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INTRODUCTION AND OVERVIEW

Addressing complex systems such as health-care delivery, sustainable energy, financial systems, urban infrastructures, and national security requires knowledge and skills from many disciplines, including systems science and engineering, behavioral and social science, policy and political science, economics and finance, and so on. These disciplines have a wide variety of views of the essential phenomena underlying such complex systems. Great difficulties are frequently encountered when interdisciplinary teams attempt to bridge and integrate these often-disparate views.

This book is intended to be a valuable guide to all the disciplines involved in such endeavors. The central construct in this guide is the notion of phenomena, particularly the essential phenomena that different disciplines address in complex systems. Phenomena are observed or observable events or chains of events. Examples include the weather, climate change, traffic congestion, aggressive behaviors, and cultural compliance. A team asked to propose policies to address the problem of overly aggressive motorist behaviors during inclement weather in the evening rush hour might have to consider the full range of these phenomena.

Traditionally, such problems would be decomposed into their constituent phenomena, appropriate disciplines would each be assigned one piece of the

puzzle, and each disciplinary team would return from their deliberations with insights into their assigned phenomena and possibly elements of solutions. This reductionist approach often leads to inferior solutions compared to what might be achieved with a more holistic approach that explicitly addresses the interactions among phenomena and central trade-offs underlying truly creative solutions. This book is intended to enable such holistic problem solving.

Five themes are woven throughout this book.

- Understanding the essential phenomena underlying the overall behaviors of complex systems and enterprises can enable improving these systems.
- These phenomena range from physical, behavioral, and organizational, to economic and social, all of which involve significant human components.
- Specific phenomena of interest and how they are represented depend on the questions of interest and the relevant domains or contexts.
- Visualization of phenomena and relationships among phenomena can provide the basis for understanding where deeper exploration is warranted.
- Mathematical and computational models, defined *very* broadly across disciplines, can enable the necessary deeper understanding.

This chapter proceeds as follows. We first consider the nature of a range of perspectives on systems. This begins with an exploration of historical perspectives, drawing upon several disciplines. We then consider the nature of complexity and complex systems. This leads to elaboration of the contrast between complex and complicated systems and the notion of complex adaptive systems. We then consider systems practice over the past century. This background is intended to provide a well-informed foundation that will enable digesting the material discussed in later chapters.

SYSTEMS PERSPECTIVES

It is useful to reflect on the roots of systems thinking. This section begins with a discussion of the systems movement. We then elaborate the philosophical underpinnings of systems thinking. Finally, we review a range of seminal concepts. Brief sketches of these concepts are presented here; they are elaborated in greater depth in later chapters.

Systems Movement

The systems movement emerged from the formalization of systems theory as an area of study during and following World War II, although it can be argued that the physicists and chemists of the 19th century contributed to the foundations of this area. Before delving into the ideas emerging in the 1940s and beyond, it is important to distinguish four aspects of the systems movement:

- *Systems Thinking* is the process of understanding how things influence one another within a whole and represents an approach to problem solving that views "problems" as components of an overall system.
- *Systems Philosophy* is the study of systems, with an emphasis on causality and design. The most fundamental property of any system is the arbitrary boundary that humans create to suit their own purposes.
- *Systems Science* is an interdisciplinary field that studies the characteristics of complex systems in nature and society, to develop interdisciplinary foundations, which are applicable in a variety of areas, such as engineering, biology, medicine, and economics.
- *Systems Engineering* is an interdisciplinary field focused on identifying how complex engineering undertakings should be designed, developed, and managed over their life cycles.

Contrasting these four aspects of systems, it is important to recognize that different disciplines tend to see "systems" quite differently, for the most part due to the varying contexts of interest (Adams et al., 2014). Thus, a systems scientist studying marsh ecosystems and a systems engineer designing and developing the next fighter aircraft will, from a practical perspective at least, have much less in common than the term "system" might lead one to expect. The key point is that systems exist in contexts and different contexts may (and do) involve quite disparate phenomena.

Philosophical Background

There are many interpretations of what system thinking means and the nature of systems thinkers. Some are inclined toward model-based deduction, while others are oriented toward data-driven inference. The former extol the deductive powers of Newton and Einstein, while the latter are enamored with the inferential capabilities of Darwin. These different perspectives reflect different epistemologies.

The study of epistemology involves the questions of what is knowledge, how can it be acquired, and what can be known. The empiricism branch of epistemology emphasizes the value of experience. The idealism branch sees knowledge as innate. The rationalism branch relies on reason. The constructivism branch seeks knowledge in terms of creation. These branches differ in terms of how they represent knowledge, in particular how this knowledge is best modeled and simulated (Tolk, 2013).

There are many possible ways of thinking about complex systems and enterprises (Rouse, 2005, 2007). Systems paradigms for representation of knowledge include hierarchical mappings, state equations, nonlinear mechanisms, and autonomous agents (Rouse, 2003). For hierarchical mappings, complexity is typically due to large numbers of interacting elements. With uncertain state equations, complexity is due to large numbers of interacting state variables and significant levels of uncertainty. Discontinuous, nonlinear mechanisms attribute complexity to departures from the expectations stemming from continuous, linear phenomena. Finally, autonomous agents generate complexity via the reactions of agents to each other's behavior and lead to emergent phenomena. The most appropriate choice among these representations depends on how the boundaries of the system of interest are defined (Robinson et al., 2011).

Horst Rittel argued that the choice of representation is particularly difficult for "wicked problems" (Rittel & Webber, 1973). There is no definitive formulation of a wicked problem. Wicked problems have no stopping rule – there is always a better solution, for example, "fair" taxation and "just" legal systems. Solutions to wicked problems are not true or false, but good or bad. There is no immediate or ultimate test of a solution to a wicked problem. Wicked problems are not amenable to trial-and-error solutions. There is no innumerable (or an exhaustively describable) set of potential solutions and permissible operations. Every wicked problem is essentially unique. Every wicked problem can be considered a symptom of another problem. Discrepancies in representations can be explained in numerous ways – the choice of explanation determines the nature of problem's resolution. Problem solvers are liable for the consequences of the actions their solutions generate. Many real-world problems have the aforementioned characteristics.

The notion of wicked problems raises the possibility of system paradoxes (Baldwin et al., 2010). Classic paradoxes include whether light is a particle or a wave. Contemporary paradoxes include both collaborating and competing with the same organization. The conjunction paradox relates to the system including element A and element not A. The biconditional paradox holds if A implies B and B implies A. For the equivalence paradox, system elements have contradictory qualities. With the implication paradox, one or

more system elements lead to its own contradiction. The disjunction paradox involves systems that are more than the sum of their parts. Finally, the perceptual paradox reflects perceptions of a system that are other than reality.

Finally, there are fundamental theoretical limits as to what we can know about a system and its properties (Rouse and Morris, 1986; Rouse et al., 1989; Rouse and Hammer, 1991). There are limits of system information processing capabilities (Chaitin, 1974), limits to identifying signal processing and symbol processing models, limits of validating knowledge bases underlying intelligent systems, and limits of accessibility of mental models in terms of forms and content of representations. The implication is that models are inherently approximations of reality and may be biased and limited in significant ways. This topic is pursued in more depth in Chapter 5.

This broad – and very brief – review of the philosophical underpinnings of the systems arena leads to two very important observations. First, the range of disciplines involved and the variety of formalisms they employ has led to a lack of crispness in the nature of the field. Second, this state of affairs can, to a great extent, be attributed to the very wide range of phenomena of interest, for example, biological cells to urban infrastructures to macroeconomic policies. Chapters 4–7 address this variety by partitioning it into classes of phenomena, then recombining these elements in Chapters 8–10.

Seminal Concepts – Systems Science

The experiences of the problem-driven research in World War II led many now-notable researchers to develop new concepts, principles, models, methods, and tools for specific military problems that they later generalized to broader classes of phenomena. The systems theorists included Norbert Wiener (1961), who generalized control theory into the concept of cybernetics. Weiner defined cybernetics as the study of control and communication in the animal and the machine. Studies in this area focus on understanding and defining the functions and processes of systems that have goals and that participate in circular, causal chains that move from action to sensing to comparison with desired goals and back again to action. Concepts studied include, but are not limited to, learning, cognition, adaptation, emergence, communication, efficiency, and effectiveness. Later extensions of control theory include optimal state filtering (Kalman, 1960) and optimal control (Bellman, 1957; Pontryagin et al, 1962).

Shannon (1948) developed information theory to address the engineering problem of the transmission of information over a noisy channel. The most important result of this theory is Shannon's coding theorem, which establishes that, on average, the number of bits needed to represent the result of

an uncertain event is given by its entropy, where entropy is a measure of the uncertainty associated with a random variable. In the context of information theory, the term refers to Shannon entropy, which quantifies the expected value of the information contained in a message, typically measured in binary digits or bits. Shannon's noisy-channel coding theorem states that reliable communication is possible over noisy channels provided that the rate of communication is below a certain threshold, called the channel capacity. The channel capacity can be approached in practice by using appropriate encoding and decoding systems.

Ashby (1952, 1956) added the Law of Requisite Variety to the canon. Put succinctly, only variety can destroy variety. More specifically, if a system is to be fully regulated, the number of states of its control mechanism must be greater than or equal to the number of states in the system being controlled. Thus, in order for an enterprise to reduce the variety manifested by its environment to yield less varied products and services, it must have sufficient variety in its business processes.

Bertalanffy (1968) developed General Systems Theory over several decades, with particular interest in biological and open systems, that is, those that continuously interact with their environments. The areas of systems science that he included in his overall framework encompass cybernetics; theory of automata; control theory; information theory; set, graph, and network theory; decision and game theory; modeling and simulation; and dynamical systems theory – in other words, virtually all of systems science. Bertalanffy includes consideration of systems technology including control technology, automation, computerization, and communications. Had the field of artificial intelligence existed in his time, that area would have surely been included as well. As is often the case with grand generalizations, it is often difficult to argue with the broad assertions but sometimes not easy to see the leverage gained.

Ackoff (1971) coined the term "system of systems" that has gained great currency of late. He recognized that organizations could be seen as systems. In this context, he outlined a classification of systems (self-maintaining, goal-seeking, multigoal seeking, purposive system), and elaborated the notions of system state, system changes, and system outcomes, where outcomes are seen as the consequences of system responses, not just the response variables in themselves. He further elaborated organizational systems as being variety increasing or variety decreasing, and also discusses adaptation and learning.

Seminal Concepts – Economics/Cognition

It may seem odd to group economics with cognition. However, much seminal thinking arose from people who studied behavioral and social phenomena

associated with economic processes. Nobel Prize winner Kenneth Arrow (Arrow, 1951; Arrow and Debreu, 1954) developed social choice theory, the associated impossibility theorem, equilibrium theory, and the economics of information. Nobel Prize winner Herbert Simon (1957, 1962) studied bounded rationality, satisficing versus optimizing, behavioral complexity as a reflection of environmental complexity, human information processing, and artificial intelligence. Nobel Prize winner Daniel Kahneman (2011), with his colleague Amos Tversky, studied human decision-making biases and heuristics for several decades. Finally, George Miller (1956) contributed to cognitive psychology, cognitive science, psycholinguistics (which links language and cognition), and studies of short-term memory – coming up with oft-cited "magic number seven."

This body of work provides important insights into complex systems laced with behavioral and social phenomena (as well as into how to win a Nobel Prize in Economics). Put simply, the classical notional of "economic man" as a completely rational, decision maker who can be counted on to make optimal choices is often a wildly idealistic assumption. The phenomena studied by Arrow, Simon, Kahneman, and Miller make classical mathematical economics quite difficult. On the other hand, these phenomena can make agent-based simulations quite important. In Chapters 5, 7, and 9, human decision making and problem solving are considered in some depth, with many concepts traceable back to the seminal thinkers discussed in this section.

Seminal Concepts – Operations Research

Operations research (OR) emerged from World War II and efforts to study and improve military operations. Philip Morse was a pioneer in the research philosophy of immersing problem solvers in the complex domains where solutions are sought. The key element was the emphasis on research in operational contexts rather than just study of mathematical formalisms. Morse and Kimball (1951) and Morse (1958) authored the first books in the United States in this area, and went on to publish an award-winning book on the application of OR to libraries (Morse, 1968).

C. West Churchman was internationally known for his pioneering work in OR, system analysis, and ethics. He was recognized for his then radical concept of incorporating ethical values into operating systems (Churchman, 1971). Ackoff received his doctorate in philosophy of science in 1947 as Churchman's first doctoral student (Ackoff et al., 1957). He became one of the most important critics of the so-called "technique-dominated Operations Research" and proposed more participative approaches. He argued that any human-created system can be characterized as a "purposeful system" when its "members are also purposeful individuals who intentionally and collectively

formulate objectives and are parts of larger purposeful systems" (Ackoff & Emery, 1972).

More recently, OR has come to be dominated by applied mathematicians who pursue mathematical techniques as ends in themselves. The quest for provably optimal solutions of problems has resulted in problems being scaled down, often dramatically, to enable analytical proofs of optimality. The constructs of theorems and proofs have often displaced the intention to actually solve realistically complex problems. The value of immersing researchers in complex operational domains has often come to be discounted as impractical by the researchers themselves.

Seminal Concepts – Sociology

Talcott Parsons was one of the first social scientists to become interested in systems approaches. He developed action theory, the principle of voluntarism, understanding of the motivation of social behavior, the nature of social evolution, and the concept of open systems (Parsons, 1937, 1951a, 1951b; Parsons and Smelser, 1956). This very much set the stage for the emergence of socio-technical systems as an area of study in its own right.

The idea of work systems and the socio-technical systems approach to work design was originated by Trist, Emery, and colleagues (Trist & Bamforth, 1951; Emery & Trist, 1965, 1973). This included research on participative work design structures and self-managing teams. It also led to a deep appreciation of the roles of behavioral and social phenomena in organizational outcomes and performance.

COMPLEXITY AND COMPLEX SYSTEMS

The six archetypal problems that are introduced in Chapter 2 can be viewed as complex systems problems. This begs the question of the meaning of complexity and complex systems. There is a range of differing perspectives on the nature of complex systems (Rouse, 2003, 2007; Rouse & Serban, 2011). In particular, different disciplines, in part due to the contexts in which they work, can have significantly varying views of complexity and complex systems (Rouse et al., 2012).

Several concepts are quite basic to understanding complex systems. One key concept is the dynamic response of a system as a function of structural and parametric properties of the system. The nature of the response of a system, as well as the stability and controllability of this response, is a central concern. Many OR studies focus on steady-state behavior, while economics research

addresses equilibrium behavior. However, transient behaviors – whether of the weather or the financial system – are often the most interesting and sometimes the most damaging.

Another basic concept is uncertainty about a system's state. The state of a system is the quantities/properties of the system whose knowledge, along with future inputs, enables prediction of future values of this set of variables. Uncertainty of system state limits the effectiveness of control strategies in assuring system performance. State estimation – filtering, smoothing, and prediction – is an important mechanism for obtaining the best information for controlling a complex system. Related topics include the value of information and performance risks, for example, consequences of poor performance.

It is useful to differentiate the notions of "system" and "complex system" (Rouse, 2003). A system is a group or combination of interrelated, interdependent, or interacting elements that form a collective entity. Elements may include physical, behavioral, or symbolic entities. Elements may interact physically, computationally, and/or by exchange of information. Systems tend to have goals/purposes, although in some cases, the observer ascribes such purposes to the system from the outside so to speak.

Note that a control system could be argued to have elements that interact computationally in terms of feedback control laws, although, one might also argue that the interaction takes place in terms of the information that embodies the control laws. One could also describe the control function in terms of physical entities such as voltages and displacements. Thus, there are (at least) three different representations of the same functionality – hence, the "and/or" in the definition.

A complex system is one whose *perceived* complicated behaviors can be attributed to one or more of the following characteristics: large numbers of elements, large numbers of relationships among elements, nonlinear and discontinuous relationships, and uncertain characteristics of elements and relationships. From a functional perspective, the presence of complicated behaviors, independent of underlying structural features, may be sufficient to judge a system to be complex. Complexity is perceived because apparent complexity can decrease with learning.

More specifically, system complexity tends to increase with
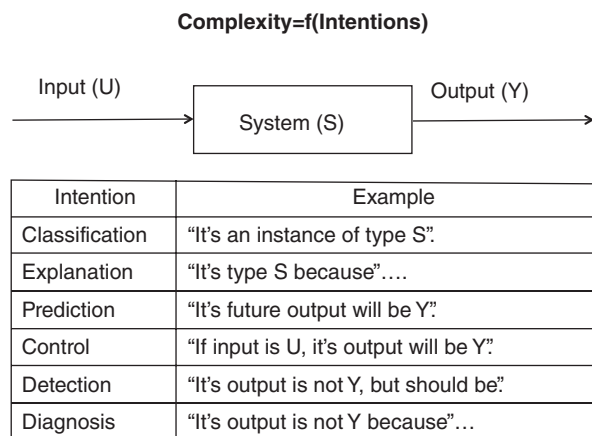
- Number of elements
- Number of relationships
- Nature of relationships
  - Logical: AND versus OR and NAND
  - Functional: linear versus nonlinear
  - Spatial: lumped versus distributed

- Structural: for example, feedforward versus feedback
- Response: static versus dynamic
- Time constant: (not too) fast versus (very) slow
- Uncertainty: known properties versus unknown properties
- Knowledge, experience, and skills
  - Relative to all of the above
  - Relative to observer's intentions

Of course, the preceding list begs the question of whether the elements of a system are knowable. For example, this list is of limited use in describing a city, except perhaps for the utility infrastructures. Thus, as elaborated later, we have to differentiate complex and complicated systems.

The issue of intentions is summarized in Figure 1.1 (Rouse, 2007). If one's intention is simply to classify as observed object as an airplane, the object is not particularly complex. If one wanted to explain why it is an airplane, the complexity of an explanation would certainly be greater than that of a classification. For these two intentions, one is simply describing an observed object.

If one's intention is to predict the future state of the airplane, complexity increases substantially as one would have to understand the dynamic nature of the object, at least at a functional level but perhaps also at a structural level. Control requires a higher level of knowledge and skill concerning input–output relationships. Intentions related to detection and diagnosis require an even greater level of knowledge and skill concerning normal

Complexity=f(Intentions)

Intention	Example
Classification	"It's an instance of type S".
Explanation	"It's type S because"….
Prediction	"It's future output will be Y".
Control	"If input is U, it's output will be Y".
Detection	"It's output is not Y, but should be".
Diagnosis	"It's output is not Y because"…

Figure 1.1   Relationship of Complexity and Intentions

and off-normal behaviors in terms of symptoms, patterns, and structural characteristics of system relationships. The overall conclusion is that the complexity of a system cannot be addressed without considering the intentions associated with addressing the system.

This observation is fundamental, and often hotly debated. It argues that complexity involves a relationship between an observer and an object or system. The implication is that there is no absolute complexity independent of the observer. In other words, the complexity of a system depends on why you asked the question, as well as your knowledge and skill relative to the system of interest.

COMPLEX VERSUS COMPLICATED SYSTEMS

Snowden and Boone (2007) have argued that there are important distinctions that go beyond those outlined earlier. Their Cynefin Framework includes simple, complicated, complex, and chaotic systems. Simple systems can be addressed with best practices. Complicated systems are the realm of experts. Complex systems represent the domain of emergence. Finally, chaotic systems require rapid responses to stabilize potential negative consequences. The key distinction with regard to the types of contexts discussed in this book is complex versus complicated systems. There is a tendency, they contend, for experts in complicated systems to perceive that their expertise, methods, and tools are much more applicable to complex systems than is generally warranted.

Poli (2013) also elaborates the distinctions between complicated and complex systems. Complicated systems can be structurally decomposed. Relationships such as listed earlier can be identified, either by decomposition or, in some cases, via blueprints. "Complicated systems can be, at least in principle, fully understood and modeled." Complex systems, in contrast, cannot be completely understood or definitively modeled. He argues that biology and all the human and social sciences address complex systems.

Poli also notes that problems in complicated systems can, in principle, be solved. The blueprints, or equivalent, allow one to troubleshoot problems in complicated systems. In contrast, problems in complex systems cannot be solved in the same way. Instead, problems can be influenced so that unacceptable situations are at least partially ameliorated.

Alderson and Doyle (2010) also discuss contrasting views of complexity and distinguish the constructs of simplicity, disorganized complexity, and organized complexity, drawing upon several of the post World War II

seminal thinkers discussed earlier. With simplicity, "Questions of interest can be posed using models that are readily manageable and easy to describe, theorem statements are short, experiments are elegant and easy to describe, and require minimal interpretation. Theorems have simple counterexamples or short proofs, algorithms scale, and simulations and experiments are reproducible with predictable results."

Disorganized complexity "Focuses on problems with asymptotically infinite dimensions and develops powerful techniques of probability theory and statistical mechanics to deal with problems. As the size of the problem and the number of entities become very large, specific problems involving ensemble average properties become easier and more robust and statistical methods apply."

They illustrate this view with a discussion of the new science of complex networks, "which emphasizes emergent fragilities in disorganized systems. Proponents of this paradigm view architecture as graph topography." Their view of the Internet, for example, is "random router and web graphs without system-level functions other than graph connectivity, architecture solely in terms of graph topology, and components as homogeneous functionless links and nodes."

In contrast, organized complexity "Addresses problems where organization is an essential feature, which include biological systems, urban systems, and technological systems. Organized complexity manages the fragility–complexity spiral." For example, it views architecture as involving layering and protocols, rather than just the random connections of disorganized complexity.

The distinctions articulated by these authors are well taken. Complicated systems have often been designed or engineered. There are plans and blueprints. There may be many humans in these systems, but they are typically playing prescribed roles. In contrast, complex systems, as they define them, typically emerge from years of practice and precedent. There are no plans and blueprints. Indeed, much research is often focused on figuring out how such systems work. A good example is human biology.

The nature of human and social phenomena within such systems is a central consideration. Systems where such phenomena play substantial roles are often considered to belong to a class of systems termed complex adaptive systems (Rouse, 2000, 2008). Systems of this type have the following characteristics:

- They tend to be *nonlinear, dynamic* and do not inherently reach fixed equilibrium points. The resulting system behaviors may appear to be random or chaotic.

- They are composed of *independent agents* whose behaviors can be described as based on physical, psychological, or social rules, rather than being completely dictated by the physical dynamics of the system.
- Agents' needs or desires, reflected in their rules, are not homogeneous and, therefore, their *goals and behaviors are likely to differ or even conflict* – these conflicts or competitions tend to lead agents to adapt to each other's behaviors.
- Agents are *intelligent and learn* as they experiment and gain experience, perhaps via "meta" rules, and consequently change behaviors. Thus, overall system properties inherently change over time.
- Adaptation and learning tends to result in *self-organization* and patterns of behavior that emerge rather than being designed into the system. The nature of such emergent behaviors may range from valuable innovations to unfortunate accidents.
- There is *no single point(s) of control* – system behaviors are often unpredictable and uncontrollable, and no one is "in charge." Consequently, the behaviors of complex adaptive systems usually can be influenced more than they can be controlled.

As might be expected, understanding and influencing systems having these characteristics creates significant complications. For example, the simulation of such models often does not yield the same results each time. Random variation may lead to varying "tipping points" among stakeholders for different simulation runs. These models can be useful in the exploration of leading indicators of the different tipping points and in assessing potential mitigations for undesirable outcomes. This topic is addressed in more detail later.

SYSTEMS PRACTICE

The evolving collection of approaches to understanding and influencing complex systems and enterprises can be termed systems practice. The development of systems practice has a rich history.

- During the 1900–1920s, Henry Gantt (1861–1919), Frederick Taylor (1856–1919), and Frank Gilbreth (1868–1924) pioneered scientific management.
- Quality assurance and quality control emerged in the 1920–1930s, led by Walter Shewhart (1891–1967).
- Peter Drucker (1909–2005) and Chester Barnard (1886–1961) formalized corporate operations management in the 1940–1950s.

- During and following World War II, Philip Morse (1903–1985), C. West Churchman (1913–2004), George Dantzig (1914–2005), and Russell Ackoff (1919–2009) were leading thinkers in OR.
- Stafford Beer (1926–2002) articulated the foundations of management cybernetics in the 1960–1970s.
- W. Edwards Deming (1900–1993) and Joseph Juran (1904–2008) brought total quality management to the United States in the 1970–1980s.
- Michael Hammer (1948–2008) and James Champy led the wave of business process reengineering in the 1990s.
- Taiichi Ohno's (1912–1990) innovations in six sigma and lean production gained traction in the United States in the 1990–2000s.
- Most recently, Daniel Kahneman has led the way for behavioral economics in the 2010s.

The cornerstone of systems practice is usually considered to be systems thinking, which has been characterized in a variety of ways, depending on the analytic paradigms of interest, for example, (Checkland, 1993; Weinberg, 2001; Jackson, 2003; Meadows, 2008; Gharajedaghi, 2011). Over more than a century, systems thinking tried to become increasingly rigorous, focusing on mathematics, statistics, and computation. During the 1960–1970s, many thought leaders began to recognize that forcing all phenomena into this mold tended to result in many central phenomena being assumed away to allow for the much-sought theorems and proofs to be obtained. In particular, behavioral and social phenomena associated with complex systems were simplified by viewing humans as constrained but rational decision makers who always made choices that optimized the objective performance criteria – which were linear, if lucky.

The reaction, particularly in the United Kingdom, to such obviously tenuous assumptions was the emergence of the notion of hard versus soft systems thinking (Pidd, 2004). Table 1.1 contrasts these two points of view. Hard systems thinking seeks quantitative solutions of mathematical models that are assumed to be valid representations of the real world and, consequently, will inherently be embraced once they are calculated. Soft systems thinking sees modeling as a means for exploration and learning via intellectual and inherently approximate constructs open to discussion and debate.

Table 1.2 contrasts systems approaches (Jackson, 2003). Hard systems thinking represents but one cell in this table. Other methods are much less "closed form" in orientation, relying more on simulation as well as participative mechanisms. The keys for these latter mechanisms are insights and consensus building.

TABLE 1.1   Hard versus Soft Systems Thinking (Pidd, 2004)

Hard Systems Thinking	Soft Systems Thinking
Oriented to goal seeking	Oriented to learning
Assumes the world contains systems that can be "engineered"	Assumes the world is problematical but can be explored using models or purposeful activity
Assumes systems models to be models of the world	Assumes systems models to be intellectual constructs to help debate
Talks the language of problems and solutions	Talks the language of issues and accommodations
Philosophically positivistic	Philosophically phenomenological
Sociologically functionalist	Sociologically interpretative
Systematicity lies in the world	Systematicity lies in the process of inquiry into the world

TABLE 1.2   Systems Approaches (Jackson, 2003)

		Participants		
		Unitary	Pluralist	Coercive
Systems	Simple	Hard systems thinking	Soft systems approaches	Emancipatory systems thinking
	Complex	System dynamics Organizational cybernetics Complexity theory		Postmodern systems thinking

   Table 1.3 contrasts methodologies and problems (Jackson & Keys, 1984). Again, only one cell of the table includes traditional OR and systems analysis. For other than mechanical problems with a single decision maker, much more participative approaches are warranted, at least if the goal is solving the problem of interest rather than just modeling the "physics" of the context.

   Table 1.4 summarizes Ulrich's (1988) levels of system practice. He differentiates hard versus soft in terms of three categories – one hard and two versions of soft. One class of soft management addresses change while the other addresses conflict. The key disciplines and tools vary substantially across these three categories.

TABLE 1.3   Methodologies versus Problems (Jackson & Keys, 1984)

	Mechanical	Systemic
Unitary – one decision maker	Operations research Systems engineering Systems analysis	Organizational cybernetics socio-technical systems
Pluralist – multiple independent decision makers	Singerian inquiry systems Strategic assumption methods Wicked problem formulations	General systems theory Complex adaptive systems Soft systems methodology

Table 1.5 summarizes Jackson's (2003) Critical Systems Practice. The most important aspect of his guidance is to remain open to the range of possibilities in Tables 1.1–1.4. From the perspective of understanding complex systems, this means that the nature of models entertained should be driven by the issues of interest, the phenomena underlying these issues, and the orientations of the key stakeholders in the problem framing and solving processes.

Pidd (2004) offers the notion of complementarity as a way of rationalizing the relationship between hard and soft approaches. He argues that hard and soft approaches are complementary to each other, but their complementarity is asymmetric. He asserts that any problem situation in human affairs will always at some level entail differences in world views that the "soft" approaches can be used to explore. Within that exploration, any or all of the hard approaches can be adopted as a conscious strategy. The reverse strategy is not available because it entails abandoning the ontological stance of hard approaches. In other words, hard approaches are often inextricably tied to paradigms and assumptions that are central to their problem-solving power.

There is a wealth of formal methods that can play a role in systems practice. Approaches to systems modeling, from a range of disciplinary perspectives, are discussed in Haskins (2006) and in Sage and Rouse (2009). A variety of paradigm-specific treatments are also available, such as Forrester's (1961) classic on systems dynamics modeling and Sterman's (2000) contemporary treatment of system dynamics modeling. Chapter 9 elaborates a variety of formal theories in terms of typical assumptions and outcomes predicted, along with brief expositions of the basic mathematics.

Gharajedaghi (2011) articulates a system methodology for supporting complex adaptive systems. The methodology focuses on functions, structure,

TABLE 1.4 Levels of Systems Practice (Ulrich, 1988)

Aspect	Operational Systems Management	Strategic Systems Management	Normative Systems Management
Dominating interpretation	Systematic	Systemic	Critical idea of reason
Strand of systems thinking	Hard – mechanistic paradigm	Soft – evolutionary paradigm	Soft – normative paradigm
Dimension of rationalization	Instrumental	Strategic	Communicative
Main object of rationalization	Resources – means of production	Policies – steering principles	Norms – collective preferences
Task of the expert	Management of scarceness	Management of complexity	Management of conflict
Type of pressure	Costs	Change	Conflict
Basic approach	Optimization	Steering capacity	Consensus
Goodness criterion	Efficient	Effective	Ethical
Theory-practice mediation	Decisionistic	Technocratic	Pragmatistic
Key disciplines	Decision theory, economics, engineering	Game theory, ecology, social sciences	Discourse theory, ethics, critical theory
Example tools	Cost–benefit analysis, linear optimization	Sensitivity analysis, large-scale simulation	Systems assessment, ideal planning
Trap to avoid	Suboptimization	Social technology	Excluding the affected

TABLE 1.5   Critical Systems Practice (Jackson, 2003)

|	
Creativity	
Task	To highlight significant concerns, issues, and problems
Tools	Creativity-enhancing devices employing multiple perspectives
Outcome	Dominant and dependent concerns, issues, and problems
Choice	
Task	To choose an appropriate generic systems methodology
Tools	Methods for revealing methodological strengths and weaknesses
Outcome	Dominant and dependent generic systems methodologies
Implementation	
Task	To arrive at and implement specific positive change proposals
Tools	Generic systems methodologies
Outcome	Highly relevant and coordinated change yielding improvements
Reflection	
Task	To produce learning about the problem and solution
Tools	Clear understanding about the current state of knowledge
Outcome	Research findings that fed back into practice

and processes. To define functions, he argues that one should clarify which products solve which problems for which customers. To define structure, he advances the idea of a modular design that defines complementary relationships among relatively autonomous units. Finally, design of processes involves using a multidimensional modular design based on the triplet input (technology), output (products), and environments (markets).

This brief discussion of systems approaches serves to set the stage for alternative approaches to understanding complex systems and enterprises. The nature of these systems usually precludes fully modeling them with first-principles physics models. These systems are, by no means, as mechanistic and predictable as purely physical systems like bouncing balls or gear trains. Yet, there are well-developed approaches for addressing problem solving in complex systems and enterprises. Valid predictions, and occasionally optimization, are certainly of interest. However, insights into phenomena, sensitivities to key parameters, and consensus building are often the overarching goals.

The material discussed in this section sets the stage for the methodological discussions in Chapter 2. The emphasis on problem formulation and hard versus soft approaches are highly relevant. The first four steps of our ten-step methodology are very much focused on problem formulation. The great emphasis placed on visualization first and computation later enables taking advantage of "soft" approaches early and only resorting to "hard" approaches for aspects of problems that warrant such investments.

PHENOMENA AS THE STARTING POINT

The construct of "phenomena" is central to this book. Problem solving should not begin with the selection of mathematical or computational models, but instead should commence with consideration of the phenomena that must be understood to successfully answer the questions that motivated the modeling effort in the first place.
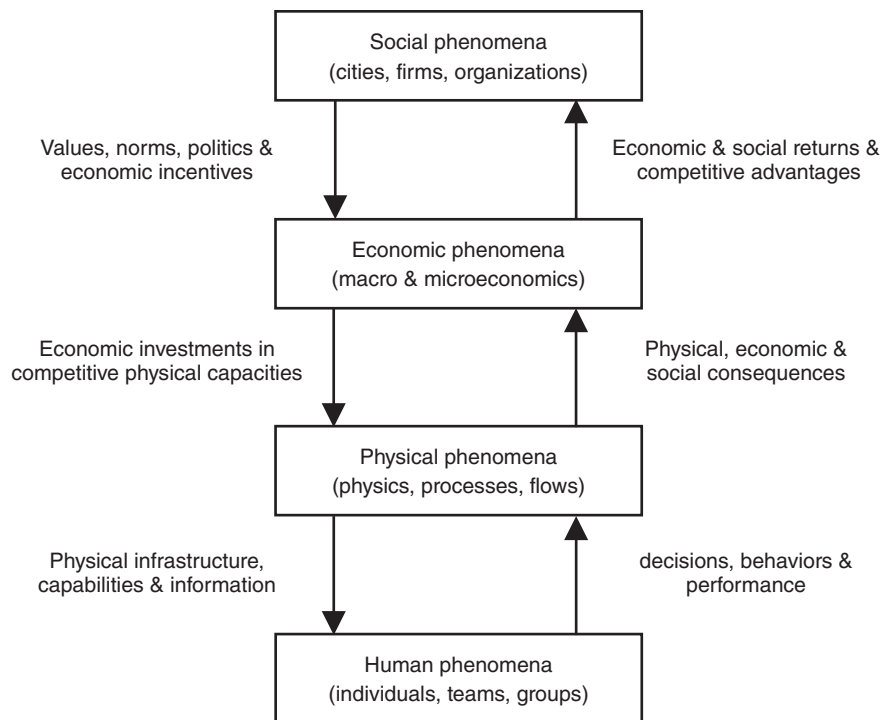
Figure 1.2   Hierarchy of Phenomena

TABLE 1.6   Eight Classes of Phenomena

Class of Phenomena	Example Phenomena of Interest
Physical, natural	Temporal and spatial relationships and responses
Physical, designed	Input–output relationships, responses, stability
Human, individuals	Task behaviors and performance, mental models
Human, teams or groups	Team and group behavior and performance
Economic, micro	Consumer value, pricing, production economics
Economic, macro	Gross production, employment, inflation, taxation
Social, organizational	Structures, roles, information, resources
Social, societal	Castes, constituencies, coalitions, negotiations

Figure 1.2 provides a framework for thinking about phenomena and relationships among phenomena. There are four levels – physical, human, economic, and social – as well as typical relationships among phenomena. Of course, there are many subtleties that are not reflected in Figure 1.2, but will be elaborated in Chapters 3–7.

Table 1.6 provides a glimpse into the eight classes of phenomena addressed in this book. The overall taxonomy of phenomena is elaborated in Chapter 3, while physical, human, economic, and social phenomena are addressed in Chapters 4–7, respectively. We also discuss in Chapter 3 the phenomena associated with the six archetypal problems that are introduced in Chapter 2.

OVEVIEW OF BOOK

This final section of this introductory chapter provides synopses of the chapters in this book and the lines of reasoning that connect them.

Chapter 1: Introduction and Overview

This chapter begins by placing modeling and visualization of complex systems in the context of the evolution of the systems movement, its philosophical background, and a wide range of seminal concepts. Constructs associated with complexity and complex systems are discussed. The important contrast between complex and complicated systems is elaborated. The last century of systems practice is briefly reviewed to provide a foundation for the methodology advocated in this book. The use of phenomena as a starting point is then argued. Finally, an overview of the book is provided.

Chapter 2: Overall Methodology

This chapter begins with a discussion of human-centered methods and tools. The emphasis is on assuring that a methodology is both useful and usable. We then discuss six problems archetypes that are addressed throughout this book. The choice of this set of problems was motivated by the desire to assure that the methodology not be problem specific. Attention then turns to the overall ten-step methodology. An example is used to illustrate application of the methodology to congestion pricing of urban traffic. The chapter concludes with discussion of an environment that supports use of the methodology.

Chapter 3: Perspectives on Phenomena

In this chapter, we explore the fundamental nature of phenomena and the role that this construct plays in technology development and innovation. The construct is discussed from both historical and contemporary perspectives. Numerous historical and contemporary examples are used to illustrate the evolution of technology as well as the increasing scope of its application. A taxonomy of phenomena is introduced, with particular attention paid to its behavioral and social components. Use of the taxonomy is illustrated using the six archetypal problems introduced in Chapter 2. Finally, visualization of phenomena is discussed in the context of the examples used throughout Chapters 4–7.

Chapter 4: Physical Phenomena

This chapter considers two types of physical phenomena. First, we discuss naturally occurring phenomena such as weather and water flow. We consider two examples – human biology and urban oceanography. Then we address designed phenomena such as systems engineered to move people and goods. Examples of interest here include vehicle powertrains and manufacturing processes. We also discuss the intersection of designed and natural physical phenomena, which is a central issue in urban oceanography. The chapter concludes with an elaboration of the archetypal example of deterring or identifying counterfeit parts.

Chapter 5: Human Phenomena

This chapter begins by contrasting descriptive and prescriptive approaches. Descriptive approaches focus on data from past instances of the phenomena of interest. Prescriptive approaches attempt to calculate what humans should do given the constraints within which they have to operate. A wide range of models of human behavior and performance are outlined. Examples discussed

include manual control, problem solving, and multitask decision making. This exposition is followed by a detailed look at the traffic control problem from our set of archetypal problems. Many of the models discussed make assumptions about what humans know relative to the tasks at hand. Some of this knowledge is characterized using the notion of "mental models." The nature of this construct is discussed in terms of approaches to assessing mental models and use of the outcomes of such assessments. Finally, fundamental limits in modeling human behavior and performance are addressed.

Chapter 6: Economic Phenomena

This chapter reviews concepts and models from microeconomics, macroeconomics, and behavioral economics. Within microeconomics, the theory of the firm and the theory of the market are reviewed. Examples presented include optimal pricing and the economics of investing in people. Macroeconomic issues frame the context for microeconomic decisions. We consider gross domestic product growth, tax rates, interest rates, and inflation, which can strongly affect the economic worth of alternative investments. Behavioral economics is addressed in terms of how people actually behave rather than how traditional economists assume they behave. A final section addresses the economics of health-care delivery. This example is laced with the microeconomic and macroeconomic phenomena discussed throughout this chapter.

Chapter 7: Social Phenomena

This chapter begins with consideration of the social phenomena identified for the six archetypal problems discussed throughout this book. Emergent and designed phenomena are then contrasted, as well as direct versus representative political systems. The overall problem of modeling complex social systems is then considered, with an example of modeling the earth as a system. Several approaches to modeling social systems are presented, including physics-based formulations, network theory, game theory, and simulations. Examples include castes and outcastes, acquisition as a game, port and airport evacuation, and the emergence of cities. Attention then shifts to urban resilience, including introduction of a framework for understanding the full nature of resilience.

Chapter 8: Visualization of Phenomena

This chapter first briefly addresses human vision as a phenomenon, primarily to recognize the topic as important but also to move beyond the science of vision to the design of visualizations. We next review the basics of visualization to provide grounding for the subsequent discussions. We then address the

purposes of visualization. The object of design, it is argued, is the fulfillment of purposes. A visualization design methodology is then presented and illustrated with an example from helicopter maintenance. Visualization tools are then briefly reviewed. Various case studies from Stevens Institute's *Immersion Lab* are discussed. The notion of policy flight simulators is introduced and elaborated. Finally, results are presented from an extensive study of what users want from visualizations and supporting computational tools.

Chapter 9: Computational Methods and Tools

This chapter addresses modeling paradigms potentially useful for addressing the phenomena associated with the six archetypal problems discussed throughout the book. Paradigms discussed include dynamic systems theory, control theory, estimation theory, queuing theory, network theory, decision theory, problem solving theory, and finance theory. A multilevel modeling framework is used to illustrate how the different modeling paradigms can be employed to represent different levels of abstraction and aggregation of an overall problem. The next consideration is moving from representation to computation. This includes discussion of model composition and issues of entangled states and consistency of assumptions. This chapter also provides a brief overview of software tools available to support use of these computational approaches.

Chapter 10: Perspectives on Problem Solving

This chapter brings all the material in this book together to discuss a large set of case studies involving well over 100 enterprises and several thousand participants. Case studies cover broad areas of business planning, new product planning, technology investments, and enterprise transformation. Discussion of these case studies focuses on how problem solving was addressed, the roles that interactive models played in problem solving, and the types of insights and decisions that resulted. These observations on problem solving are summarized in terms of guidance on starting assumptions, framing problems, and implementing solutions. This chapter concludes with consideration of key research issues that need to be addressed to advance the approach to problem solving advocated in this book.

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