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What is Systems Thinking? A Review of Selected Literature Plus Recommendations

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Abstract Systems Thinking is a popular current topic in the world of Systems Engineering. However, as yet there is no commonly accepted definition or understanding of it. In this paper, we analyze some of the popular Systems Thinking literature and attempt to identify common themes. We conclude that Systems Thinking is a perspective, a language, and a set of tools. Specifically, Systems Thinking is the opposite of linear thinking; holistic (integrative) versus analytic (dissective) thinking; recognizing that repeated events or patterns derive from systemic structures which, in turn, derive from mental models; recognizing that behaviors derive from structure; a focus on relationships vs components; and an appreciation of self-organization and emergence. Specific Systems Thinking tools include systemigrams, system archetypes, main chain infrastructures, causal loops with feedback and delays; stock and flow diagrams; behavior-over-time graphs, computer modeling of system dynamics, Interpretive Structural Modeling (ISM), and systemic root cause analysis.

Keywords Systems Thinking

1. Introduction

Systems Thinking has its foundation in General Systems Theory (Bertalanffy) and has been applied to a wide range of fields and disciplines. It has great power in solving complex problems that are not solvable using conventional reductionist thinking. It can be used to explain dynamic non-linear behaviors like market reactions to new product introductions or predator-prey relationships; to understand complex socio-economic problems such as the effects of marijuana laws; and to understand the seemingly illogical behaviors of individuals, countries, and organizations such as ISIS's provocative actions.

However, many systems engineers do not fully grasp Systems Thinking—many believe it is simply the fundamental concepts of Systems Engineering as articulated by Kossiakoff et al. and Blanchard and Fabrycky, comprising V-diagrams, risk management, needs analysis, architecture and design, integration and test, and project management. This is not the case. Some practitioners have co-opted the term "Systems Thinking" to include *all* aspects of systems including general systems theory, cybernetics, family therapy, and Model-Based Systems Engineering (MBSE). We think this inappropriate. The *Systems Engineering Body of Knowledge* devotes a chapter to Systems Thinking. However, this chapter is a compendium of literature articles on systems thinking concepts, principles, and patterns. It is quite vague and does not appear to integrate the disparate articles into a cohesive whole. Furthermore, several key references (Meadows, Kim, Richmond) have been omitted. The dozens of books and articles written on Systems Thinking have some common threads, but different focuses and interpretations. In this paper we attempt to make sense of this chaos and develop a firm conceptual framework for Systems Thinking.

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2. Literature Review

We do not purport to have done a comprehensive analysis of all systems thinking literature. We selected approximately 30 of the more popular works; works that we interpret to be "key" contributors to the understanding of systems thinking and that had "systems thinking" in either their title or subject description. To ensure that we had not missed any key references, we then submitted this list to 14 published experts in the field of Systems Thinking and asked for their suggestions regarding relevant literature; 9 of them (acknowledged at the end of this paper) were kind enough to reply with suggestions. We then evaluated their suggestions and added those that we believe advance the understanding of systems thinking (we did not include references focused on other aspects of systems, such as systems *engineering*, sources describing primarily predecessors to or precursors of systems thinking, or items that addressed sub-sub-elements of systems thinking such as the details of system dynamics programming.) The result is an edited list of approximately 33 references that we deem important to the understanding of systems thinking. These references are organized into 4 categories: Introductory Works, Applications of Systems Thinking, Self-organization and Emergence, and General Works.

Introductory Works

- Kim, Daniel H., *Introduction to Systems Thinking*. This 20-page booklet is probably the best concise introduction to systems thinking that is available. All of the basics are covered, including the definition of a system, the systems thinking "Iceberg Model," and systemic behavior including feedback loops and delays. The Iceberg Model argues that in a system, repeated events represent patterns and that patterns are invariably caused by systemic structure. In human-designed systems, systemic structure develops as a result of mental models. If one could read only one work to get a good grasp of Systems Thinking, this would be it.
- Richmond, Barry, *An Introduction to Systems Thinking with iThink*. iThink and Stella are 2 excellent system dynamics modeling software packages available from isee systems of Lebanon, NH. This instruction manual for these packages does much more than explain how to use the software; it is in fact a primer on systems thinking, covering such topics as system dynamics, feedback loops, stock-and-flow diagrams, main chain infrastructures, mental models, and non-linear effects. The most excellent aspect of this book, however, is its ability to relate everyday real-world situations to a systems thinking perspective. It is a terrific resource, whether one uses the software or not. Richmond includes a definition of Systems Thinking: "… systems thinking is the art and science of making reliable inferences about *behavior* by developing an increasingly deep understanding of the underlying *structure*."
- Meadows, Donella H., *Thinking in Systems: A Primer*. In our opinion, this is the seminal work on systems thinking. It was published posthumously from Dana Meadows's notes. It covers system definition, stock and flow diagrams, feedback loops, resilience in systems, hierarchies, self-organization, unintended consequences, the 10 systemic archetypes, system leverage points, and rules for systems. However, it does a superb job in using real world examples (such as the inadvertent impact of DDT on bird eggshell thickness and the folly of spruce budworm control) to make its points. No student of systems thinking should miss this book.
- Anderson and Johnson, *Systems Thinking Basics, from Concepts to Causal Loops*. This relatively short book is a good study guide for introductory students of systems thinking. It is consistent with Kim, Meadows, and Richmond and covers the Iceberg Model, causal loop diagrams, archetypes, and behavior-over-time graphs. The book defines systems thinking as a set of tools (includes a "palette of systems thinking tools", a framework for looking at issues, and a language. It is somewhere between Kim and Meadows in its level of detail and examples.

  Kauffman, *Systems One: An Introduction to Systems Thinking*. This relatively early (1980) 40-page pamphlet is a concise introduction to the field. It discusses stability and feedback in systems, complexity, and archetypes, and it gives good examples of causal loop diagrams involving float valves, predator-prey relationships, thermostats, crime and punishment, compound interest, growth of power, and growth of knowledge. It is consistent with Meadows, Kim, Richmond, and Anderson and Johnson, but it does not discuss the Iceberg Model or dynamic modeling; it is thus less comprehensive than some other sources.
- Sweeney and Meadows, *The Systems Thinking Playbook.* This book attempts to teach many systems thinking principles through the use of games. It focuses on "habits of mind" --- identifying and then breaking them. Unfortunately, many of the games are sophomoric and don't make the points well. One exception is "Avalanche" in which several people try to lower a hula hoop simultaneously while supporting the hoop with just one finger. Contrary to everyone's mental model, the hoop goes up instead of down. This is an excellent demonstration of incorrect mental models and how they can dominate behavior. The book in general, however, falls short of teaching systems thinking principles via games.
- Galley, *Think Reliability: Investigation Basics — The Systems Approach*. This is a very good short article explaining how systems thinking enhances conventional root cause analysis. It argues that Systemic Root Cause Analysis should not identify a single root cause, but instead a root cause *system*: a paradigm, culture, environment, or set of attitudes that yield the specific identifiable causes. The sinking of the Titanic is used as an example.
- Aronson, *An Overview of Systems Thinking, (http://resources21.org/cl/files/project264_5674/OverviewSTarticle.pdf).* This article provides a good summary of how systems thinking is fundamentally different from reductionist thinking. It provides an example of how pesticides used to control insect damage to crops can give rise to alternative predatory insect damage that was not previously envisioned as an unintended consequence.
- Goodman, Kemeny, and Roberts, *The Language of Systems Thinking: 'Links' and 'Loops'*. This article provides a brief tutorial on the use of causal loops and delays to represent system behavior over time. It illustrates how they can be used to model the ups and downs of sales cycles, exponential growth or collapse in investment strategies, and stabilization in the number of patient visits to an outpatient clinic.
- Lawson, *A Journey Through the Systems Landscape.*

The Lawson book discusses system classification and topologies as well as the Iceberg Model. It gets into systems archetypes, causal loop diagrams, system life cycles, and decision analysis, and it includes several good case studies involving crisis management, organizational development, architectural concepts, and ontology life cycle management. It is a good book and consistent with Meadows, Kim, and Richmond.

- Weinberg, *An Introduction to General Systems Thinking.* Weinberg presents several interesting and useful systems thinking concepts; among them the following plot (Figure 1) of Randomness versus Complexity, showing where systems (organized complexity) fit (a surprisingly large area of the plot.) (The original concepts of simplicity, organized complexity, and unorganized complexity are attributable to Weaver (1948)).

Weinberg also proposes 3 Great Systems Thinking Questions:

- Why do I see what I see?
- Why do things stay the same?
- Why do things change?

He includes several good examples such as the inadvertent impacts of waste heat from nuclear reactors, the unintended consequences of targeted pesticides, and the detrimental effects of agricultural herbicides on fertility.

Applications of Systems Thinking

- Boardman and Sauser, *Systems Thinking: Coping With 21st Century Problems.* The best aspect of this book is its use of good, interesting, current systems thinking examples such as the impact on a rural community of new baby-boomer retirees, the September 11th attack on the world trade center, President Kennedy's national challenge to land men on the moon before 1970, and the privatization of the U.K. railroad industry. It also explains Systemigrams in good detail (see "Systems Thinking Tools"). The book refers extensively to other systems books such as Senge and Meadows. However, it is poorly organized and does not seem to provide a coherent, operational definition of systems thinking.
- Haines, *The Systems Thinking Approach.* Haines does a good job of applying systems thinking to business and discusses it in terms of current versus future states and how to move from one to the other. He argues for a focus on outcomes instead of activities and on processes and structures. While these are all elements of systems thinking, the book seems disjointed and does not provide a comprehensive, coherent picture of systems thinking.
- Gharajedaghi, *Systems Thinking.* Gharajedaghi's book argues that there are 5 systems principles: Openness, Purposefulness, Multi-dimensionality, Emergent Properties, and Counter-intuitiveness. He talks about System Context in terms of the environment, control, and influence; and he devotes substantial space to a health systems case study. However, the book is disorganized and does not present a clear explanation of systems thinking.

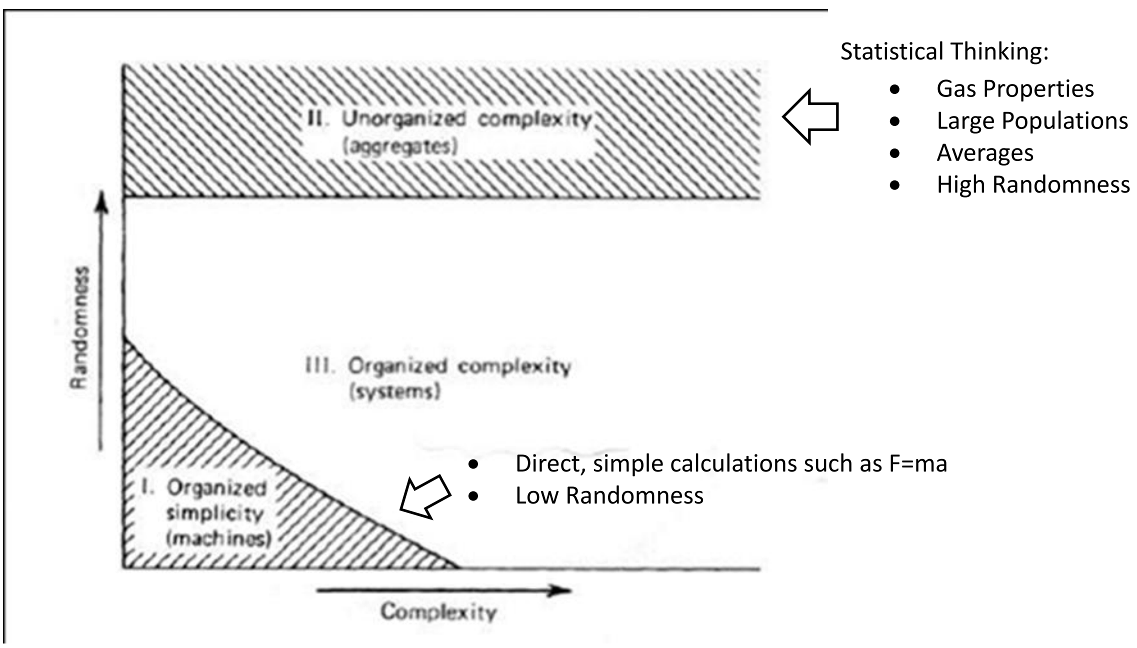

Figure 1. Weinberg's Systems Map of Randomness versus Complexity

- Senge, *The Fifth Discipline*. Senge's 1990 book may not have started the trend in systems thinking, but it certainly accelerated it. In it, he provides some excellent examples of compensating feedback, application of systems thinking to terrorism, and systems archetypes. He also provides a generic definition: "Systems thinking is a discipline for seeing wholes. It is a framework for seeing interrelationships rather than things, for seeing patterns of change rather than "snapshots."… It is also a set of specific tools and techniques, originating in two threads: in "feedback" concepts of cybernetics and in "servo-mechanism" engineering theory…" Senge's book is pivotal because it applies systems thinking to management in organizations, and for that reason alone it is worth reading. Systems Thinking is (of course) the 5th discipline of a learning organization, the other 4 being personal mastery, mental models, building shared vision, and team learning. Senge argues that Systems Thinking is the most important because it integrates the other 4.
- Senge, Kleiner, Roberts, Ross, and Smith, *The Fifth Discipline Fieldbook.* While *The Fifth Discipline* presents the background and theory of systems thinking, this field book is much more applied. It presents many relevant examples and case studies (e.g. Sears's auto repair quality, the impact of Toyota's manufacturing quality on America's automobile expectations, water supply failures and fixes in Africa, and dealing with price wars) along with a systems thinking problem-solving approach. It discusses archetypes, systemic root cause analysis, system dynamics, and it provides a clear explanation of the Iceberg Model. It also provides a detailed, lengthy analysis of The Beer Game, which has been used for many years to demonstrate system oscillations when there are feedback loops with delays. The book helps apply systems thinking to real-world issues.
- Ballé, *Managing With Systems Thinking: Making Dynamics Work for You in Business Decision Making*. Ballé's text focuses on applying systems concepts to the workplace. He observes that a typical management reaction to an issue is a myopic, short -term solution instead of a long-term systemic analysis, and that therefore many "solved" problems recur. His basic points include:

  1. Detect patterns, not just events.
  2. The use of circular causality (feedback loops)
  3. Focus on the ***relationships*** rather than the parts

- Norman, *Systems Thinking: A Product is More Than the Product(http://www.jnd.org/dn.mss/systems_thinking_a_.html)*. A terrific article applying systems thinking to product development using examples such as the iPod, Kindle, and Mini-Cooper. The article explains that a product is more than just the physical entity; it is the experience of researching, shopping, buying, using, and maintaining the product. For example, the iPod is so successful not only because the physical device is beautiful and functional, but also because the music downloading and listening experiences are pleasurable.

Self-Organization and Emergence

- Mano, *Self-Organization in Natural Systems*. Mano presents a variety of examples of self-organization in natural systems, including zebra stripes, leopard spots, sand dune ripples, mud cracks, herding of wildebeests, and honeycomb cell structure. He also explains the forces underlying self-organization.
- Camazine, Deneubourg, Franks, Sneyd, Theraulaz, & Bonabeau, *Self-Organization in Biological Systems*. In this text, the authors describe and explain a variety of self-organized natural structures such as ant trails, the synchronization of fireflies, the schooling of fish, bee honeycomb patterns, and termite cathedrals. They also discuss emergent properties.
- Smolin, *The Self Organization of Space and Time.* This is a mind-expanding article explaining how space and time themselves are self-organizing. Smolin explains how self-organization mechanisms create complexity from simple rules and that imbalance in the fundamental forces (gravity, electromagnetic, strong nuclear, weak nuclear) lead to inhomogeneity and complexity. He argues that the structure of the universe and even its origins are caused by self-organization. The article raises significant questions about the necessity of a prime mover in explaining the structure and existence of the universe.
- Beckenkamp, *The Herd Moves? Emergence and Self-Organization in Collective Actors*. This article focuses on self-organization in the natural sciences. It links self-organization and emergence as well as self-organizational concepts in biology, economics, and sociology. It explains why reductionist thinking does not work for complex systems.

General Works

- Midgley (Ed.), *Systems Thinking.* This 2003 4-volume set comprises 76 papers by renowned scholars such as Bertalanffy, Boulding, Wiener, Ashby, Bateson, Forrester, Meadows, Beer, Ackoff, Checkland, Senge, Sterman, and Jackson. However, the set covers a much broader base than just Systems Thinking; it covers most topics associated with systems including ecological modelling, systems theory, cybernetics, applications to society, family therapy, and management. In fact, the editor admits that he included the "broadest possible range of system ideas." Midgley appears to have co-opted the term "Systems Thinking" to include all topics associated with systems, which we think inappropriate. Despite that, there are some excellent papers on reductionism, holism, emergence, self-organization, and complexity. There is no attempt at integration into a common definition or understanding.

- Checkland, *Systems Thinking, Systems Practice*. This book, originally published in 1981, draws a distinction between "hard" systems thinking (for which problems may be formulated by making choices among alternatives to achieve an end) and "soft" systems thinking, such as human activity or social systems, which are poorly structured and often harder to deal with. Checkland includes a history of systems thinking (and of science in general) and notes that science's historical preoccupation with reductionism is an obstacle to systems thinking. He states that "Systems thinking, then, makes conscious use of the particular concept of wholeness captured in the word "system" to order our thoughts," and "Systems thinking implies thinking about the world outside ourselves." He believes that systems thinking is founded on a) emergence and hierarchy and b) communication and control. Checkland presents a 7-step methodology for dealing with real-world soft systems problems and provides examples including the declining performance of a textile firm, mining equipment problems, executing useful and meaningful surveys, and the decision to land a man on the moon before 1970.
- Davidz and Nightingale, *Enabling Systems Thinking to Accelerate the Development of Senior Systems Engineers.* This article helps by providing a definition of systems thinking: Systems thinking involves "Utilizing modal elements to consider the componential, relational, contextual, and, dynamic elements of the system of interest." Its principal focus is on how systems thinking develops in engineers, and it identifies enablers, barriers, and precursors to systems thinking. The authors interviewed 205 senior systems engineers and conclude that the principal mechanisms for developing systems thinking are experiential learning, a supportive environment, and personal characteristics such as personality, curiosity, open-mindedness, and the ability to tolerate uncertainty.
- Maani, *Systems Thinking International*. Maani states that

"Systems Thinking is a way of thinking about life, work, and the world based on the importance of relationships (interconnections). Systems Thinking also provides a language and a scientific technology for understanding and dealing with complexity and change. Systems Thinking has three aspects. These aspects can be used individually or in combination. They are:

- A way of thinking (paradigm) about the world and relationships. The Systems Thinking Paradigm consists of a set of principles and theories.
- A language for understanding change, uncertainty and complexity. The Systems Thinking language uses diagrams to explain non-linear cause and effect relationships.
- A technology for modeling complex situations underlying business, economics, scientific, and social systems. Systems Thinking modeling tools can be used to create powerful simulation models of organizational situations such as strategy development, process design and re-engineering, and team and organizational learning."

- Maani and Cavana, *Systems Thinking, System Dynamics: Managing Change and Complexity.* This book starts with a fairly conventional definition of "system" and goes on to argue that systems thinking is a paradigm involving the big picture view (including components and their interactions), dynamic thinking, operational thinking including the "physics" of operations, and closed-loop thinking. It states that systems thinking is also a language involving diagrams, a syntax with precise rules, the translation of perceptions into pictures, and an emphais on closed-loop interdependencies. It advocates several tools including causal loop diagrams, stock-and-flow diagrams, computer simulations, learning laboratories, and group model building. Maani and Cavana embrace a 4-tiered Iceberg Model and suggest 5 phases of systems thinking and modeling: 1) Structure the problem, 2) Construct Causal Loop diagrams, 3) Model dynamically, 4) Scenario Planning and Modelling, and 5) Implementation and Organizational Learning using Flight Simulators. The book ends with several case studies including the bird flu pandemic, quality in health services, the New Zealand fishing industry, and telecommunications business strategy.
- Valerdi, *Why Systems Thinking is Not a Natural Act.* Valerdi describes 7 systems thinking competencies:
  1. Ability to define the "universe' appropriately - the system operates in this universe
  2. Ability to define the overall system appropriately - defining the right boundaries
  3. Ability to see relationships - within the system and between the system and universe
  4. Ability to see things holistically - within and across relationships
  5. Ability to understand complexity - how relationships yield uncertain, dynamic, nonlinear states and situations
  6. Ability to communicate across disciplines - to bring multiple perspectives to bear
  7. Ability to take advantage of a broad range of concepts, principles, models, methods and tools - because any one view is inevitably wrong
- Hitchins, *System World (www.hitchins.net)*, explains systems thinking in terms of 3 generic areas: synthesis, the organismic analogy, and holism:

"**Synthesis** is the opposite of reduction. Synthesis proposes that the various parts of a complex system cannot exist/survive/operate/ behave/even be considered in mutual isolation. A system comes into existence when the complementary parts are brought together. Each then depends for its very existence on interchanges with the other parts. In turn, this implies that open systems are/have to be active/dynamic. The **organismic analogy** proposes, not that all complex systems are organisms, but rather that, like biological organisms, they behave as unified wholes. Each has a life-cycle, each exhibits growth, stability and death - often sudden, collapsing death. **Holism** proposes that everything within a system is connected/related to - and affects - everything else, so there is mutual interdependence. Viewing, or even considering, parts on their own is irrational. Systems and their problems have to be viewed as a whole. Holism observes the tendency of the natural world to create 'wholes,' and that a whole may be more than the sum of its parts ...".

Hitchins believes that systems thinking is "…. simply thinking about the world around us, about situations and problems, and how things might/could/should/do work;…thinking about emergent properties, capabilities and behaviours, how they come about, what benefit they might be, what problems they might create… unravelling the inner workings of complex systems… "Hitchins embraces causal loop diagrams and modelling using STELLA and iThink, Interpretive Structural Modelling, N^2 Charts, and a rigorous soft systems methodology but he does not embrace the iceberg model.

- Bellinger, *Systems Thinking – A Disciplined Approach (http://www.systems-thinking.org/stada/stada.htm).* This article focuses on a suggested approach for developing models to gain an understanding of the underlying structure(s) which give rise to observed patterns of behavior. Bellinger proposes that such an approach consists of the following steps:
  1. Define the Situation
  2. Is Systems Thinking Appropriate?
  3. Develop Patterns of Behavior
  4. Evolve the Underlying Structure
  5. Simulate the Underlying Structure
  6. Identify the Leverage Points
  7. Develop an Alternate Structure
  8. Simulate the Alternate Structure
  9. Develop an Adoption Approach

The author also provides a description of the basic structures and constructs used to model systems in terms of Causal Loop Diagrams (CLDs) and a method for translating them to Stock and Flow Diagrams at http://www.systems-thinking.org/stsf/stsf.htm

- Jackson, *Systems Thinking: Creative Holism for Managers.* This interesting book begins with a conventional definition of "system," the concepts of holism and reductionism, and a discussion of hard versus soft systems thinking. It goes on to outline and critique 10 applied systems approaches: hard systems thinking, system dynamics, organizational cybernetics, complexity theory, strategic assumption surfacing and testing, interactive planning, soft systems methodology, critical systems heuristics, team syntegrity, and post-modern systems thinking. The overviews and critiques are balanced and fair; however, Jackson concludes with a recommendation for "Total Systems Intervention" or TSI which seems to argue that no one approach will address all problems and that one must therefore pick and choose the combination of approaches that work best for a situation. This approach is unclear to us and does not represent an integrated perspective. The book is excellent, however, in describing and critiquing several popular systems approaches.
- At the 2015 Conference on Systems Engineering Research, Arnold and Wade proposed a novel self-referential description of systems thinking in which they suggest that systems thinking is itself a system. They then developed a "Systems Test" for systems thinking definitions: the definition must describe the purpose, elements, and interconnections of systems thinking and must identify systems thinking itself as a *system*. They next compared systems thinking definitions from 7 different authors and demonstrated that each definition fails their Systems Test; however they do identify the following commonalities among the definitions: interconnections, the understanding of dynamic behavior, systems structure as a cause of that behavior, and the idea of seeing systems as wholes rather than parts. Arnold and Wade argue that previous definitions do not adequately describe what systems thinking does and propose a new definition: "Systems thinking is a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects. These skills work together as a system." Although their definition is helpful and their approach is unique, we see no *a priori* reason why definitions of systems thinking must pass their systems test in order to be valid, useful definitions.
- Russell Ackoff's, Herbert Addison's, and Andrew Curley's short book, *Systems Thinking for Curious Managers,* is more about Ackoff's famous f-Laws than about systems thinking, although some consider his f-Laws a distillation of systems thinking concepts. (Some f-Law examples include "The amount of time a committee wastes is directly proportional to its size," "The less sure managers are of their opinions, the more vigorously they defend them," and "Administration, management, and leadership are not the same thing.") Although the f-Laws are sometimes droll and even poignant, they are presented randomly and do not directly advance the understanding of systems thinking. On the other hand, Ackoff's co-authors propose the following working definition of systems thinking: "Systems thinking looks at relationships (rather than unrelated objects), connectedness, process (rather than structure), the whole (rather than just its parts), the patterns (rather than the contents) of a systems, and context. Thinking systemically also requires several

shifts in perception, which lead in turn to different ways to teach, and different ways to organize society." The book goes on to discuss feedback loops, tropisms, self-organization, interconnectedness, equifinality, events versus systems, parts versus the whole, the whole in context, mess, analysis versus synthesis, failure to learn, change, aims and intentions, and people.

3. What is Systems Thinking? --- Recommendations

There are many different views regarding the definition of Systems Thinking, and as yet there does not seem to be a precise, widely-accepted definition. However, there appear to be common themes that are repeated in many of the sources. This section will attempt to identify and integrate those common themes into a coherent definition.

→Systems Thinking is a perspective, a language, and a set of tools.

The Systems Thinking Perspective

Most sources agree that systems thinking is the opposite of linear thinking, and that it focuses on the relationships among system components, as opposed to the components themselves. It is holistic (integrative) thinking instead of analytic (dissective) thinking. The scientific method prevalent in the last 2 centuries has taught us that we must break up complex situations into smaller and smaller pieces to understand them: dissective thinking. While this has great benefits, it also has the great disadvantage of ignoring the relationships among system components; those relationships often dominate systems behavior. Systems thinking requires that we study systems holistically. This holistic thinking involves both spatial and temporal elements, as shown in Figure 2.

The space element is often easier to grasp than the time element. But systems thinking requires that we ask: What circumstances and attitudes led to this point? What actions and behavior patterns led to this point? What are the likely attitudes, actions, and patterns going forward? What are the probable reactions of my: allies, enemies, competitors, neutral 3rd parties, and the environment? Systems Thinking thus requires a vision of the future as well as an understanding of the past.

Systems thinking acknowledges that systems are dynamic, and has evolved from the field of General Systems Theory (Bertalanffy). Systems are constantly subject to various forces and feedback mechanisms, some of which are stabilizing and some of which are reinforcing or de-stabilizing. If there are feedback loops with delays, systems may oscillate—examples are one's checking account balance, employee turnover, the national economy, predator-prey populations, or a mass at the end of a spring. This behavior is often counter-intuitive. System dynamics and system dynamics modeling are used to help understand the behavior of systems over time, to identify the driving variables so that system behavior may be positively impacted, and to help predict future states.

It is important to note that systems thinking does not supplant either statistical or reductionist (analytic) thinking; it complements them, as shown in Figure 3:

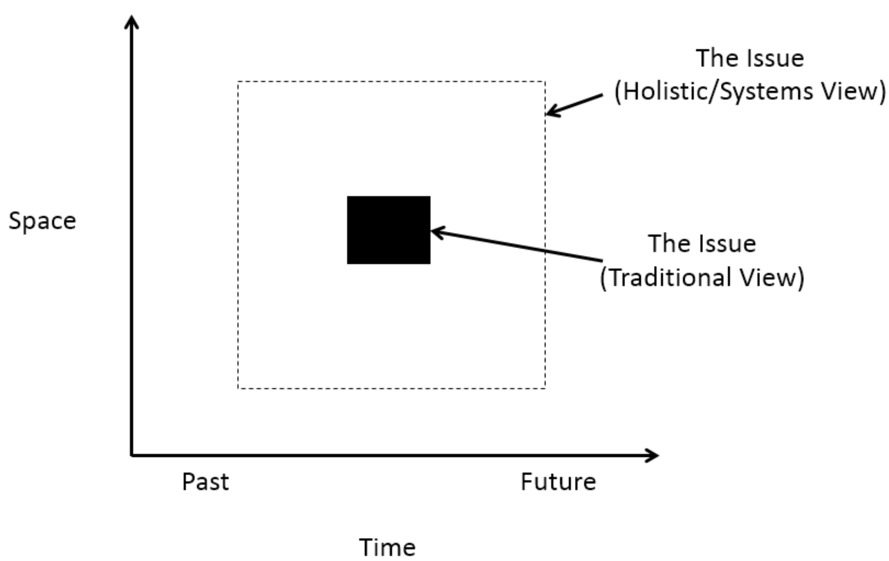

Figure 2. Systems Thinking versus Traditional Views

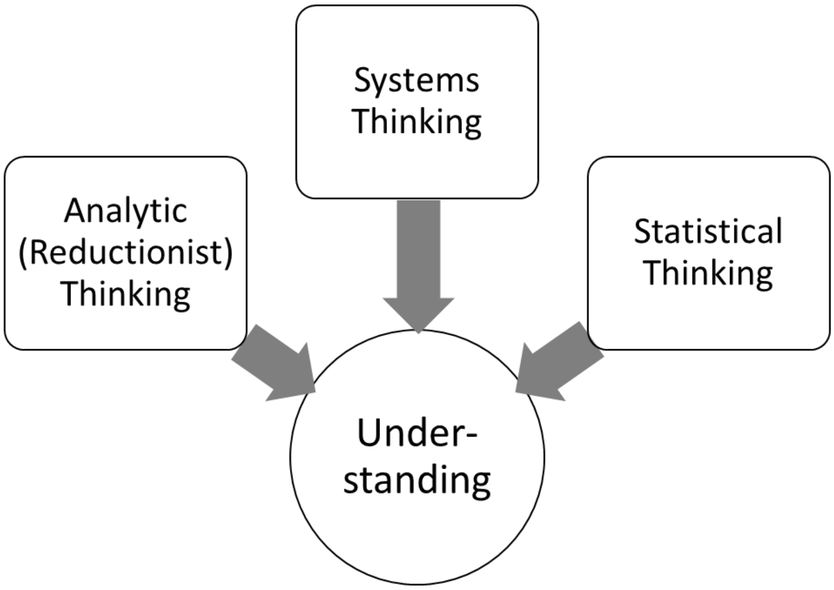

Figure 3. Systems Thinking Complements Analytic and Statistical Thinking

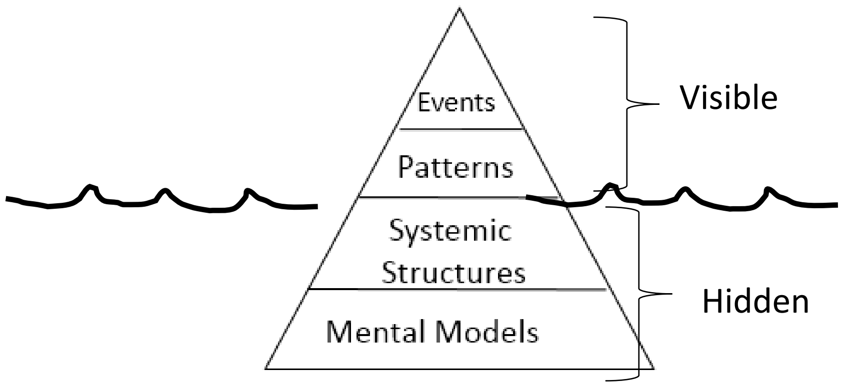

Figure 4. The Iceberg Model

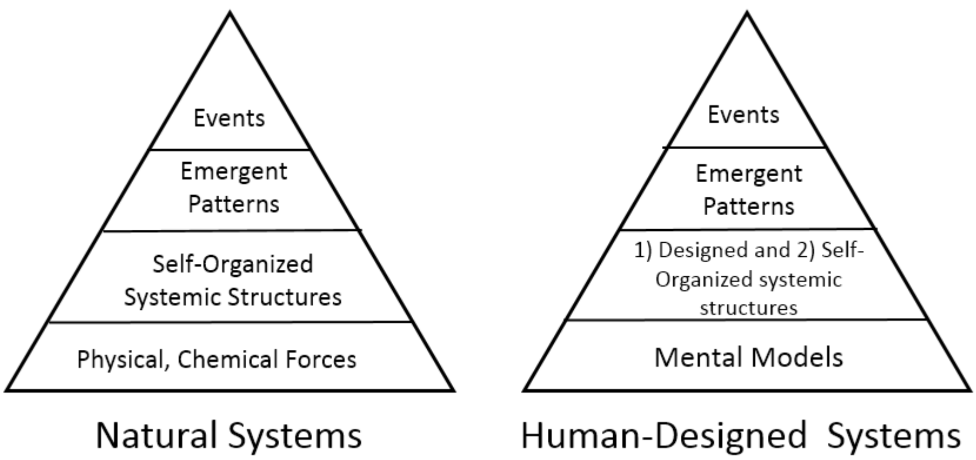

Figure 5. The Iceberg Model Applied to Natural versus Human-Designed Systems

Following Weaver's original explanations, Weinberg (see Figure 1) pointed out that systems thinking deals with **organized complexity** as opposed to **organized simplicity** (which can be dealt with analytically using the laws of physics, for example) and **unorganized complexity** (which can be dealt with statistically using statistical mechanics.) All three approaches provide different but complementary perspectives on gaining more insight into and understanding of the behavior of a system.

Systems Thinking requires that we recognize that in human-designed systems, repeated events or patterns derive from systemic structures which, in turn, derive from mental models. This is clearly depicted in the ***Iceberg Model*** *(Figure 4)*, which is a core element of systems thinking:

The Iceberg Model argues that events and patterns (which we can observe) are caused by systemic structures and mental models, which are often hidden. Systemic structures are the organizational hierarchy; social hierarchy; interrelationships; rules and procedures; authorities and approval levels; process flows and routes; incentives, compensation, goals, and metrics; attitudes; reactions and the incentives and fears that cause them; corporate culture; feedback loops and delays in the system dynamics; and underlying forces that exist in an organization. Behaviors derive from these structures, which are (in turn) established due to mental models or ***paradigms***. A fundamental systems thinking concept is that different people in the same structure will produce similar results—per Deming, the structure causes 85% of all problems; not the people! In order to understand behaviors, we must first identify and then understand the systemic structures and underlying mental models that cause them. (Note: Some versions of the Iceberg Model omit the lowest level, while some add a 5^{th} level at the bottom entitled "container." There are also other versions involving "vision" and "beliefs." We believe that the 4-level model depicted in Figure 4 is the most useful.).

At this point, the Iceberg Model must be modified to distinguish natural systems from human-designed systems (Figure 5):

In natural systems, the structures are always self-organized, while in human-designed systems the structures may be either self-organized or designed. But what is self-organization? Camazine explains it well: "Self-Organization is a process in which a pattern at the global level of a system emerges solely from numerous interactions among the lower level components of the system. Moreover, the rules specifying interactions among the system's components are executed using only local information, without reference to the global pattern. In other words, the pattern is an emergent property of the system, rather than a property imposed on the system by an external influence." Thus, self-organization exists if – independent of the intentions or even existence of an organizer or a central plan – regular or arranged patterns emerge from the interactions in the system itself. This concept has significant implications for the origin of life and of the universe itself.

Camazine's definition introduces the concept of ***emergence.*** Emergent properties are properties of the system as a whole rather than properties that can be derived from the properties of its components. Emergent properties are a consequence of the ***relationships*** among system components—they can therefore only be assessed and measured once the components have been integrated into a system. This means that one cannot address emergent properties using reductionist thinking. Examples of emergence in natural systems include the flocking of birds, V formations of geese, schooling of fish, ant colony structure, termite "cathedrals", pressure of gases, and entropy or disorder. Examples of emergence in human-designed systems include the meaning of words, traffic jam patterns, reliability, security, usability, countries, and the power of religion to influence behavior. The relationships among system components (and the behaviors and patterns deriving from those relationships) *are additional key elements* of systems thinking.

Literature Commonalities. With respect to perspective, then, most system thinking sources agree that systems thinking is the opposite of linear thinking; that it focuses on relationships versus components, and integration versus dissection; that it recognizes and addresses the dynamic nature of systems and that system feedback loops are essential to understanding system dynamic behavior; that systems exhibit self-organization and emergent properties; and that systems thinking has great power in analyzing, understanding, and influencing complex business, socio-economic, and natural problems and behaviors.

Literature Disparities. From the systems thinking literature, however, it also seems that there exist two general schools of thought or common themes regarding systems thinking: one school focuses on the Iceberg Model and on the patterns and events that are caused by systemic structures and mental models. This school sees system dynamics as a fundamental element of systems thinking, but does not equate it to systems thinking. The other school focuses on the inter-relationships among system components, the dynamic behaviors that arise therefrom, and system dynamics modeling, and tends to equate systems thinking with system dynamics, but does not embrace the Iceberg Model. We believe that both the Iceberg Model and system dynamics are fundamental to systems thinking. In fact, the causal loops, inter-relationships among components, and dynamic behavior of systems all fall under the "Systemic Structures" level of the Iceberg Model. Those structures are the causative factors behind patterns and events. Thus the Iceberg Model represents a broader context and demonstrates how the underlying structures impact our daily lives in observable ways. It goes beyond dynamics and considers the psychology behind structure.

For example, a systems thinking analyst may attack a complex problem by first constructing a causal loop diagram, and then translating it into a stock-an-flow diagram, and eventually into a dynamic model using iThink or similar software. The model will lead to the identification of key leverage points and ways to impact the system's behavior. But this new knowledge is then useful in affecting the patterns of behavior deriving from the systemic structure, and subsequently to the events that impact people's lives. In addition, the Iceberg Model's attention to mental models will help determine *why* the structures exist and *how* they may be changed.

The Integrated Model. Complete systems thinking thus integrates concepts from the Iceberg Model and concepts from causal loop diagrams and dynamic modeling into an overarching framework. This integrated model is depicted in Figure 6.

The Systems Thinking Language. The Iceberg Model introduces some of the key language of systems thinking: events, patterns, systemic structures, and mental models. Other key words include self-organization, emergence, feedback, system dynamics, and unintended consequences. Causal loop diagrams and stock-and-flow diagrams (described below under "Systems Thinking Tools") are important parts of the systems thinking language and a key means for communicating system components and relationships. A concise summary of systems thinking terms is provided here (some definitions are taken from Kim and are included here with the kind permission of Leverage Networks, Inc. (www.leveragenetworks.com):

- Accumulator: Anything that builds up or dwindles; for example, water in a bathtub, savings in a bank account, inventory in a warehouse. In modeling software, a stock is often used as a generic symbol for accumulators. An accumulator is also known as a Stock or Level.
- Balancing Process/Loop: Combined with reinforcing loops, balancing processes form the building blocks of dynamic systems. Balancing processes seek equilibrium: They try to bring things to a desired state and keep them there. They also limit and constrain change generated by reinforcing processes. A balancing loop in a causal loop diagram depicts a balancing process.
- Complexity: Characteristic of a system having many components and the multiple ways that those components interact.
- Emergence: Properties of the system as a whole rather than properties that can be derived from the properties of the system components. Emergent properties are a consequence of the ***relationships*** among system components. Examples include the flocking behaviour or murmuration of birds, the schooling of fish, the shape of an apple, traffic jam patterns, the concept of countries, and the ability of religion to influence behaviour.
- Events: Things that happen that we can see or observe.
- Feedback: The return of information about the status of a process. For example, annual performance reviews return information to an employee about the quality of his or her work.
- Flow: The amount of change something undergoes during a particular length of time. Examples are the amount of water that flows out of a bathtub each minute, or the amount of interest earned in a savings account each month, which are also called rates.
- Hierarchy: The various levels of organization in a system. In systems, hierarchies often *evolve* from the bottom to the top; stable levels of the hierarchy provide system stability and resilience. Hierarchies also facilitate the evolution of simple systems into complex systems.
- Holism: The theory or philosophy that systems display characteristics that are more than the sum of their parts and that system understanding cannot be attained by analyzing the parts in isolation.
- Leverage Point: An area where small change can yield large improvements in a system.
- Mental Models: paradigms or belief structures that attempt to interpret and/or simplify the universe in which we live. Examples are "An MBA will make you rich," "Incentive compensation increases productivity," and "Girls like Corvettes." Mental models often lead to systemic structures which are either intentional or emergent.
- Patterns: Sets of consistent and recurring *observable* events. Patterns may be physical, behavioral, or mental. Patterns are usually caused by underlying systemic structures and forces.

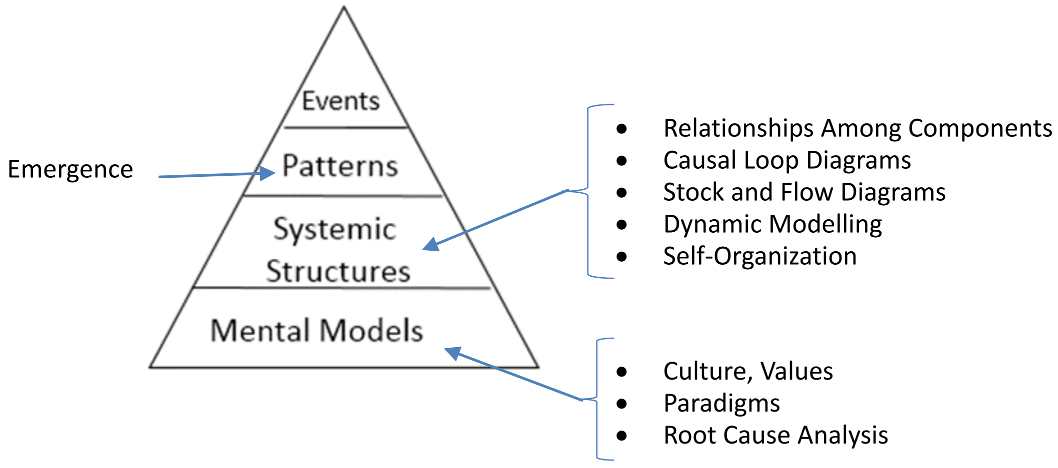

Figure 6. Integrated Model of Systems Thinking

- Reinforcing Process/Loop: Along with balancing loops, reinforcing loops form the building blocks of dynamic systems. Reinforcing processes compound change in one direction with even more change in that same direction. As such, they generate both growth and collapse. A reinforcing loop in a causal loop diagram depicts a reinforcing process, which is also known as a vicious cycle or a virtuous cycle.
- Self-organization: The tendency of a system to develop structures or patterns without the intervention of a designer or central plan, simply because of the interactions among the system elements. Good examples include the tendency of a free market system to organize into buyers, sellers, traders, and bankers, and the tendency of geese to organize into a V-formation.
- Structural Diagram: Depicts the accumulators and flows in a system, giving an overview of the major structural elements that produce the system's behavior. Structural diagrams are also called flow diagrams or accumulator/flow diagrams.
- Structure: The manner in which a system's elements are organized or interrelated. The structure of an organization, for example, could include not only the organizational chart but also information flows, interpersonal interactions and relationships, rules and procedures, authorities and approval levels, process flows, routes, attitudes, reactions and the incentives and fears that cause them, corporate culture, and feedback loops.
- System: A group of interacting, interrelated, or interdependent elements forming a unified whole that attempts to maintain stability through feedback, has boundaries and constraints, and for which the arrangement of the parts is significant. There are both human-designed systems (which serve a specific purpose) and natural systems such as the solar system (which may not have a specific purpose or whose purpose is unknown to us.)
- Systems Thinking: A school of thought that focuses on recognizing the interconnections between the parts of a system and synthesizing them into a unified view of the whole.
- Stock: See Accumulator.
- Unintended Consequences: Results of actions that were nether planned nor foreseen due to a lack of systems thinking. Examples include the negative impact of DDT on the environment, the dramatic increase in organized crime as a result of prohibition, the over-use of antibiotics resulting in antibiotic-resistant bacteria, and the devastation caused by gypsy moths, which were original imported to the United States as a cheaper source of silk.

Systems Thinking Tools. There are many systems thinking tools, but not all of them are fundamental or integral to the practice of systems thinking. To identify those that are fundamental, we have established the following criteria:

1. The tool must be widely applicable to most systems, not to a narrow sub-category of systems
2. It must be described in the systems thinking literature
3. The tool must be easy to use and understand without extensive training
4. It must address at least one of the concepts described above under the definition of systems thinking
5. Its principal focus must be on the understanding of *existing* systems as opposed to the design of new systems (which we would describe as a system *design* tool)

We believe that the following eight tools meet these criteria:

- Systems Archetypes
- Behavior over Time Graphs
- Causal Loops Diagrams with Feedback and Delays
- Systemigrams
- Stock and Flow Diagrams (including Main Chain Infrastructures)
- System Dynamics/Computer Modeling
- Root Cause Analysis
- Interpretive Structural Modeling (ISM)

Systems Archetypes. In systems thinking, archetypes are ***problem-causing*** structures that are repeated in many situations, environments, and organizations. Being facile at identifying them is the first step in changing the destructive structure. There are 10 common archetypes: Accidental Adversaries, Fixes that Fail (policy resistance), Limits to Growth, Shifting the Burden (addiction), The Tragedy of the Commons, Drift to Low Performance (eroding goals), Escalation, The Rich get Richer, Rule Beating, and Seeking the Wrong Goal. These 10 archetypes are very common in business situations, and the literature presents many suggestions for dealing with them. The key is to first identify them.

Behavior Over Time (BOT) Graphs. Behavior Over Time graphs plot the values of pertinent system variables over time. They are often useful first steps in developing an understanding of systemic behavior and of how variables inter-relate.

Causal Loops with Feedback and Delays. System behavior is usually determined by the presence of reinforcing and balancing processes. These are sometimes obvious (such as the reinforcing process of compound interest) and sometimes not (as in the stabilizing impact of terrorism on international collaboration). In either case, drawing causal loop diagrams helps to see the interrelationships among all system components. These can become quite complicated as cause-and-effect relationships, many of which are hidden (or at least hard to see), are identified. But one of the first steps in attempting to understand system behavior is the construction of a causal loop diagram. Kim and Meadows both present good examples and explanations. An example of a very simple temperature control causal loop diagram is shown in Figure 7:

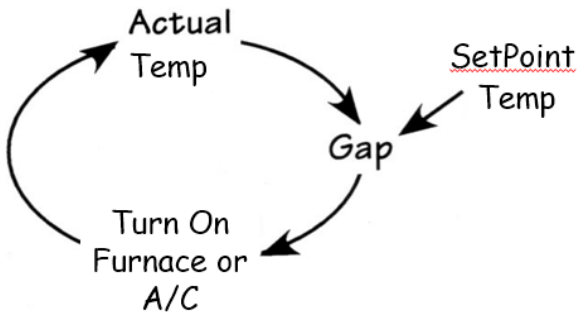

Figure 7. A Simple Causal Loop Diagram

Stock and Flow Diagrams. Systems often involve accumulators or stores of "things." The things may be physical quantities such as volume of water, quantity of electric charge, number of rabbits in a field, number of customers of a company, or amount of money in a Certificate of Deposit. They may also be non-physical things such as emotions: love, greed, angst, or lust. In systems, these quantities of things are called stocks. Stocks may increase or decrease due to flows into or out of them. Stock and flow diagrams show the stocks, inflows, and outflows. They are often developed in conjunction with causal loop diagrams, and they are important precursors to system dynamics modeling. Stock and flow diagrams, like causal loop diagrams, are invaluable in understanding system behavior, and Bellinger provides a method for translating causal loop diagrams into stock-and-flow diagrams. In addition, Goodman, Kemeny, and Roberts provide a detailed description of the language of loops and links. A simple stock-and-flow diagram depicting logging impact on a forest (from Meadows) is shown in Figure 8:

Main Chain Infrastructures. Some stock-and-flow infrastructures are repeated frequently in business and scientific systems. These include human relations, customer, administration, manufacturing, sequential work flow, and queue/server. Primarily used for system dynamics modeling, these main chains are described well in Richmond and provide a head-start for anyone attempting to model system dynamic behavior. An example of a manufacturing main chain infrastructure (from Richmond) is shown in Figure 9:

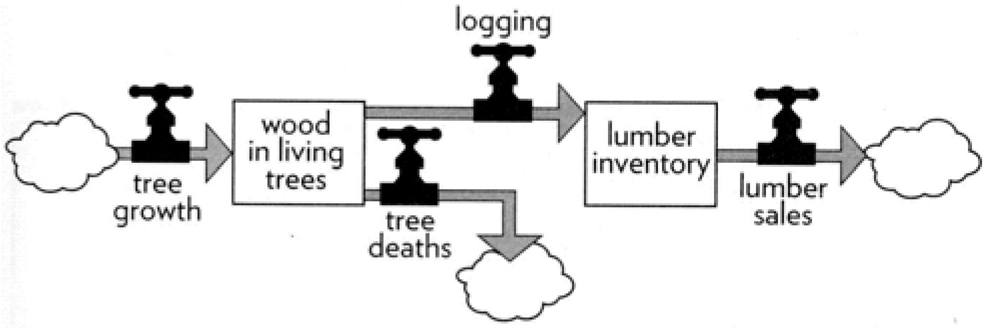

Figure 8. A Simple Stock-and-Flow Diagram (from Meadows)

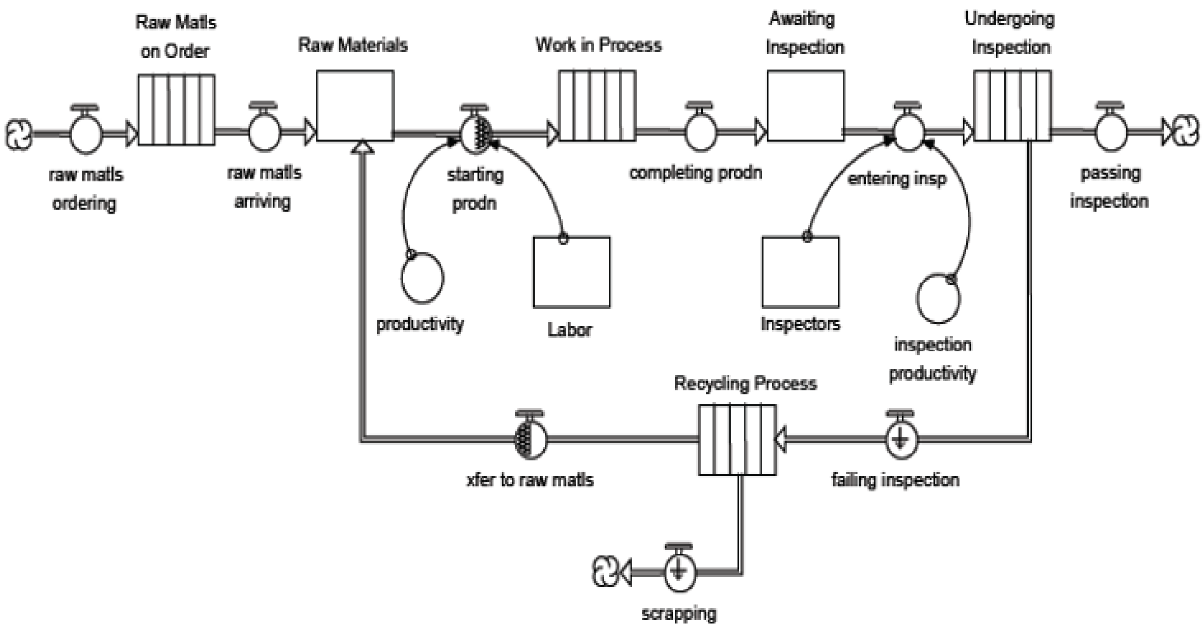

Figure 9. Manufacturing Main Chain Infrastructure (from Richmond)

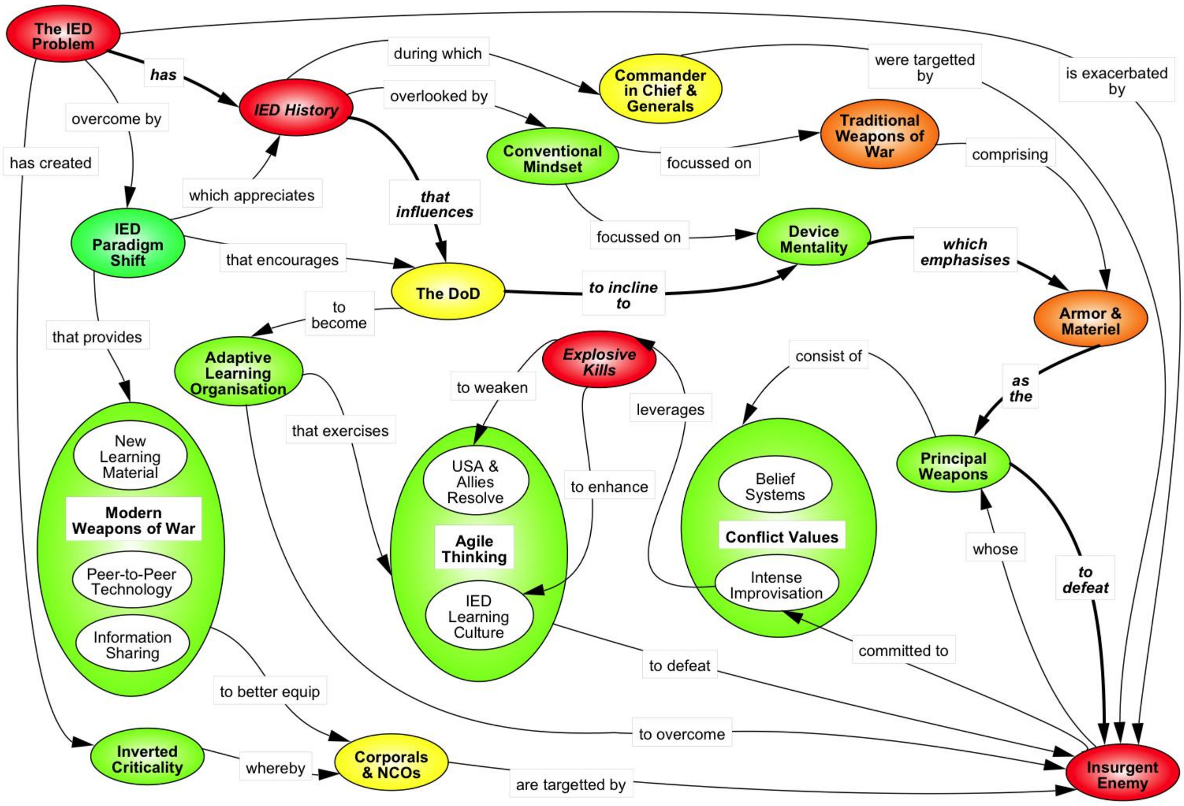

Figure 10. IED Systemigram (from Sauser)

Systemigrams. Derived from the words "Systemic Diagram," systemigrams attempt to translate a system problem (expressed as structured text) into a storyboard-type diagram describing the system's principal concepts, actors, events, patterns, and processes. They typically read from the upper left to the lower right, communicating thereby the chief message of the text. Per Boardman, the diagram is a network comprising nodes, links, flows, inputs, outputs, beginning, and end, and it must fit on a single page (although that page may be quite large.) Figure 10 (from Sauser) shows a beautiful systemigram describing the IED problem as it affects U. S. soldiers. Colors may be used to indicate similar or linked concepts or transformations, or to draw attention to key elements. One can see that although systemigrams contain elements of causal loop diagrams, they are substantially more than that and their main thrust is not feedback loops, but rather telling a story. Although systemigrams are very useful in understanding existing systems, there have been recent attempts (Cloutier et al.) to use them to bridge the gap between systems thinking and MBSE. Details of systemigrams (and more examples) may be found in both Sauser, and Boardman and Sauser.

System Dynamics/Computer Modeling. System Dynamics is the study and analysis of system behavior over time (feedback loops, time delays, non-linear behavior). System dynamics was originally developed in the late 1950s by Jay W. Forrester of the MIT Sloan School of Management with the establishment of the MIT System Dynamics Group. It is difficult to understand a system without understanding its behavior over time, which is often non-intuitive. Modeling of a system helps understand why the system (company/ individual/ department) behaves as it does. Modeling also helps identify control points and how one can influence the system. Several software packages are available for systems dynamics modeling, including Stella and iThink from isee Systems, Vensim from Ventana Systems, and Powersim from Powersim AS. A more complete list system dynamics modeling tools can be found at http://en.wikipedia.org/wiki/List_of_system_dynamics_software.

Interpretive Structural Modeling (ISM). ISM is a computer-aided interactive learning process that attempts to identify systemic structures by transforming vague, poorly defined mental models into clear, well-defined graphic representations. ISM begins by first identifying relevant variables and plotting them as points on a graph. Those elements that are related are connected by a directional line. The existence and nature of the relationships are determined by a brainstorming group whose collective judgment determines the final model; it is thus a group learning process. Typical steps in ISM are: 1) Develop a Structural Self-Interaction Matrix (SSIM). In this step, a group of experts plot system elements and determine inter-relationships, indicating them with arrows. 2) In the 2nd step a "Reachability Matrix" is developed by using symbols to represent the relationships between elements as unidirectional, bi-directional, or non-existent 3) Step 3 calls for Partition Leveling. First, all elements that are impacted by a particular element (the "reachability set") are identified.

Then, all elements that impact that element (the "antecedent set") are identified. An intersection set (representing the intersection of the reachability and antecedent sets) is identified for each element. Those elements for which the intersection set is the same as the reachability set are identified as "Level 1" and are removed from further consideration. Level 1 elements display closed feedback loop impacts; that is every element impacted by the element also impacts the element. The process is repeated until the level of all elements has been determined. 4) A Canonical Matrix is developed by grouping elements of the same level. 5) Based on the Canonical Matrix, a Digraph or hierarchical structure is developed showing the most important factors at the top and less-important factors beneath 6) The ISM Model is developed from the digraph by replacing nodes with verbal descriptions. This technique identifies those elements that are most strongly dependent upon other elements, and also those elements that are the strongest influencers of other elements. The Analytic Hierarchy Process (Saaty, 1980) is often used in conjunction with ISM to assess the relative importance of elements at the same hierarchical level of the ISM Model. The beauty of ISM is that it takes advantage of the knowledge and views of experts and synthesizes them into a system pictogram that clearly identifies the most important elements and relationships in a system. ISM is explained in detail by Warfield (1974), Attri *et al*. (2013), and Lendaris (1980).

Systemic Root Cause Analysis (RCA). RCA is a class of problem solving methods aimed at identifying the root causes (not the symptoms) of problems or events. It is especially good for solving problems caused by the system (and many are). Root Cause Analysis is a step by step method that leads to the discovery of a fault's first or root cause, typically starting with the Five "Why's". But according to Mark Galley of *Think Reliability*, "…. most organizations stop their RCA too early, at (for example) one of the following: human error, procedure not followed, training less than adequate, or equipment failure." Galley goes on to say that while it is true that these things occur, addressing them is like a Band-Aid. To cure the disease, we must identify and change the *systemic structure* that allowed them to occur by asking specific "Why?" questions. The systems approach to RCA is based on this principle of systemic cause and effect.

Most of us are familiar with the "Oil-On-the-Floor" example. In this scenario a Plant Manager walks into the plant and finds oil on the floor. He calls the Foreman over and asks him why there is oil on the floor. The Foreman indicates that it is due to a leaky gasket in the pipe joint above and that an entire batch of gaskets is defective. The Plant Manager then talks with Purchasing about the gaskets; the Purchasing Manager indicates that they were bought from an unknown vendor because that vendor was the lowest bidder. The Plant Manager then asks the Purchasing Manager why they went with the lowest bidder, and he indicates that was the direction he had received from the VP of Finance. When the Plant Manager asks the VP of Finance why Purchasing had been directed to always take the lowest bidder, the VP of Finance says, "Because you indicated that we had to be as cost conscious as possible!" The Plant Manager is horrified to realize that ***he*** is the reason there is oil on the plant floor. And in conventional linear thinking, the scenario ends there. ***But that's not the solution in systems thinking!*** The plant manager could very well conclude that he should be more careful in the future when giving directives, and that he should consider ramifications and how people might react; he might even conclude that he should be more of a systems thinker. But until every manager in the plant understands "unforeseen consequences" and systems thinking, this type of problem will recur! Systems thinking requires that we address the ***system*** that allowed the plant manager to give such a directive and that allowed the VP of finance ("be cost-conscious" means "buy from the lowest bidder"-linear!), purchasing manager, etc., to react in such non-constructive, linear-thinking ways. We have found it interesting that very often, it is the *environment* or *corporate culture* that is the systemic root cause of many problems (e.g. the space shuttle Challenger disaster, the Jerry Sandusky child-abuse debacle.)

Several of these tools couple together nicely. Causal Loop Diagrams, for example, are good precursors to stock-and-flow diagrams which, in turn, are helpful in developing dynamic system models using iThink, Stella, or similar software packages. Bellinger (2004) does a nice job explaining how CLDs can be translated into stock-and-flow diagrams. Root cause analysis and archetypes also couple well.

4. Conclusions

There is a good deal of literature about Systems Thinking presenting a variety of concepts and viewpoints, many of which are disparate. In this paper we have reviewed some of the key literature and attempted to identify common threads and integrate them into a coherent definition. Systems thinking is 1) a perspective that recognizes systems as collections of components that are all interrelated and necessary, and whose *inter-relationships* are at least as important as the components themselves; 2) a language centered on the Iceberg Model, unintended consequences, causal loops, emergence, and system dynamics, and 3) a collection of tools comprising systemigrams, archetypes, causal loops with feedback and delays, stock and flow diagrams, behavior-over-time graphs, main chain infrastructures, system dynamics/computer modeling, interpretive structural modelling, and systemic root cause analysis.

Systems Thinking provides a great deal of power and value. It can be used to solve complex problems that are not solvable using conventional reductionist (dissective) thinking, because it focuses on the relationships among system components, as well as on the components themselves; those relationships often dominate system performance. It focuses on the properties of the whole that are neither attributable to nor predictable from the properties of the components. Systems Thinking can be used to explain and understand dynamic non-linear behaviors like the inventory oscillations in supply chain management and the populations of predators and their prey; it can be used to understand complex socio-economic problems, predict behaviors, and identify leverage points (e.g. the instability in Afghanistan and the failure of drinking water systems in Togo); and it can be used to explain and understand the apparently illogical behaviors of individuals, organizations, and even countries (such as the rationale behind John Hinckley's attempted assassination of President Reagan, ISIS's apparently self-destructive behavior, and the failure of Research In Motion to remain competitive in the Smart Phone industry.)

5. Future Work

The real measure of any definition of Systems Thinking is its ability to help understand and address systems issues. Future papers will investigate the application of the above-described description of systems thinking to real-world problems such as root cause analysis of the space shuttle "Challenger" disaster and of the Penn State sex abuse scandal, the demise of Research In Motion, Inc. and of Polaroid, Inc., how to deal with ISIS, the decline of the fin fishing industry off the coast of New England vs the success of Maine's lobster fishing industry, the failure of our domestic drug policies, the British Petroleum Gulf of Mexico oil spill, the 2008 U.S. economic bailout, and the success of Emperor Palpatine of *Star Wars*.

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