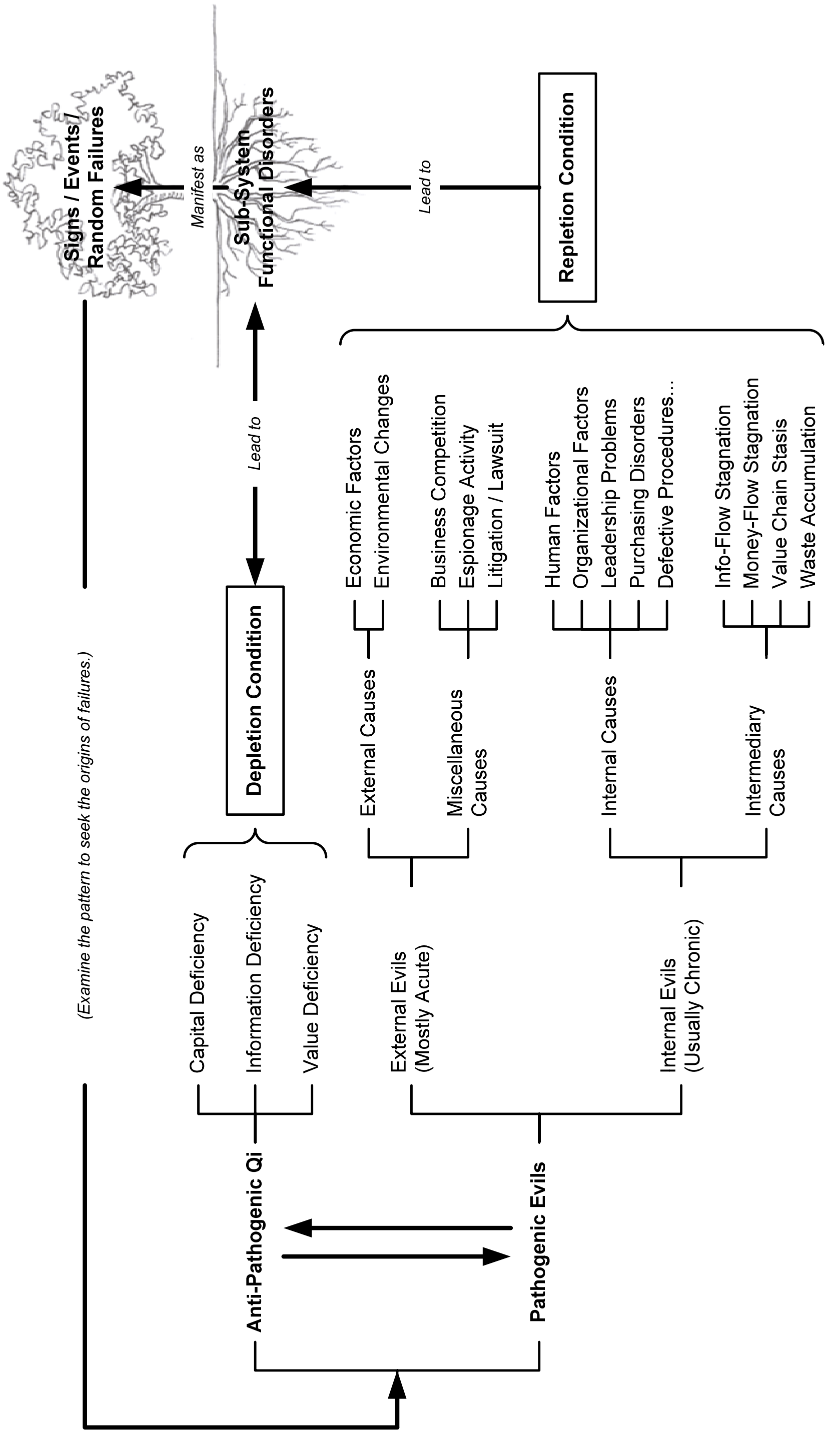

Figure 10-8. Origins of Disorder in Complex Engineered Systems

Risk Pathology: Pattern Differentiation (Step 5)

Risk pathology explains how a functional disorder arises and develops, how its manifestations change and how they can be resolved. The conventional approaches to risk management analyze how accidents occur at a microscopic level and trace back in the timeline for every piece of evidence of failure in order to reconstruct the cause and effect of the accidents. The process of developing remedies for those accidents, however, is often separate from such analyzing processes. Our proposed risk pathology instead is concerned only with the broad process and change of functional disorders in light of their general characters and pathological trends such as the relative strength between anti-pathogenic *qi* and pathogenic evils and the balance between *yin* and *yang*. Such analysis is crucial because it becomes the basis of treatment that determines the restoration principles and prevention strategies later in the system health control processes. One can see how the two approaches, although quite different, can be complementary because conventional approaches could benefit from the assessment of the broad picture provided by our proposed methodology. The foci of this step are:

- To differentiate between depletion/repletion patterns;
- To differentiate between yin/yang patterns;
- To analyze the pathomechanism and potential pathological changes according to wu xing interrelationships.

Due to time constraints of this research, when applying to complex engineered system, we employ only *repletion/depletion*, *yin/yang* patterns and the concept of *wu xing* interrelationships as the basis for our proposed risk pathology.

As shown in Figure 10-9, when applying the *repletion/depletion* concept to complex engineered systems, the system of “stocks and flows” represents a functional part of the system with a vital substance flowing into and out of it. Various anti-pathogenic and pathogenic factors affect in- and out-flows of the system. When vital substance is deficient, levels of *anti-pathogenic qi* become weak, causing problems to other parts of the system that are supported by the relevant vital substance. In this case, the system presents a *depletion* pattern since the problem results from the deficiency of vital substances.

When the *pathogenic evils* are in excess, the inflow of vital substance decreases and its outflow increases, causing problems to system function. The system may present a *repletion* pattern since vital substance is sufficient; however, if the *repletion* pattern persists, vital substance may deplete further, causing further problems to the system and making the pattern transform into *depletion*. The converse is true as well – a *depletion* pattern may sometimes transform to a *repletion* pattern.

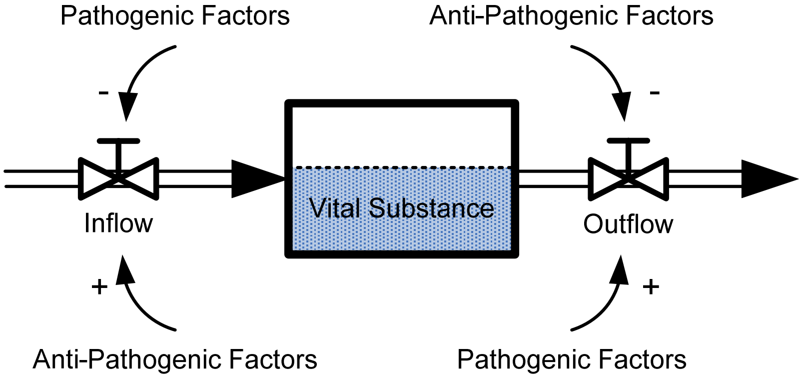

Figure 10-9. Pathology of Repletion and Depletion

In complex engineered systems, there may not exist a complete set of generating, restraining, overacting, and counteracting relationships between subsystems similar to that of the *wu xing* system. However, there will always be *some* form of relationships between them. Thus, the interrelationships of *wu xing* can serve as a model for checking the completeness of the complex engineered systems in question. By identifying those relationships and checking on whether functional sub-systems are there (for instance, whether there is a budget department, whether it works sufficiently and indeed if one is needed), we are able to formulate necessary restoration principles and prevention strategies as we are going to discuss in Step 6.

Treatment: Balance Restoration & Deterioration Prevention (Step 6)

The fundamental idea of our proposed system health control is maintaining the dynamic balance of the system. There are myriad of hazards and accidents that could make the system suffer, but they are all rooted in one source – the breakdown of the system's dynamic balance. Similarly, there are myriad of remedies for hazards and accidents, but they are all aimed at one goal – restoring broken dynamic balance and preventing further functional deterioration. Thus, the foci of this step are:

- To formulate restoration principles;
- To formulate prevention strategies;
- To modify goals, constraints and functional model of the system.

10-2-3. The Two Paradigms of Risk Analysis

Conventional Risk Analysis (the Risk of Chance)

Conventional risk analysis acts on failure events. Identifying and mitigating those events are the focus of such analysis.

- Before failure: We perform hazard analysis, event-tree/fault-tree analysis to identify potential failures and rank them with their risks. We then come up with risk management options to prevent major risks from happening.
- During failure: We perform interactive management (if events are anticipated) or crisis management (if events are not anticipated) to reduce and mitigate possible consequences.
- After failure: We perform investigation into the failure events (case history), reconstruct the failures and learn from them.

Major problems of the conventional approaches:

- Failures that happen are often outside of expectation.
- Diagnosis (risk assessment) before the failure events provides the severity and possibility of them. The treatment (risk management) of those events is designed event by event. In case of crisis management, diagnosis and treatment are remotely connected.
- The investigation afterwards (case history) helps prevent the next failures that may or may not be the same as investigated.

Proposed Risk Analysis (the Risk of Change)

The proposed risk analysis acts on the changes of system health state. Identifying the disorders during normal operation of a system and restoring balance of system functionality are the focus.

- Start of System: We plan and model system operation to understand its constitution (capabilities and constraints).
- Normal Operation of System: We perform diagnosis, risk etiology and pathology to monitor and assess system health conditions.
- Disorder of System: According to the assessment and treatment principles, we create adequate remedies to restore balance and prevent further deterioration.

Major features of the proposed approach:

- We do not anticipate specific failures to happen or we expect any kinds of failures to happen. System boundaries are simply set at where the system has control over during normal operation.
- We try to examine signs, events and (small) random failures carefully, identify the pattern of disorders (origins, locations, characters and trends), and maintain system's normal operations. Treatment for the system is closed related to the diagnosis of its disorders.
- Our new approach provides a framework to consider various kinds of forces (quantitative and qualitative) that affect system behaviors. The system as a whole is analyzed, with the only principle being the maintenance of dynamic balance.
- System dynamics modeling provides a way to properly record and synthesize what we understood about the system. We evaluate the potential impacts of changes and policy decisions on risk by model simulation.
- The two approaches to risk analysis act on different focuses and stages. Although different, they complement each other.

Just as with TCM, our system does not speak about the management of emergency situations; in such states, the established discipline of crisis management "kicks in" and the role of system health control ceases. Rather, our system speaks as to the core managerial difficulties of *knowing what to do*, particularly in the non-emergency states that comprise the majority of engineered system operation.

A comparison of the two paradigms of risk analysis is showing in Table 10-3.

Table 10-3. Risk of Change Analysis vs. Risk of Chance Analysis

	Risk of Change Analysis	Risk of Chance Analysis
Risk Analysis Framework	Lay out system structures Identify critical state variable Set the desired state Analyze inflow and outflow rates Differentiate etiology Restore balance	Anticipate accidents / events Analyze loss and possibility for each accidents / events Rank risks Allocate resources
Risk Indicator	System inertia and speed of change of processes, procedures, patterns, habits, etc.	Probability and consequence of random failures, events, accidents, etc.
Risk Management	React to system state patterns (by adjusting inflow and outflow rates) Reserve power Reflex mechanisms	Proact, react, and interact to events / accidents Crisis management Backup systems / backup plans
Judging on	Processes	Results

10-3. Validation and Case Study

10-3-1. Validity of the Framework

Chief amongst the arguments that may be made against the account of systemic risk we set forth is the argument that all analogies fail. It may be argued here that those approaches used on human body may not applicable to complex engineered systems which are far more complex in terms of scale and with vague boundaries around systems when considering their potential consequences. In addition, the learning curve for the approach we set forth may be slow, especially when applied to a new system. However, the arguments that we make with regard to accurate (versus complex) continuous adjustments and iterative modeling (in particular to our reading of Marais) constrain the difficulties that emerge from possible system mis-match. Further, the argument that "all analogies fail at some point" does not deny the value of the analogy, merely arguing that such value should be modulated. We essentially argue for proper modulation of the analogy that we set forth. Lastly, the argument we make that the body/systems analogy underlies Western thought about risk grounds our approach in a critique of conventional paradigms of risk; as such, the validity of that critique must be held prior to its bases. Whether or not the critique is correct and produces valid results is a logically different question than whether it has valid bases.

Although the system of risk we discussed has a very fine-grained functional view of system components, oftentimes profound changes emerge from events completely outside of system control; this is the very definition of unpredictability outside bounds. If the change unfolds rapidly, crisis management should “kick in”; if the change unfolds gradually, however, our recommendations with regard to interactive management and adaptive control become particularly necessary to implement.

An additional difficulty with our concept of risk is that problematic patterns may vary from system to system and need time and experience to identify. Not all active forces can be identified and measured easily, requiring constant iterative improvement of system behavior models to adapt to system changes.

The approach that we set forth is not able to detect rare but severe events with sudden major impacts, nor does it claim to do so. With regard to accident preparedness, however, we suggest a measure of system health control to foster *reserve power* that can increase *system resilience* and reduce the possible consequence of severe sudden events.

Finally, it may be objected that the preventive health measures and consideration of non-crisis system states is insufficiently “sexy” or exciting to be implemented. Vitamins, it must be remembered, are considered rather dowdy, routine pills that no one ever sees as particularly important, while pain relievers, which have literal, tangible benefits, are considered of more importance. (Chesbrough 2003 p.65) However, avoidance of avitaminosis can prevent the necessity of taking pain relievers, and much like vitamins, implementers of our paradigm of risk may not be able to see improved system health immediately, but the net result of improved performance, especially when couched in terms of the functional emphasis of our framework, provide a tangible benefit to prevention over time. While people do not like to insure against the abstract (Taleb 2005 p.37), when managing the future cautiously, “The best way to predict the future is to invent it.” That is, the solution is to be practically focused, being the risk manager and the boss of operation at the same time.

The logical validity of our framework of risk as we argue it can be divided into two categories: internal validity, establishing the soundness and internal consistency of the concepts that we set forth, and external validity, establishing that our concepts of systems and risk are usefully predictive when applied. However, since our approach deals in particular with the behavior of imperfectly cognizant agents at certain points in system history, the validity of our philosophical and metaphysical assumptions and their consistency, or their internal validity, are tested effectively by their usability when applied. Conflicts and contradictions within the conclusions that we set forth are largely eliminated by the concept of holistic dynamic balance, which would dictate resolution of all practical questions regarding conflicts in principle through recourse to practical adaptive value. Since internal validity may or may not be logically relevant to our thesis while external validity is almost obviously required, we will touch on both in the case study that we will set forth primarily with regard to external validity.

Nonetheless, the conceptual bases for which we have to demonstrate internal validity may be considered to be as follows: system complexity, TCM, System Dynamics and the mutual agreeability thereof. TCM's validity we have touched on in our historical review; it is an established, WHO-recognized medical typology that continues to produce fruitful primary research to this day. With regard to the validity of our view of complex systems, since it rests on a critique of the risk of chance, acceptance of its validity requires only that the risk of chance be proven as an unacceptably quantifiable notion, which is demonstrated with regard to the unpredictability of future events ("unknown unknowables"). Finally, as we have demonstrated by using stocks and flows to adapt TCM systems of representation to system health, TCM does not conflict with system dynamics – indeed, it is possible to view *wu xing* as an endogenous form of systems theory that predates its modern form by over two millennia. We have demonstrated in-depth that these concepts produce harmonious, balanced operation in real cases like the floodplains of Amsterdam as well as hypothetical cases like our moving truck example. We turn now to a consideration of a case study to demonstrate the external validity of this approach when used in real cases.

10-3-2. Case Background: Marshall vs. Bureau of Reclamation Case

The conclusions we drew have value and produce non-trivial answers when applied to real situations. Here, we demonstrate that conventional solutions failed at multiple levels of system—for the system managers (Bureau of Reclamation), sub-system managers (Marshall Associated Contractors, Inc.), and indeed the environment (Borrow

Area C) as a system. When decomposed in light of the approach we set forth in this work, solutions based on the states of knowledge that decision-makers had demonstrated that what in hindsight appears to be the correct conclusion could have been arrived at *during* the course of the case. The case, here, is in essence one of sand. Moreover, one important point to note here is that this case study is our very first trial test application for the proposed framework; we do not claim nor can we prove that our suggested treatments for the participants in the case would have been the best solution for them since the history has been decided in this case study. However, the point we would like to make in this case study is that with the help of the principles established in our framework, it is possible to make a "better" decision along the way (when events unfold) based on the overall situation and information available at the time.

In 1982, the Utah district of the federal Bureau of Reclamation (BOR), a part of the federal Department of the Interior, began to solicit bids for supply of ASTM C33 sand for the purposes of building the Upper Stillwater Dam, located 40 miles from Duchesne, Utah. Marshall Associated Contractors, Inc. (Marshall), which had recently acquired an excavation and rock-processing company named Columbia Excavating, J.V., won the bid, signing a fixed-price contract for the supply of approximately 1 million cubic yards of sand and coarse aggregate.

Initially, several aspects of the contracting and bidding process seemed unusual to industry observers. The bid offered by the Bureau of Reclamation, notably, was short on geographical information, neglecting to inform bidders of overall geological conditions and withholding important survey data (as later established in legal proceedings). Contractors were prevented from obtaining their own survey information. Further, the raw material to be processed into sand was strictly controlled by the BOR, limited to only controlled parts of the "borrow sites" from which sand and aggregate could be drawn. Over the course of three years, the project broke down into an acrimonious lawsuit, a timeline of which is tabulated in Table 10-4. (Parrette 2002; Rome 2001)

Table 10-4. Timeline of the Marshall/Bureau of Reclamation dispute

Date	Events
23-Jul-1982	The invitation for bids from BOR issued—a project to supply, for a price of about $6.6M, about 1 million cubic yards of sand and course aggregate before the Upper Stillwater Dam project starts in 1983. Marshal takes the bids as the low bidder later. The original due dates and quantities of C33 sand were as follows: 1-Jul-1983, 289,350 cy; 1-Aug-1983, 385,800 cy; 1-Apr-1984, 578,700 cy; 1-Jun-1984, 771,600 cy; 1-August-1984, 964,500 cy; 1-Oct-1984, the full 1,061,000 cy.
27-Aug-1982	Marshall visits the borrow area with BOR personnel; it gets an impression that the material there would be easy to crush and there would not be a lot of crushing from visual inspection and the contract specifications.
31-Aug-1982	Bid opening.
27-Sep-1982	Marshall receives Notice to Proceed
Nov-1982	Marshall does its own sample test in a private laboratory, raising concerns about suitability of raw material for production of aggregate.
1-Dec-1982	Marshall notifies BOR of "friability" of the crushed material; BOR responds that it is unnecessary to change specifications based on high tolerances for differing composition and performance of the aggregate to be produced by Marshall.
11-Jul-1983	Marshall first notifies BOR of differing site conditions relating to unsuitable rocks for production of aggregate.
Jul-1983	Marshall reports 2/3rds shortfall in required production; BOR, in response, asks for an updated schedule. Gary Tucker, a recognized crushing expert, is hired to evaluate the situation and suggests that additional plant capacity appeared to be necessary to achieve the schedule.
23-Aug-1983	Marshall has produced only 20%, plans to double the productivity for 1983
13-Sep-1983	BOR's contracting officer (CO) writes to Marshall noting Marshall is delinquent in production, endangering contract performance, because it has produced only 20% of contract requirement, due 1-Aug-1983
22-Sep-1983	Marshall complains again the sand is degrading abnormally
28-Sep-1983	BOR personnel meet with Marshall's representatives and obtain a revised production schedule, agree to add plant improvements and hire a new superintendent with more crushing experience, in order to double its 1983 production rate. Results are due May-1984.
11-May-1984	BOR warns liquidated damages will be assessed daily beginning on 2-Nov-1984; Marshall's production does not improve.

19-Jul-1984	Marshall responds to BOR with the conclusion that most problems are the result of a differing site condition (hard and abrasive material).
23-Aug-1984	BOR meets again with Marshall. Marshall reports it is spending $50,000 daily to maintain production, and by October its revenue shortfall has amounted to nearly $8,400,000; BOR does not agree that the material at the site is different.
28-Sep-1984	Marshall files a certified claim with the BOR's contracting officer (CO)
6-Dec-1984	The CO terminates Marshall's contract for default on failing to produce the required amount of sand within the extended contract time.
26-Dec-1984	Marshall appeals the default termination decision.
11-Jan-1985	Marshall requests a final CO's decision on its differing site condition claim; but the CO never issues one.
Jan-1985	The CO and Marshall's surety orally agrees that BOR will convert the default termination to a termination for convenience and pay Marshall a lump sum amount to settle its claim. BOR's Commissioner in D.C. rejects the compromise.
(Jan-)1985	A re-procurement contract is awarded for $4.4 with relaxed requirements and the site condition is made clear that it "can be expected to produce heavy wear on crushing equipment." Results due in two year (Dec-1986).
1985	The new contractor is able to produce only about 20% of the required amount in the first year
May-1987	The new contractor produces only 389,334 cubic yards in total, as contrasted with the 472503 cubic yards produced by Marshall, in two seasons rather than three, at one third of the re-procurement contractor's price per cubic yard.

Several facts of this case are of interest before we proceed with an in-depth examination.

The underlying health conditions of Marshall and the Bureau of Reclamation (or BOR) could be ascertained prior to the beginning of the contract work. In legal proceedings, Marshall established that it expected at least a 10% profit on the overall operation, and had built infrastructure like access roads and bridges well in advance of need. (Parrette 2002 p.5) Independent experts, given the same set of specifications and tasked with the same project given Marshall's resources, produced similar plans projecting even higher profits, as much as 21%. Marshall had, at the time, a form of crusher known as "impact crushers" which were particularly well suited to the task of producing the type of sand that the Bureau of Reclamation requested. Since the initial solicitation presented the work as primarily screening of naturally existing sand deposits with comparatively little crushing work, Marshall's project managers and owners of course saw the BOR project as a natural fit. (Rome 2001 p.19-20)

In contrast, the Bureau of Reclamation existed in a state that legal proceedings have established as one of miscommunication and bureaucratic inertia. As it turns out, the basis of the specification problem that Marshall cited as being its chief objection to the work stemmed from Bureau regulations that prohibited surveyors (without geologic background) from using geographical terminology and mineral names to describe site lithology. (Rome 2001 p.35) Thus, differing estimates of the quantity of available natural sand that did not require processing stemmed from differing definitions of the term "sand"—in this case, either a United Soil Classification or an ASTM specification. At a profound conceptual level, the Bureau of Reclamation operated on what was legally recognized to be unsound bases.

The geology of the area, later established by expert testimony, was important information to the failure and to adopt a holistic vision of corporate and excavation processes as taking place against a backdrop of ongoing geological change. This meant that, as the court put it, "the contractor had alleged Type I and Type II differing site conditions and defective specifications." (Rome 2001 p.40) As we will show, this resulted in what is termed a Type III error or error of the third kind: solution of the incorrect problem. As later emerged during expert testimony, the borrow sites from which Marshall was obligated to draw sand were geologically unsuitable for sand production, not for any complex reason, but due to the underlying geological "story" of the region: (Rome 2001 p.35)

> *BOR offered expert evidence from Dr. William F. Brummond of Golder Associates ...In Dr. Brummond's view, the contract logs reflect that the soils are stratified, indicative of glacial outwash or river deposit, so-called alluvial soils. Rock Creek is a meandering stream, a "unique signature" indicative of river-deposited alluvial soil. The stream had at one time wandered across the Borrow Area. The bottom soils are covered by a layer of alluvial soils. With the exception of TP 127, the other pits appear to be located in the valley floor, which is overlain by alluvial material and underlain by glacial outwash, which produces rounded [and] semi-rounded rock. At the bottom of the valley floor is glacial till—unsorted and unstratified material that has been plastered down as a glacier has passed. (Tr. VI 132, 137, 139, 144.)*

> *The upper glacial outwash aid river-deposited soils tend to be stratified [and] are better sorted, meaning that they are separated in the size fractions, [that] is the underlying till, which has large boulders, cobbles and silts mixed together. Dr. Brummond would expect that the outwash has a higher percentage of sand than the underlying till, because the outwash does not have the same frequency of large boulders and cobbles. Also, the outwash and the alluvium, being near the surface, have undergone more weathering.*

In somewhat oversimplified terms, the ground that Marshall was working from was a combination of silt-rich, fine "glacier flour" too small for use as ASTM sand and extremely hard, weathered mineral deposits unsuitable for the manufacture of aggregate. A different expert, working from the same story, presented a similar conclusion: (Rome 2001 p.20)

> *It is believed that the upper portion of the deposit, sampled by [BOR], contains material which has been subjected to surface weathering. The material from the lower portion is composed of very hard, basically fresh boulders and cobbles coated with very fine silty material which probably represents the "rock flour" formed by the scraping action of the glaciers. The material from the upper portion of the deposit, on the other hand, appears to be softer, more deeply weathered, and does not contain such large amounts of silt. Professor Kopp concluded that the resistant rocks, mainly quartzite, making up the lower portion of the borrow deposit, caused much more wear on equipment than could have been anticipated based upon site conditions indicated in the contract.*

Although this could be anticipated by a "professional geologist familiar with the area," such a complete picture was not sought by either party. As Kopp continued: (Rome 2001 p.21)

> *The rocks were very hard, tough, quartzite. Glaciers had eroded the quartzites and they had been incorporated into the alluvium of streams flowing from the Uinta mountains, which should have been anticipated by a professional geologist familiar with the area. ...the Project solicitation had not covered the drainage basin's general geology and did not mention the vast amount of quartzite present in the major part of the source that supplied rock particles to Rock Creek.*

Further complicating the overall picture, the Bureau of Reclamation was pressed for time due to a water delivery contract requiring the dam, while also attempting to use a new type of concrete for the dam which did not require standard-at-the-time concrete cooling methods. (Parrette 2002 p.3) This new construction method, in fact, led to a later "satisficing" move on the BOR's part—rather than attempt to revise the specifications which were acknowledged by Marshall as well as independent experts to be flawed, the BOR simply relaxed the specifications on the sand it required for the dam: (Rome 2001 p.12)

> *The Aggregate Quality Evaluation reports for M-6447 and M-6448 listed L.A. abrasion test results for the samples after 500 revolutions at 43.9% loss and 42.9% loss, respectively. To permit use of material from Borrow Area C, BOR changed its usual specification limit from 40 percent loss to 44 percent loss.*

10-3-3. Case Analysis

In order to demonstrate external validity when constrained by bounded rationality, a key condition of our thesis, we will examine potential risk solutions at different stages of the affair mainly from Marshall's perspective.

Prior to Contract Award (Mid-1982)

Step 1. *Planning: System Constitution Identification* would have taken place, including innate factors and acquired factors to better understand system goals (mission) and capability (safety and operational constraints) for judging whether the system (Marshall) is suitable to take the bid or not.

Innate factors: Marshall was in good condition when BOR announced the bid, with a good reputation, good financial standing, and expanded capacity thanks to its acquisition of Columbia Excavating. In fact, at the time, Marshall was about to finish a crushing job in Oregon and needed a new location for its crushing plant, thus making the BOR contract in Utah a convenient fit.

Acquired factors: Operationally, Marshall was in a good standing; however, they neglected important geological data (that indicate the environment Marshall was working in) and petrological data (that indicate the quality of the essential "diet" for Marshall's system operation) that would severely affect their system constitution in the performance of BOR's contract.

Marshall could have sensed two red flags in the contract:

- The pre-test of the borrow site materials was not allowed, and site survey information as presented lacked a holistic geological picture of site conditions;
- Bidders would be responsible for all site conditions. Thus, even though on-site test samples were not available, Marshall could have hired a geologist to better understand the geological environment and its operation, thus attaining an idea of the constitutional nature of the borrow area, as well as the capability and constraints that Marshall would face working in that area. Since system constitution is not fixed and predetermined, but rather evolves over time in response to environment, learning about the environment that Marshall would be working in was of paramount concern at this point.

Thus, for diagnosis and treatment at this point, little difference would occur. It made sense for Marshall to bid on the job, as it needed the job to sustain its business. Although the conditions were not established at the time, the preliminary site examination and the data (which turned out to be flawed) BOR provided showed good potential for this project. Thus, only better flows of information, here a *vital substance*, would balance out the problem of insufficient realization.

Beginning of Contract (Late September 1982)

Here, ***Step 2.*** *Modeling: Vital Substances and Functional Structure* would better create an understanding of the circulation of vital substances and overall system functionality that Marshall's operation would experience. Thus, acquired constitutional factors based on the environment would be further examined and confirmed in this step.

Ideally, the system behavior model is best when created at the conception of the company and modified along the way (as a recording tool of system development since many evolutionary defects accumulate over time). Marshall may have had such a complete model, though its existence cannot be assumed as a given. Due to limited quantitative data available, we will limit our case study to a qualitative analysis with a simplified system model as shown in Figure 10-10. If a quantitative System Dynamic model is available, such a model could provide additional operational data (such as estimating the time in which Marshall's capital would be drained in this case, and assessing its subsystems' health conditions, etc.) for the risk of change analysis in the next step.

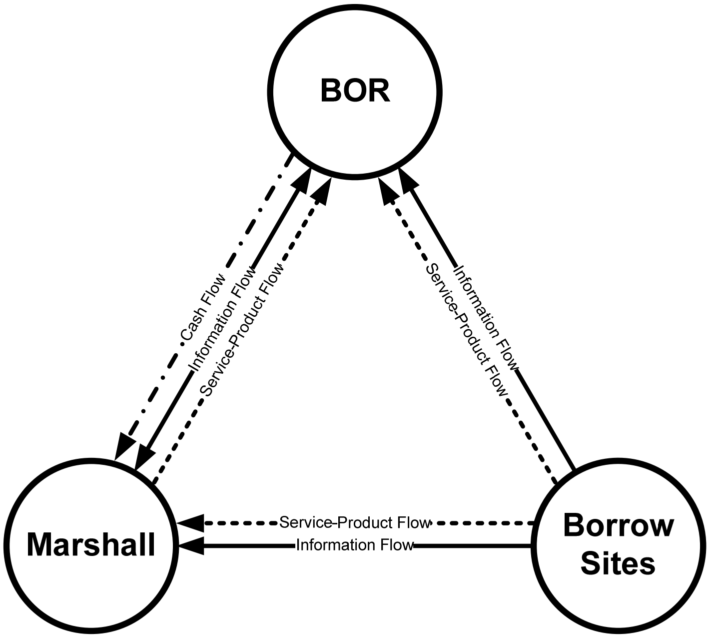

Figure 10-10. BOR-Marshall Contract System Model

One thing Marshall could and should have done in this stage was to request more site information from BOR or at least do an on-site sample test to confirm soil condition (its acquired constitution). Through such action(s) it could have found out that the data and specifications BOR provided were ignorant of the abrasive nature of the site material. Thus, with such information, Marshal could have filed a formal differing site condition claim and ask for a change order, and adjusted its original operation system designed for "mostly screening" operation to one better suited to crushing.

With regard to diagnosis and treatment at this point, Marshall missed its first chance to fix the problem early on. Thus, the *root* of functional deterioration persisted and started to develop over time. Since Marshall had a stockpile of reserve power (positive momentum), they were able to keep going despite serious operational difficulties and rising costs; such advantages, however, also blinded Marshall to the looming catastrophic changes. Marshal's health condition at this point would be at the section A-B as shown in Figure 7-3.

Awareness of Low Productivity (Mid-1983)

At this stage, ***Step 3.*** *Diagnosis: System Health Assessment* to monitor signs, events and random failures and detect abnormal performance fluctuation would have been performed. If a quantitative system dynamic model was available, it would be possible to analyze system performance in detail and find out potential operational problems.

From the record, it was at this stage that things started to go wrong (section B-C as shown in Figure 7-3). Signs (or in our framework, manifestations) emerged at this stage, like the friability of the crushed materials and low productivity as noted, and lack of support and promised supervision from the BOR. Given these manifestations, it would be incumbent upon Marshall to look for the *root* of the problem. Such problems were worsened by the constraints in operation; Marshall's working area was restricted, prohibiting it from excavating sand from other parts of the borrow site.

At this stage, Marshall was at B-C section of the health curve depicted in Chapter 7. From the results of Step 3, ***Step 4.*** *Risk Etiology: Origins of Disorder* would identify the disordered *locations*, differentiating between *root* and *manifestation* and investigating the *origins* of disorder.

At the time, expert opinions simply pointed out that there was a substantial throughput deficiency, and recommended measures to increase throughput (like increases in processing capacity). While correctly first examining internal processes, these analysts failed to identify the external *pathogenic evil* – in this case, the unexpectedly tough quartzite – because they focused on the particular problem (low throughput) instead of thinking in terms of how the pattern of rapid breakdown and replacement and low throughput were in fact system's reaction or *adaptations* to the *pathogenic evil* at work.

Only in hindsight, however, did expert opinion suggest that the *root* of the problem was the underlying soil condition that made the raw material that Marshall was to use into a *pathological evil*. Thus, proper treatment at this time, based solely on the evidence available (not knowing that the soil was very problematic), would have been to find a way to restore this balance in the final product, allowing the system to recover its balance. Attempting to expand the list of available borrow sites was one such solution (in fact, the BOR when they re-contracted explicitly allowed this, as if recognizing that this was one of the best ways that they could get the sand/aggregate mixture they wanted).

Running into Revenue Shortfall (August 1984)

Proper analysis according to ***Step 5.*** *Risk Pathology: Pattern Differentiation* would have pointed out a better solution for them at this stage. Based on the preponderance of evidence gathered in the case report, which relies on existing trends within Marshall's operation instead of the statistics of soil samples, it is clear that Marshall was initially healthy with abundant *anti-pathogenic qi*. Subsequently, Marshall's operation system was attacked by *pathogenic evil* (even though the true evil, the abrasive raw material, was not clear at the time) and resulted in a *repletion* condition at the previous stage. The proper solution would have been at the very least to *obtain more information* about the petrological conditions focusing on expel the pathogenic evil as suggested by TCM's treatment principle shown in Figure 9-6.

Marshall, however, made another wrong decision, based on experts' opinion, to substantially increase their production capacity, which clearly put its original healthy operation (with sound budget and schedule and a proper crusher) into a hyperfunctional state and gradually drained out its capital (a vital substance for the system). Until the beginning of this stage, Marshall's health condition has transformed from a *repletion* condition (inflow of excessively abrasive raw material for aggregate production) into a serious *depletion* condition.

Marshall had an identifiable "way" or *Tao*, which was to deal with primarily natural sands, and not crush a whole lot (based on the BOR initial report). Thus a healthy balance for Marshall's original production system would have been, for instance, 17% natural sands, 83% crushed/processed material. When the mixture changed (or discovered), financial consequences resulted requiring further adaptations. From the *yin yang* imbalance-pattern perspective, in the beginning, vital substances (*yin*) were present at good levels and functionality (*yang*) was normal, but since the wrong decisions were made to increase functionality (*yang*), a depletion of vital substances – in this case, capital or money – occurred. To treat it, our framework would dictate "cooling down" the functionality. Since the root cause in this case is clearly the unexpectedness of the raw material, as well as the BOR's lack of providing information, the pathomechanism, the contract's lack of information, required direct address before supplementing more vital substance (money) to enhance its functionality. The latter treatment would eventually cause backfire to the system since it treats the wrong problem.

The most important action at this point would still be to get rid of the *root* cause, which was incorrect site information. This would put Marshall's system in a balance state between *pathogenic evil* and *anti-pathogenic qi*. Importantly, considering constitution in the context of the environment, it becomes necessary to:

- Do a geological site survey which is sensitive to the "story" of the work site, presenting a holistic view of what exactly the raw material is.
- Consider the insufficiency of externally originating flows of money and information from the BOR and attempt to remedy.

Beyond this stage, ***Step 6.*** *Treatment: Balance Restoration & Deterioration Prevention* would have been incapable of providing further suggestions. Marshall simply needed more money; when they experienced a serious revenue shortfall, which was the beginning of the sign that Marshall was doomed, and when crisis management should have kicked in. Our methodology would cease to provide answers at this point; it would shift from a health control concern to a crisis management problem.

Bureau of Reclamation's Perspective

BOR's perspective is based on its being a governmental organization (an innate constitution), with a high degree of system inertia and complex relationship with other agencies. It also has its own legal power, was incredibly busy, and most likely possessed a strong form of dominant logic. Figure 10-11 shows the BOR's current organizational structure[11]. The primary crisis for BOR was that the dam was not getting built, due to a sub-system (the sand portion) failure. Though we could look into its functional structure and create a behavior model for the BOR, such an examination is outside the scope of this paper. The root problem the BOR experienced can be summed up as being global and systemic, and not confined to any particular subsystem. This can be deduced by the nature of the dysfunction at work in the Marshall case; simply put, the BOR suffered from information stagnation (communication between its divisions was problematic) and various defective procedures (e.g. the way it conduct borrow site surveys), forms of internal *pathogenic evils* as discussed in Section 9-2. In fact, the BOR did face several similar claims at the time.

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[11] Source: Bureau of Reclamation Homepage http://www.usbr.gov/main/images/br_org_chart.pdf Date Accessed: October 20, 2010.

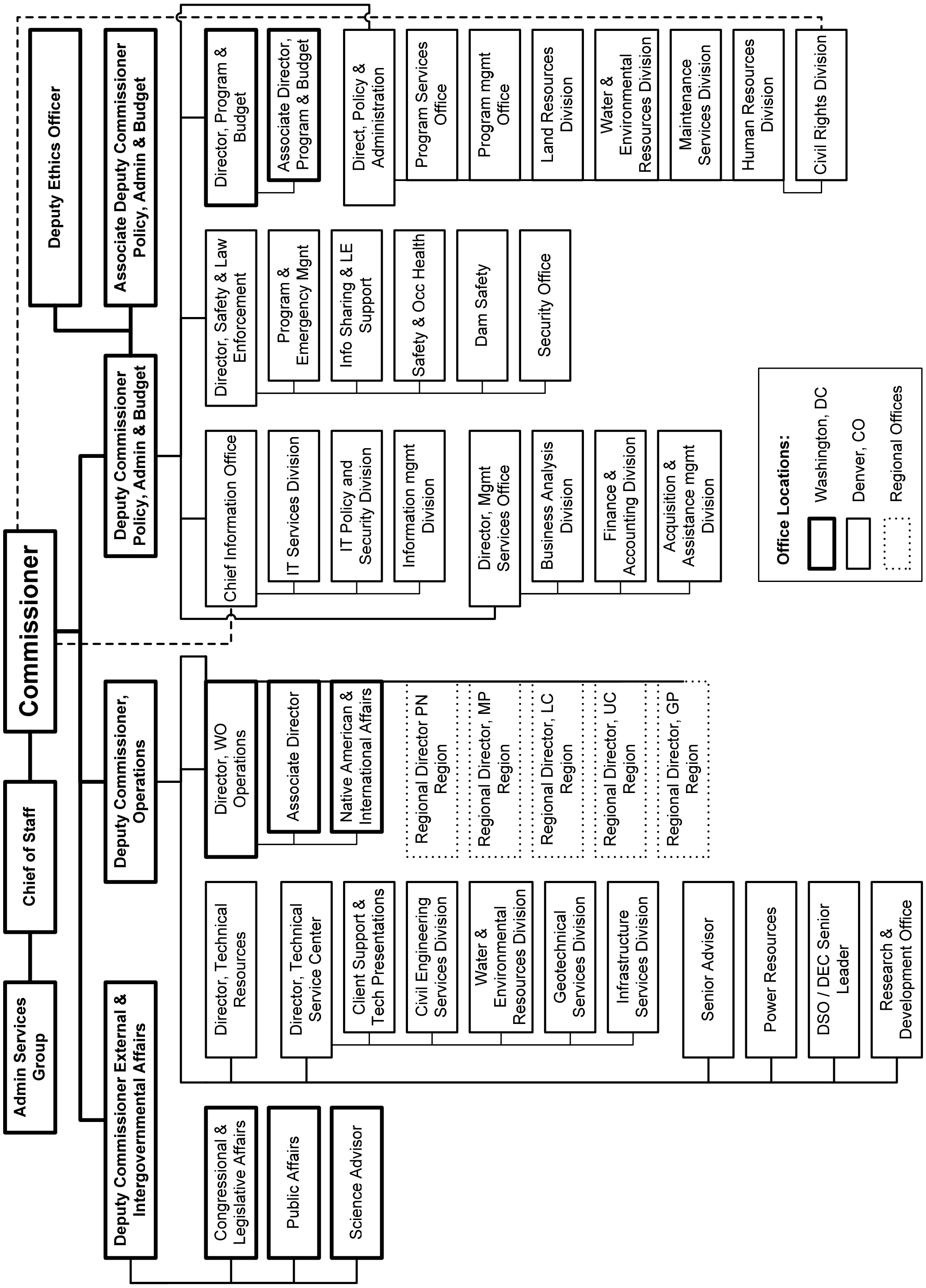

Figure 10-11. BOR Organizational Structure

Prior to borrow site procurement, when *planning*, the BOR had to plan the entire dam, Marshall being just one part of the project system, thus considering the innate and acquired constitution of the geographical environment and how the dam would interact with it, producing specifications from this in accordance with existing regulatory systems both internal (BOR regulations) and external (overall standards of professional conduct in governmental agencies). From legal proceedings, it becomes clear that organizational problems pertained throughout the BOR that prevented its effective operation:

- The BOR did not know its survey procedure was faulty, and could not have known
- Organizational culture—since the BOR was a governmental agency, it did not experience the same need to perform to survive as the parties it dealt with, resulting in a root cause that produced effects:

1. Non-holistic paradigm of information—acquisition of an unsuitable site without awareness of background geography
2. "Satisficing" organizational culture—alteration of specifications to conform to test results

Rather than attempting to diagnose their sub-system, Marshall, in-depth, the BOR instead opted for virtually amputating the sub-system altogether, after attempting unsuccessfully to increase its outflows by imposing a more demanding schedule. A better solution would have been to send a supervisor to diagnose what was happening and work with Marshall at Marshall's level

Overall, the BOR experienced problems with subjective data (as discussed with regard to its surveyors), and a dominant logic/corporate culture of incompetence and poor communication. Most policy recommendations should take place for the BOR, but we do not have enough information about the BOR from the case reports to discuss in adequate depth on the BOR's perspective.

EPILOGUE—CONCLUSIONS & FUTURE RESEARCH

Research Contributions

This research provided an overall framework that integrates multiple disciplines and approaches to risk analysis (like complexity science, *I Ching*, PRA, QRA, systems theory, System Dynamics, TCM, concept of resilience, etc.) and combined them into a usable, process-oriented answer for complex engineered systems.

- Complexity science and I Ching were reviewed as a foundation for understanding how complex engineered systems work;
- PRA, QRA deterministic approaches were integrated into the planning stage;
- TCM's notion of constitution was applied at step 1; its notions of systems and holism were included in step 2 (must include environment and internal sub-systems = holism);
- System Dynamics (in some domains only – not in all) was applied to the modeling stage;
- TCM account of healthy functioning and dynamic balance were integrated into step 3-5 diagnosis, etiology and pathomechanism identification and step 6 of prevention and treatment;
- The concept of resilience (from Resilience Engineering and HRO) was incorporated throughout as a basic concept of system health;

- Time-based concepts of risk (the risk of change) were developed by analogy with Newton’s Three Laws of Motion and applied throughout the process.

The dynamic-balance characteristic of our approach made it uniquely able to cast all these different approaches in their proper light. Our goal was to provide a new perspective on and framework for thinking about risk. It bears mention that methods of pattern differentiation as we discuss them were not complete. Many other methods needed to be discovered.

Rather than arguing that the details of the framework we have drawn out should overwhelm or contradict the traditional understandings, we believe that the two systems should be complementary, just as photons may be thought of as waves or particles (Mintzberg et al. 1996) or the *complementarity* proposed by Niels Bohr (Sheikh and Sheikh 1989 p.404-405), risk can be thought of as having a similarly indeterminate property. The old paradigm is not completely replaced; it is complementary to the new paradigm. Similar to the balance bewteen frequency / belief duality in probability, theory and judgment must be seen as complementary, not competing, sources of understanding.

As the Cambridge University physicist, Stephen Hawking (2003), suggested in a public lecture at Texas A&M University, which was titled *Gödel and the End of Physics*. We may never find “an ultimate theory that can be formulated as a finite number of principles.” That means we may never be able to predict the world accurately as we wish. That being said, our proposed pattern differentiation methods and treatment principals may not be perfect or specific enough at this point; however, we believe our intention to seek a new means of synthesizing information and judging unfolding situations along the way, rarther than to provide more accurate risk quantification. We can provide a new perspective of risk and an alternative way of managing ever-changing systems without endless anticipation of failure modes.

Research Conclusions

Here, we summarize the main conclusions of this research. We conclude that:

- The concept of time is added to risk through our concept of the risk of change.
- Considering risk in terms of time provides a new paradigm for thinking about risk, for our framework, one inflected by the empirical work of traditional Chinese medical practitioners.
- In complex engineered systems, dynamic balance must be maintained, not single deterministic states of perceived system health.
- Understanding complex risk should be made easier and more intuitive, which can be achieved through our proposed framework. When people's perception of risk is changed, the way people manage risk will change.
- Systems should try to navigate to success by focusing on positive potentials and creating reserve power, instead of "drifting to failure" by focusing on negative potentials.
- Current approaches attempt with more or less success to anticipate future events.
- The results of risk analysis provide solutions for current and past situations instead of lessons learned for future events
- Instead of anticipating the future, system behavior models should be used to judge and adjust current situation and used as a recording tool of system development
- Crisis management is fundamentally treatment of a disease when it has already happened. Thus, the best a crisis-management based risk system can hope for is a crisis-free system, not a healthy system. System/patient's own responsibility for health is an inseparable portion of risk management effort, that must be shaped and cannot be displaced.

Future Research

The holistic approach we set forth challenges the field of risk analysis to address issues concerning sustainability with respect to complex engineered systems before they are widely deployed and before irreversible consequences have occurred. It is a challenge not to be taken lightly. Applied research in these directions will require further understanding of functional components of specific engineered systems, research with its own conditions of validity independent from the validity of the system as a whole.

More than the TCM theories we have discussed are applicable. Research into similar qualitative methods for reasoning with imperfect information are necessary, particularly given the critiques and flawed decision criteria that have arisen (e.g. Herber Simon's notion of bounded rationality, or Kahneman and Tversky's attacks on the notion of "reasonable" decision makers). Non-quantifiable systems of assessment providing descriptions, rather than ineffectual attempts at explanation, will become valuable as levels of information complexity increase to the point that system decision makers begin aggressively filtering their input.

An important next step for the change-oriented paradigm of risk we set forth is to further clarify the new forms of data needed and new ways of organizing them to analyze the risk of change. In any case study, a breadth of data available at any given point in time is necessary to reconstruct how decisions were made. The way that the risk of change is analyzed is closely related to the state of health of a system at a given point in time, thus figuring out how to judge such states of health becomes important. Traditionally, we have used past data from other cases for our current systems. We argue that in order to "invent the future" and manage it, we need more practical ways of organizing data that elucidate relationships between functional sub-systems.

The conceptual work we have done with general relativity as it related to a reference frame for system mass (consequence, inertia) may be a useful avenue for exploration. Such a concept, in our view, may frame a useful interdisciplinary collaboration between quantitative system measurement and qualitative, perspectival effects on system changes. The holistic and dynamic characteristics of this paradigm of risk we set forth are not inseparable. One might accept, for instance, the necessity of dynamic balance that we argue for, without necessarily accepting at face value the *wu xing* sub-system typologies and flows. In place of TCM as we use it, other forms of native systems concepts and historical/philosophical traditions can be placed, all of which can be mined for useful system dynamics patterns. The psychological, economic, philosophical and risk-analytical work we did may provide an overall frame of reference for interdisciplinary collaboration into the field of dynamic preventive system-health maintenance.

The notion of “constitution” as we presented it is a useful notion for understanding the character of complex systems. The constitutions of different systems and their behaviors under various force fields can test and develop this notion and its implication for risk further. For instance, isomorphic systems with different constitutions may be susceptible to certain accidents; certainly we can observe certain nomothetic principles of risk management which seem to extend across multiple domains of risk. Though we set forth a holistic view best used for large-scale engineered systems, some particular domains may have their own endogenous logic or *Tao* that must be respected, and will thus constitute themselves and their subjects differently.

The patterns of change we argue for are open to discussion. We suspect that there exist *static* and *dynamic patterns* of change over time defining systems for which a constantly adaptive state may or may not be a productive way or *Tao*. There may be a “way” of “waylessness.” Future research may have fruitful avenues of exploration questioning some of our basic assumptions.

More practically, the impact of these new instrumental definitions of risk on current decision-making processes will need to be assessed. Where necessary, various mechanisms for adjusting current decision-making processes will be required so that they are congruent with any new framework for risk quantification. Questions such as the following proposed by Professor Kastenberg shed some light on our way ahead, “What constitutes an acceptable risk when the definition is not an expected value, but rather some measure of emergent property (functional) degradation?” and “How does one choose among risk reduction strategies when the risk is not an expected value, but rather some indication of bifurcation and chaotic behavior?” Our emphasis on adaptability and responsiveness to change foreshadows to some extent the direction that we believe research should take. However, our goal here is to develop a risk-based decision-making process that is congruent with the nonlinear nature of the complex systems being assessed which encompasses other theories and casts their results in useful terms.

There are a myriad of possibilities to proceed; as a point of re-departure, it is possible to start with the following:

- Conduct more case history studies and further modify the framework.
- Perform the risk of change analysis with a quantitative System Dynamics model
- Explore further the concept of resilience and define it quantitatively if possible.

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