Understanding Systems

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Introduction

The sustainability challenges we face on the planet are multifaceted, complex, and interconnected. To understand them and address them effectively requires a holistic "systems" view that is still largely absent from most mainstream approaches in science, government, business, and education. It could be argued, in fact, that the many sustainability-related issues—climate change, desertification, potable water shortage, biodiversity loss, economic and social instability, and more—are the result of a non-systemic, fragmented, simplistic, and short-sighted world view that dominates our industrial civilization.

Recent decades, however, have seen a significant surge of interest in holistic ways of looking at reality with the associated development of multiple frameworks and tools which, all together, have been hailed as the emergence of a new paradigm. The combined result has been referred to in the related, burgeoning literature as "systems thinking," "the system approach," or "the system view of the world". At The Sustainability Laboratory, we subscribe to the view that systems thinking and a deeply ingrained ability to "think systems" is an indispensable tool for future sustainability leaders. We have therefore made systems thinking and systems modelling a central part of The Lab's educational curriculum.

The story of the essential link between issues of sustainability and system thinking is intensely personal for me. It began in the 1960s, when as a young architectural student in London, I met Buckminster Fuller. This life-changing event launched a long association with him first as a student, and then as a collaborator in several projects in different parts of the world. This fruitful association opened my eyes to many of the issues addressed today under the "sustainability umbrella."

An intuitive recognition of the essentially systemic nature of such issues drove me to explore concepts that were emerging at the time from the system sciences, and these included system dynamics courses at MIT. In the course of a management consulting career, opportunities soon developed to explore the use of systems dynamics as a tool for synthesizing strategies in different sectors and in relation to different issues, and a few of these cases will be touched upon further below. This preoccupation with a system perspective then led to pursuing a doctorate in cybernetics, studying with some of the leaders in this discipline. Along the way, as a student, co-worker, or friend, I have had the fortune to encounter some of the key protagonists in the field.

The purpose of this essay is to provide a basic familiarity with the concept of "system," and explore key ideas associated with general system theory and cybernetics, two main complementary scientific disciplines that underlie system thinking.

The intention is to take a random, introductory walk in the systems landscape, present the flavor of key concepts, trace their origin, and emphasize their significance. The material follows no particular order or strict linear logic, but rather mimics the very nature of "systems" by offering a smorgasbord of ideas that, with some overlap, linkages, and perhaps even some repetition, reflect the essence of a whole.

1. The Concept of System in Science

Imagine an organism of some kind that is struggling to survive, perhaps even thrive, in its world. Its prospects would be greatly enhanced if it were able to utilize an accurate map of its environment—a set of explanatory models of its surroundings—to guide its actions. Such models can take many forms, from a simple image, to a parable and a story, to a complex scientific theory.

From the earliest dawn of conscious awareness, human have been creating implicit or explicit theories about the world in order to navigate its challenges and complexities. Whether such theories are primitive or sophisticated, ancient or current, they all ultimately depend on the accumulation of experience by trial and error. For example, by repeatedly eating berries and experiencing the effects, humans slowly began to learn which were lethal and which were good for their health. By putting a new scientific theory to experimental test, it is established whether the theory works or if it must be discarded and replaced.

What has changed along the long and arduous trajectory of the evolution of knowledge are the essential characteristics of methods used in the construction of explanatory models. Changes in the central features of such methods are commonly identified by philosophers of science as major historical milestones, profound shifts in paradigms that shaped not only the nature of acquisition of knowledge, but also affected the very nature of social and economic reality.

For thousands of years, explanatory models—basically superstitions with strong animistic flavors—were associated with “forces” external to the phenomena that they were meant to explain. Things happened, and events unfolded as they did, because of the intervention of external factors: the spirits, the gods, mysterious arbitrary forces, and the like.

In the Western tradition, the early Greek philosophers are credited with bringing about a fundamental shift, a shift that is relatively recent—starting some two and a half millennia ago—which laid the foundations for what was later to emerge as the modern method of science. Greek philosophers laid the basis for experience-based explanation. They introduced the method of orderly observation and documentation of various aspects of nature. They also established the practice of seeking explanations by decomposing elements of the world to their component parts, down to the elemental building blocks, the “atoms,” then seeking to reconstruct an understanding of the whole. The significant shift then is in moving from an explanation by an arbitrary external cause to one that puts an emphasis on analytical decomposition of phenomena to their component parts.

The next step in the trajectory, which brought about the advent of modern science, continued to expand on the analytical, reductionist approach. This led to the dominance of the next important shift: that of viewing the world as a machine. This development is associated with such names as Copernicus, Kepler, Galileo, Bacon, and Descartes. It culminated with Newton’s mechanics and a view of the world as a giant, clock-work-like, exquisite machine, obeying the simple laws of motion.

The scientific method itself established a rigorous procedure for the acquisition and verification of knowledge. Observations are translated into a theoretical hypothesis, which is then subject to experimental testing. Only when repeatable test results are consistent with the hypothesis, the latter is accepted as an established theory. Underlying the procedure is the understanding that all theories are essentially tentative and must be replaced when new observations contradict an accepted truth.

The classical analytic approach has been responsible for a staggering and astonishingly rapid expansion in our understanding of material reality. It has also been responsible for all the gifts—and ills—of modern technology. By the 20th century, however, it began to run into considerable difficulties, even in the physical sciences. It was in biology, in particular, that the classical model proved completely inadequate in explaining the behavior of whole organisms by focusing on their component parts. This 'crisis' in scientific theory, and the realization that many aspects of the world cannot be explained by a reductionist method, catalyzed the emergence of the system sciences. Emphasis was placed on highlighting patterns of interactions and interdependencies of parts for the understanding of the behavior of wholes, and the concept of "system" was brought to the fore.

In retrospect, we can discern a historical trajectory of approaches for explaining reality. The trajectory begins with "**animism,"** with emphasis on arbitrary external forces; followed by **"atomism,"** then **"mechanism,"** both exemplifying the classical, analytical, reductionist, mechanistic world view; and then the concept of **"organism,"** a way of seeing the world as a complex of relations, interactions and interdependencies. The latter constitutes the systems view of the world.

Note that milestones along this trajectory are not as rigidly sequential as is implied by the listed steps. They overlap and coexist as a mix. Also, throughout history, there were inspired individuals who could see beyond the visibly obvious, seeking and expressing a holistic, integrated view of reality. Think of Leonardo da Vinci, Spinoza, Blake, Hegel, and many more. Genuine mystics of all times and traditions are also a good case in point.

Emergence of the systems view of the world has been hailed as a major revolution in scientific thinking that was bound to replace the older mechanistic model. It might be useful, however, to regard both as complementary theories that, existing in parallel, will continue to offer useful tools for addressing different aspects of reality.

From the sustainability perspective, critical issues occur in a context that is exceedingly complex, constituting a dynamic, multivariable universe that involves multiple social, political, economic, and cultural aspects interacting among themselves, across sectors, and with the physical and non-human living parts of the world. This systemic reality is irreducible, and it will not yield to a simple, linear, analytic approach. Using reductionist tactics when dealing with systems is fundamentally flawed, yet it is common when conceptualizing and attempting to address sustainability issues.

Approaching complex systems as though they were simple, clock-like mechanisms does not work, and typically only exacerbates the very adverse conditions meant to be resolved.

2. Definition of "System"

What is a system?

The term "system" is often used in ways that miss the deeper connotations that are at the heart of the relatively recent emergence of the systems perspective in science. The term is commonly used to denote a concept of a totality, identified by some logical consistency, but without putting an emphasis on the structure of relations, attributes, and causal interdependencies of the parts. In this sense we speak about a system of law, a political system, an educational system, a health care system, a production system, an economic system, and the like. These uses miss a deeper point, and it might be useful, therefore, to examine a few select definitions found in the system thinking literature.

The typical definition stresses the notion of system as any entity, any totality, consisting of interacting parts. A straightforward, clear definition that was offered by Ludwig von Bertalanffy, a German biologist and the father of general system theory, reads: **"A system is a complex of elements in mutual interaction."** This definition is free from all but one important criterion, that of "parts in interaction." The definition, incidentally, encompasses two important ideas. First, it distinguishes between parts and wholes, a major topic in mathematical logic in its own right. And second, it emphasizes the interaction of parts which make for the whole. Depending on the level of resolution, any individual component can itself be regarded as a whole consisting of interacting component parts. The focus on dynamic interactions and interdependencies makes all the difference. It defines the shift introduced by the system view of the world.

Russell Ackoff, another systems pioneer, follows a similar line of thought, but introduces an interesting twist by suggesting that a system can also be a conceptual entity. According to Ackoff, a system is **"an entity, conceptual or physical, which consists of interdependent parts."** This observation expands the domain of possible systems and it has implications for the construction of systems models, a topic that will be developed further below. For the moment, think about the following: any set of interactions defines a specific set among all possible sets of relations. In this sense, any given pattern of interactions represents a limiting factor that produces a particular kind of behavior and no other.

The next definition raises the level of abstraction by highlighting the dynamic consequence of systemic interactions. It emerged, in the late 1960s, out of the Information System Theory Project (ISTP), which was organized to address the description of data structures. It defines a system as **"a set of mutually constrained events,"** a powerful, compact definition indeed.

Another more pragmatic approach is taken by Jay Forrester, the originator of system dynamics, the modelling methodology originally developed at MIT. Forrester defined a system as **"a grouping of parts that operate together for a common purpose."** Inevitably, this definition introduces questions about how a “purpose” is defined. It highlights the role of an observer in interpreting an examined phenomenon. An observer can assume a purpose, for example, by suggesting that “the purpose of bees is to cross-pollinate,” or perform the role of a creative agent who actually introduces a new purpose into the world, for example, in declaring "the purpose of my invention is to purify water”.

A definition that comes from an entirely different tradition is due to Buckminster Fuller, the futurist architect-designer. In his seminal work *Synergetics—Explorations in the Geometry of Thinking,* Fuller defines a system as **“the first subdivision of universe into a conceivable entity.”** Such a subdivision is an act of cognition and, again, the role of an observer comes to the fore. It is the observer who subdivides total reality in an act that separates the focus of attention from all the rest.

Finally, a minimalist, elegant definition that is associated with information theory and the work of Ross Ashby, states simply that **“a system is a source of information.”** This definition may obscure the emphasis on parts and interactions, but like other rigorous definitions, it embodies fascinating philosophical and practical questions. These are associated with profound issues related to our deepest concepts about the nature of reality, purpose, identity, cognition, the nature of knowledge, the role of intuition, and the place of consciousness in the world.

Raising the question of the role of cognition and anchoring the identification of a system to a mental act suggest that establishing a system’s identity is an act of intelligence imposing its own criteria on the world. These criteria force practical but arbitrary separation with the consequent fragmentation of a reality that ultimately comprises one system—the meta system of all systems. This is, of course, what profound spiritual visionaries have been telling us all along.

A couple of additional observations that relate to the role of cognition might be useful for the aspiring systems modeler. These have to do with the challenge of selecting the right boundaries when modelling a system. This question of appropriate boundaries is ultimately dictated by a particular purpose, and it depends, to a large extent, on the modeler’s experience and skills. In addition, as a product of a mental act, every system’s model will always remain an abstract representation of reality. A model, it should never be forgotten, is not the real thing. It is a pragmatic device, a necessary simplification of reality that helps make the issues we need to address in a complex world handleable. It can offer only an approximation and no matter how elaborate, it will never capture the full richness of the real world.

Finally, most consequential systems that we interact with are dynamic in their very nature: they continuously change, adapt and evolve. This dynamic aspect is captured by the idea of the self-organizing system, which requires that observers continuously change their frame of reference and, often, their conclusions. There is a “time-sensitive” element involved here, suggesting the virtue of keeping an open mind and perhaps even fostering a measure of playful flexibility when dealing with a complex world. Remember Shakespeare? “There are more things to heaven and earth, than is dreamt of in your philosophy…” Contemplate for a moment what this statement means to the effectiveness of adopting stubborn, rigid dogmas when dealing with the many interlocking ecosystems that make our world.

3. Classification of Systems

Following the emergence of general system theory, several attempts have been made at developing a classification of systems. Classifications were offered based on categories such as function, sector, purpose, and other conventional attributes. These efforts have not contributed decisively to a better understanding of systems; instead they essentially reflected the existing frameworks of scientific and professional disciplines. Definitive, rigorous classification has proven difficult, perhaps due to the large variety and complex behavior of dynamic systems and the challenge of highlighting the general aspects that transcend their specific embodiments.

A very useful classification, nevertheless, was offered by the prominent British cybernetician and management scientist, Stafford Beer. The framework he proposed is helpful in honing attention on the domain of phenomena, of exactly the kind of systems that cannot be addressed by the reductionist, analytical approach.

Beer's classification is based on a matrix consisting of two axes, as depicted by the figure below. One axis consists of a three-fold distinction of simple, complex, and exceedingly complex systems. The other axis consists of a two-fold distinction between deterministic and probabilistic systems.

System	**Deterministic**	**Probabilistic**
Simple	—	—
Complex	—	—
Exceedingly Complex	—	✓

Figure 1: Beer's matrix used to classify systems

This matrix produces a distinction between six essentially different types of systems, which ultimately vary by the number of relevant components and the multiplicity and effects of interactions that are involved.

Deterministic systems represent domains where complete, reliable predictions are possible in principle. First come the “simple and deterministic,” as in the case of a simple mechanical device; next is the “complex and deterministic,” for example, an elaborate production system in industry, other kinds of intricate technologies, or even a whole solar system, the gross behavior of which obeys the classical laws of motion; next is “exceedingly complex and deterministic,” think of the very complex system required for a successful lunar exploration and other space missions, where thousands of people, extreme technologies, and millions of individual tasks are involved, and still strict control must be assumed.

Under the probabilistic criteria, in turn, we find the cases where complete predictions are not possible and only various degrees of likelihood of occurrences can be discussed. First, the “simple and probabilistic,” for example, a coin throw; next, the “complex and probabilistic,” the behavior of stock markets offers a good example; and, finally, we converge on “the exceedingly complex and probabilistic,” the domain pertaining to the kind of highly dynamic systems, multiple components and multiple interactions, numerous interdependencies, variable and unpredictable behaviors, and irreducibility in principle. This is the domain of living systems, including those of the socio-economic variety.

Note that the language of this classification reflects the somewhat older language of operational research and early cybernetics. Today, the category of exceedingly complex and probabilistic systems would be identified with the realms of chaos and complexity theories. Note too that sometimes categories overlap and that they do not always represent strict boundaries. A selfsame system may have to be described differently at times, depending on an observer’s resolution level and purpose.

The important point is that the seemingly cumbersome designation of the “exceedingly complex and probabilistic” system, helps focus our vision on the fundamental characteristics of the very realm that is essential for our ultimate wellbeing as humans: the realm associated with life. This realm represents the broad ecosystem issues that as participants-designers we need to be engaged with, in the quest of realizing the promise of a better world.

4. The Essential Characteristics of a System

Perhaps the most succinct formulation of the essential characteristics of a system is due to Russell Ackoff, the leading American organizational theorist and system thinker. This formulation goes right to the essence, by focusing on the nature of the interactions that account for the concept of systems in the first place.

According to Ackoff, three essential conditions must be fulfilled in characterizing a system. These include the following:

First, that in a system each simple element has an effect on the behavior of the whole.

Second, that in a system each element is affected by at least one other element, and none has an independent effect on the whole.

Third, that in a system no subgrouping of elements into totally independent subsystems is possible.

If you think of a visual depiction of a system as a network of dots representing key elements, with arrows drawn between them to indicate the underlying interactions, then in such an arrangement, by virtue of its links to other parts, each individual element is an integral part of the network, contributing to the behavior of the whole. Each is connected by an arrow to at least another element and each is linked, in turn, by an arrow originating from one other element, or more. Finally, every conceivable subgroup of parts connected by lines among themselves is always arrow-linked to the rest.

Whether applied to an organism, a rainforest, an urban complex, a business enterprise, or society, this characterization is at the heart of the slowly emerging ecosystems perspective, which highlights the vital significance of interdependencies. The philosophical as well as the practical implications of internalizing this perspective are huge. Contemplate, for example, the implications to the Judeo-Christian mythology of creation and its portrayal of a creator as an all-powerful force acting independently and from outside the system that is brought into being; or think of the arrogant leader, or manager, claiming full control, and acting as though they were "above" the system that they are trying to affect.

5. General System Theory

It was in the field of biology that the limitations of the classical reductionist methods of science were first emphasized, in a shift that established the system concept as a new paradigm. This shift was led by Ludwig von Bertalanffy.

The impetus came from a dawning realization that living systems show essential qualities that add up to more than the sum of their parts and depend on the integrity of the organism viewed as a whole. The validity of this synergetic, non-linear effect, incidentally, is not confined to biology, and it is relevant to aspects of the physical sciences as well. A simple manifestation can be found in metallurgy and the creation of high-performance metal alloys. For example, specific properties of individual molecules, such as tensile strength, yield much higher tensile performances in combination with specific other molecules, than would be expected from a simple sum of the corresponding parts.

Bertalanffy showed that the effectiveness of the reductionist analytical procedure depends on two key conditions. First, that interactions between parts are non-existent, or negligible, and second, that it should be possible to simply add up descriptions of parts to construct a picture and an understanding of the whole. As a tool of inquiry, it became apparent that the reductionist method was limited to dealing with two, or at most three, variables. It is not applicable to phenomena characterized by multiple variables, complex interactions, and non-linear behavior. Using the strictly analytical approach inherited from 19th century science, it was possible to tell how one cell, or one organ, reacts to one particular stimulus or how one entity reacts to the application of one kind of force. It was not possible to tell how several different variables act together when exposed to a number of different influences at the same time.

Bertalanffy advocated the importance of an “organismic” perspective, and the combined focus on patterns of interactions and the notion of systemic wholeness led to a new emphasis: the concept of “organization” as the basic unit of study. The consequence was a view of organisms as organizations and the invitation to regard organizations as organisms. The emergence of the idea of organization with its related stress on an underlying structure had a profound impact. In biology, an integrated concept of organization as a new principle replaced the need to rely on the idea of a “vital force” in explaining the special qualities of living systems. It also led to a better understanding of the relationships between specific structures and associated behaviors. Understanding the basic principles of organization drove the new way of inquiry, and the search for such principles became the central goal of general system theory. The quest aimed to produce a unifying theoretical framework across all systems in general.

6. Organization as Organism

As commonly used, the term “organization” carries the connotation of a discernable order and it is usually applied in reference to some entity, typically with institutional overtones, such as a business, government, party, or any other social or economic body.

The emphasis put by general system theory on the concept of organization as a new defining paradigm shifted the meaning to another kind of abstraction. The shift stressed the significance of underlying structures to the representation and understanding of a system’s behavior. This idea, as we shall see, had significant implications, especially to developments in cybernetics, a closely related field.

The point is that a particular structure is embodied in sets of relations. In the systems thinking context, a set of elements form an organization when some specific relation defines their interaction—when a specific pattern of relations is being conserved. A specific pattern of relations acts as a constraint, limiting the number of conceivable configurations and reducing the field of possibilities to the unique one that is then manifested as a distinct organization.

The “nesting,” recursive property of systems, whereby at a higher level of resolution, any element in a system represents a whole other system in its own right, introduces the idea of hierarchy. This nesting quality is akin to a sequence of views, as in satellite pictures, where one can zoom in on increasing levels of detail. A view of Earth, for example, is resolved into an image of a regional geography, then to that region’s main features, such as mountains, forests, rivers, and lakes, and all the way down to the minutest, most-specific details.

In the system thinking context, the concept of hierarchy found its expression in a view of the world as a stratified organization of increasing levels of complexity, stretching all the way from elementary forms of matter to the highest manifestations of life. The idea is often expressed as a sequence: basic particles, atoms, molecules, various forms of matter, simple life-forms, complex organisms, whole ecosystems—including human society—and so on. Note that levels in such a hierarchy corresponded to levels of emergence of novel qualitative properties, which distinguish one level from the next.

Each level represents a cluster of interacting sub-components, and levels can be distinguished by the relative strength of respective interactions. These interactions would be stronger within each level and weaker between levels. It is the relative strength of such relations—internal bonds, if you will—which allows for a definition of boundary conditions and makes the individual integrity of a level stand out against the background of its environment. A fascinating question in this regard is whether such a logical stratification reflects an essential property of the world and is inherent to the process of evolution, or whether it is the result of the structure of language, cognition, and the nervous system. It may turn out that the very distinction—cognition-language-nervous system-the world—is itself arbitrary, and that we are actually facing here a deeper affinity, a basic manifestation of one, continuous, co-generating, co-defining reality.

A particularly significant illustration of the aspect of nestability, or verticality, is borne by Fuller's definition of a system. Recall that Fuller defined a system as "the first subdivision of universe into a conceivable entity." Fuller's perspective is anchored in geometry and from that view point a "first subdivision" is represented by the simplest possible three-dimensional configuration, a minimum set of relations that represents a stable structure. This minimal set corresponds to a tetrahedron, a four-sided, triangular-faced pyramid.

Imagine such a structure with its four vertices, four faces and six edges. As Fuller pointed out, it subdivides the world into all that is outside the structure, the structure itself, and its interior. This, of course, offers an immediate, visual illustration of a three-tier hierarchy. Upon first glance, this may sound like an esoteric abstraction. However, it has profound, practical implications for all system designers. It means that for any constructive intervention, one needs to optimize a coherent, harmonious integration of the relevant aspects of at least three levels: the system under consideration, its environment, and its internal components. This is another way, incidentally, of addressing the question of how to set system boundaries when analyzing a particular systemic challenge or synthesizing a preferred system configuration.

In the realm of living organizations that are characterized by numerous variables and multiple interactions, the organizational paradigm calls for adjusting static concepts to a dynamic reality. The significance of this essential dynamism cannot be overemphasized. It is the inevitable consequence of the idea of "interaction" itself. At each case, groups of elements interact among themselves and across levels, settling into temporarily stable configurations—self-preserving forms—that are adapted to the constraints of their specific context. This brings us back to the concept of self-organization. A self-organizing system is an "open" system that is engaged in a constant metabolic exchange with its world. It imports substances and releases the by-products of its activity to an environment that is populated by many other species of equally active self-organizing systems. The constant mutual adjustments, adaptations, and occasional reconfiguration of novel states of equilibrium require that an observer—a manager, experimenter, or an agent of change—stays alert. It means remaining open to adjusting frames of reference, and adapting assumptions, decisions, and actions to accommodate the reality of a changing world.

From this perspective, the universe can be regarded as an immense, kaleidoscopic flux of constantly interacting, inter-transforming, sub-system events. “Reality” is forever dynamic, and distinctions that identify its individual elements are introduced by changing resolution levels imposed by observers. In this broader context, management, planning, design, and other forms of proactive intervention-type activities are among the processes through which self-organization is manifest in the social domain. An urgent challenge of our time is how to design agile, responsive, adaptive, intelligent, and inclusive organizations with the capacity to deliver an enduring advantage for all**.** This is especially the case, since all evidence suggests that most of the dominant socio-economic structures inherited from the past are no longer up to the task of securing a sustainable trajectory in a flourishing world.

7. Structures and Mechanisms: The Cybernetic Perspective

General system theory laid claim to the space of seeking prototypical characteristics, generic features, and underlying principles that hold true for systems in general and transcend specific embodiments. In this context, cybernetics emerged as a closely related discipline focusing specifically on understanding the dynamics of a system’s internal structures and the mechanisms that maintain a dynamic organization invariant. Cybernetic theories put emphasis on questions of how systems regulate themselves, how they adapt and evolve, how they self-organize and, more specifically, what the structures and mechanisms are that mediate their operation, viability, performance, and conduct.

The story of cybernetics is fascinating, and it merits a brief introduction. During the Second World War, as the speed of aircrafts increased significantly, humans who maned anti-aircraft guns became too sluggish in tracking a target, aiming at it, shooting, and correcting for deviation when they missed. In response, a project was organized at MIT, under the leadership of Norbert Wiener, a prominent professor of mathematics, to develop automatic control mechanisms for anti-aircraft guns. This called for combining capabilities in tracking a moving body, predicting its future location, targeting, and error controlling. Tackling the challenge required the integration of inputs from a number of disciplines, and Wiener’s circle included engineers, mathematicians, physiologists, neurophysiologists, information theorists, and early computer scientists. As discussions proceeded, it became apparent that questions of communication and information were central to all processes of control in general.

A conclusion emerged that the logic of circuitry involved in man-made, automatic, error-control mechanisms was analogous to the logic of homeostatic structures found in physiology. These structures work to maintain specific physiological values—body temperature, body fluid composition, blood pressure, blood sugar level, and the like—by triggering an appropriate corrective action when deviations occur from a norm. In all such cases, both mechanical and biological, circular mechanisms of feedback nature are involved—mechanisms that correct for, or amplify, differences from a given norm. These involve two essential types of loops: negative and positive feedback loops, respectively.

Negative feedback loops are associated with goal seeking behavior, in which a difference between an actual and a desired condition (hence, "negative") is used as an input to bring the actual closer to the desired value. Positive feedback loops are associated with self-reinforcing, self-amplifying behavior, such as associated with processes of growth and decay, where a particular outcome generates an even greater outcome of its kind. An important novelty was in linking the concept of controlling or regulating processes to the results of a system's actual performance. The concept of purposeful behavior could now be anchored to specific structures, processes where information content and flow play a central role.

The universality of the fundamental nature of regulating mechanisms, their applicability to the functioning of systems in general, and the fact that one theoretical framework was valid to describe regulation processes in all cases, were novel insights. This merited a new scientific discipline, one that would address communication and control processes. In 1948, Wiener's classical book, *Cybernetics,* was published and a new science had been born.

In his book, Wiener defined cybernetics as "the science of control and communication in the animal and the machine." This definition highlights two key ideas. Firstly, it classifies "control" and "communication" together, indicating the role of information in processes of regulation and control. And secondly, it claims the validity of the theory to both man-made devices and living systems. The term "cybernetics," incidentally, denotes the role of feedback mechanisms in processes of regulation and control. The term is derived from the Greek word for steersman, the person steering a boat to its destination, correcting for the influence of currents and winds. At first glance, "control" may appear to be a restricting concept. It is meant, however, in the most general sense of regulation processes, processes which mediate for particular outcomes and bind a system together as they preserve its singular identity. As it turns out, in complex dynamic systems, the structures that drive ultimate behavior take the form of intricate networks of loop-like, circular interactions, dominated by the familiar feedback mechanisms discussed above, that restrain or amplify specific conditions.

Making the link between a system's internal structure and its actual behavior was a huge step in understanding the conduct of complex systems of all kind. The idea goes back to Wiener and his colleagues, who in a seminal 1943 paper, *Behavior, Purpose and Teleology,* established the indispensable connection between a system's output—its observable behavior—and its internal structure. Historically, this insight was profound. First, it clarified the question of purposive behavior, and in tying a system's behavior to specific internal structures, it removed, once and for all, the need to resort to notions of "vitalism," and similar vague explanations. Secondly, it made it clear that in order to modify a system's behavior, a change must be made to its core structure. Simple as this may sound, think of how often, in trying to reform a system, efforts are directed at the behavior itself, rather than at the structures that drive it.

The basic tenets of cybernetics and the notion of abstracting principles of regulation to a level of comprehensive validity were taken significantly further by the British cybernetician Ross Ashby. Early concepts in cybernetics were derived from observations and direct experience with man-made servomechanisms and homeostatic processes in the body's physiology. From these direct experiences with actual systems, some general principles were derived. Ashby was able to extend the vocabulary of cybernetics by turning the method around, working from the abstract and general to sketch out a logic of regulation processes in general, which could then be related to particular cases in technology, biology, or society. The idea was that cybernetic theory would thus refer to regulation processes in all conceivable types of systems, in the same way that geometry, for example, relates to all kinds of objects in space. Ashby's seminal book, *Design for a Brain*, remains a classical source for our understanding of the dynamic behavior of complex systems.

Concepts from cybernetics were soon utilized in a broad range of fields. For example, in research concerning neural networks, in the work of Warren McCulloch and Walter Pitts; in anthropology, with the work of Gregory Bateson, Margaret Mead, and Roy Rappaport; in relation to a theory of learning, in the work of Gordon Pask; in cognitive psychology, in the work of Paul Watzlawick and his colleagues; in relation to a theory of self-organization, cognition, and the role of observers in constructing reality, with the work of Heinz Von Foerster; in management, with the work of Stafford Beer; in developing system dynamics modelling, with the work of Jay Forrester; and more.

An instructive example of importing concepts from cybernetics to the study of social systems is provided by the work of anthropologist Roy Rappaport, at the time at Columbia University. The subject of the study conducted during the 1960s was a small, aboriginal community of hunters and gatherers, the Tsembaga, who inhabited a remote territory within the Bismarck mountains of New Guinea. The group had been only minimally exposed to outside civilizations and could thus offer a good case study of a well-defined, local community that was well-adapted to the specific circumstances of its environment. Life of the Tsembaga was regulated by a ritual cycle—a prescribed routine—involving various activities and festivals performed over several years. The study was able to show how the ritual cycle acted as a homeostat, regulating the relationships between members of the group, and between the community and key elements in its environment, which together comprised a whole ecosystem.

In a nutshell, the Tsembaga lived in a close, symbiotic relationship with domesticated pigs that they raised with great care. Pigs provided an important source of proteins in times of stress. They assisted in cultivating gardens by digging for roots, eliminating weeds, and turning and softening the ground. They also kept residential areas clean by feeding on waste. Pigs represented the most important part of the group's wealth. When demands of the combined human and pig population exceed the carrying capacity of the group's territory, a year-long festival was launched during which pigs were slaughtered, meat was shared, the size of the herd was drastically reduced, and balance was restored. The ritual cycle involved many other aspects, regulating inter-tribal relations and regional social contacts, controlling warfare, and more. This fascinating story is recounted in Rappaport's book *Pigs for the Ancestors.* The crux of the matter is that the ritual cycle was shown to maintain essential variables within “desired” limits, by triggering actions that restore the system to desired norms when threatening deviations occur.

The story of the Tsembaga describes the case of an established adaptation and a socio-cultural mechanism operating to maintain a prescribed steady state. It does not address the circumstance of a major change in a context that would require a complete systemic shift. Nevertheless, it is pertinent to current issues of sustainability because it highlights the question of the interaction between a population and the carrying capacity of its environment, precisely the kind of question we face on the planet today.

8. Measuring Complexity

We talked about complexity as an inherent characteristic of dynamic, “living” systems. But what, more precisely, does the term “complexity” mean? The idea of complexity is often confused with size: the bigger, the more complex. This is an error, of course, since even a tiny, unicellular organism represents a highly complex system. Conversely, adding ever more grains to a heap of sand does not make it more complex. Ultimately, the idea of complexity is independent of size; rather, complexity relates to the number of possible distinctions that can be made about a given system.

In cybernetic terms, possible distinctions relate to a system’s internal variety, where “variety” expresses the number of a system’s possible states. The higher the number of different elements and the higher the number of pathways through which these elements interact, the higher the system’s variety. A simple electrical light switch with only on or off distinctions has a relatively low variety. If a dimmer is used to control light levels, it has a higher range of possibilities corresponding to a higher variety. A biological organism, a society, an economy, or an ecosystem all represent systems of exceedingly high variety.

Complexity is thus measured by a system’s potential variety: the number of different states that a system can assume. In dynamic systems, variety can proliferate very rapidly. Think about it this way: with large numbers of elements, a high number of interactions, and the possibility of each interaction assuming more than a single value, the number of possible states can increase exponentially and quickly.

There is an obvious sense in which the measure of a system’s variety represents an observer’s discrimination capacity. It also represents an observer’s level of uncertainty, in that the total number of distinguishable states of a system signifies the observer’s uncertainty about it—which of the many possible states will be assumed next? A quantity of variety thus offers a measure of uncertainty as well.

This is profound. Uncertainty relates to our perception of order, which relates, in turn, to detectable regularities in a system’s behavior—a sequence of a system’s changing states. Such regularities, incidentally, are produced by constraints imposed on a system’s potential variety by its internal structure. Uncertainty relates, accordingly, to a quantity of entropy, a measure of disorder in a system. Because the appearance of one state out of all possible states of a system removes some uncertainty, in the process conveying an amount of information, the concepts of uncertainty and information are closely related. They assume a similar mathematical expression, yet have opposite signs. For example, when uncertainty is at a maximum, which happens when all events in a given universe may occur with equal probability, there is no information available and variety is naught. The concept of variety is thus at the nexus of ideas involving physics, information theory and the philosophy of science, and linking concepts of organization, entropy, and order, all of which are key to our understanding of the world.

A thorough appreciation of the concept of variety and the related ramifications is vital for the system practitioner. Designing novel system configurations in the real world involves the art of mastering the intuition for when to amplify and when to attenuate variety, a typical task in managing any enterprise, and the essence of regulation in general. The concept also suggests the level of respect, and humility perhaps, that should be adopted with any design intervention in the socio-economic and eco-systemic space.

9. Other Key Cybernetic Terms

A selection of a few key cybernetic terms merits a brief exploration. All relate to one another, as well as to the concept of non-linearity that is at their base. They offer valuable tools for efforts aimed at system synthesis and design.

Synergy

We have already encountered the term synergy. It pertains to the behavior of whole systems, which is unpredictable by the behavior of the parts. Synergetic effects account for the emergence of new, often unexpected properties. The inevitable expression of synergetic effects in social interactions ought to be assumed and incorporated in all cases of social-systems design. Synergetic effects can be a source of unwelcomed surprises when they produce and amplify unintended consequences. At the same time, synergetic potentials can be deliberately used to create and increase added value to desired results.

Self-Organization

The concept of self-organization dominated early discussions of cybernetic theory. An elegant definition is due to Von Foerster. It is based on the concept of "redundancy," imported from information theory. In information theory, the term redundancy is used in the context of protecting information integrity from deterioration due to effects of background noise, by augmenting information content or increasing channel capacity. Simply stated, redundancy allows for more potential "possibilities." According to Von Foerster, a system is self-organizing if the rate of change of its redundancy remains positive.

This formulation is strongly linked to the concepts of order and order creation. Redundancy will be nil at a state of maximum disorder, when no distinctions can be made and activity ceases. On the other hand, a system can continue to exhibit dynamic, self-organizing characteristics—maintaining or increasing its manifestation of organization and order—as long as a sufficient level of redundancy and the system's internal complexity are preserved.

The dynamic characteristics of self-organizing systems have already been alluded to in previous sections. These properties force an observer who interacts with a self-organizing system—or who is a part of it—to keep an open, dynamic stance. How to work in tandem with the self-organizing properties of a system, rather than destroy them, is the challenge of all interventions in the socio-ecosystemic domain.

The Law of Requisite Variety

The law of requisite variety is due to Ashby. It has emerged as one of the central tenets of cybernetics and is fundamental to the general theory of regulation and control. Ashby's law states that "only variety can absorb variety." Effective regulation can only be achieved when the regulating system contains at least the same amount of variety as the system being regulated. The requirement for requisite variety is applicable to all systems: automated devices, technology processes, ecosystems, and social systems alike.

The law of requisite variety may sound very simple. It looks obvious once it is recognized. But contemplate the typical way that most organizations in business, government, and other aspects of human affairs are managed and structured. More often than not the conventionally familiar organizational structure perpetuates a management model that imposes structures with grossly insufficient variety, a direct consequence of a non-system-based, reductionist world view. Such a management model is simply inadequate—not rich enough—to address the demands of an increasingly more complex world. Among corporate leaders none understood this better, perhaps, than Dee Hock, founder and CEO emeritus of VISA International. Over a long and fruitful career, Dee Hock highlighted the gross deficiencies of the prevailing, hierarchical, command and control structure. He advocated a more versatile and dynamic form of organization and coined the term "chaordic" to describe it. The term itself suggests a creative combination of "order" and "chaos", which is at the heart of the ability to experiment and innovate.

Redundancy of Potential Command

This term was coined by Warren McCulloch and his colleagues, in relation to research done on the workings of neural networks and, in particular, the reticular formation. The reticular formation is a network of neurons in the brainstem that regulate various aspects of behavior, including states of consciousness.

The research found that such networks function effectively by virtue of their enormous redundancy, born by the huge number of individual nerve cells and the multiple paths of their interactions. A typical, healthy brain contains some 100 billion cells, with each connected to thousands of other brain cells. The number of possible states that can be assumed is astronomical, offering a network-redundancy that virtually eliminates the risk of the whole malfunctioning due to a failure of a few individual parts. In addition, the question of which neuron will be actually activated depends on the distribution of pertinent information in the whole network at any given time. The potential for "command" is thus distributed over a large number of components and its location shifts constantly within the network. It is not permanently localized.

In this regard, the term heterarchy was introduced to characterize a network-like structure where no vertical hierarchy of authority is discernable. Instead, processes of decision-making are distributed and determined by function and relevant knowledge rather than by precedence.

Ultrastability

Ultrastability is another term due to Ashby and the cybernetic concept of regulation. It relates to the ability of a system to restore homeostatic equilibrium after unexpected perturbations, even when a trajectory for doing so has not been built-in and fully specified in advance.

Regulation in the cybernetic model is expressed in the context of a system's capacity to maintain equilibrium states in the face of disturbances from an environment with which it interacts. In this sense, regulation can be regarded as the manifestation of a system's adaptive capacity. In the simplest case, specifications of perturbation probabilities are built into a mechanical protective barrier—for example, a wall, a skeletal structure, or a protective shell. A more complex, dynamic form of adaptation is manifest in the typical homeostatic mechanism, in which a fixed decision rule is applied to trigger an appropriate corrective action when equilibrium is disturbed.

Adaptation by ultrastability relates to the more interesting cases—brain-like systems, societies, or ecosystems—where a sufficient amount of variety is "built" into a system so that unpredictable changes in its environment can be matched by internal reconfiguration, even when a specific decision rule is not already embedded in its structure. The more general rule, instead, is "keep changing internal configurations," essentially rewiring, in the search for a subset that matches new demands as they occur.

Even if it is very high, the internal variety of any specific ultrastable system is finite. An entirely new context-condition may require, or favor, new options that the system, as it is, cannot generate. In my own doctoral research, incidentally, I was able to extend the cybernetic concept of regulation to evolutionary processes, cases in which a system actually transforms into a new entity with a higher regulation potency. Potential variety is amplified in such cases, for example, by processes of coalition formation, highlighting the importance of cooperation in evolution.

Reflexivity

In general, the term reflexivity denotes a process that is directed or turned-in on itself. In cybernetics, reflexivity refers to a circular feedback loop, whereby an observer affects a system under observation and is affected by it in return. The underlying point is that, contrary to the orthodox position that stipulates the separation of acts of observation from the observed phenomena, the two are interdependent and linked in deep ways. The idea was highlighted by Heinz von Foerster, who proposed the term "second order cybernetics" to account for the logic of observing systems. The idea was then taken to a radical extreme by Chilean scientists Humberto Maturana and Francisco Varela, who suggested that observers do not simply review an "objective," external reality, but rather they effectively create the world—in a sense in their own image—by the act of observation.

Scientist, managers, and other active agents are "participant-observers," they are actors in the very situations they attempt to understand and control. Reflexivity processes have, therefore, far-reaching practical implications. The financier George Soros, for example, used the term with respect to the behavior of financial markets, where investors' perceptions influence market behavior only to be influenced, in turn, by market events. Soros claimed that this theoretical realization guided his trading and the placement of successful financial positions. Participant-designers in the social realm—change agents of all types—should always keep an eye on the implications and potentially unintuitive impacts of reflexivity-related phenomena to their work.

Synergy, self-organization, variety, redundancy of potential command, ultrastability, and reflexivity are all related concepts. They are significant because they describe the characteristics of mechanisms that underlie the behavior of complex systems, shedding new light on the concept of complexity itself. The essential implications are clear: "living," self-organizing systems, including social systems of all types, depend on their internal complexity and inherent redundancy for resilience and long-term viability. It is this internal complexity which allows for the emergence and reemergence of different configurations in response to changing events.

Plurality, diversity, openness, and agile, responsive structures are the cornerstones of a healthy, vibrant society and ought to constitute the features of a new world order. A driving, long-term objective for design interventions in the social domain should be to focus on setting-up smart, inclusive systems that can adapt, evolve, learn, and continuously self-organize, in the process of making the world a better place.

10. System Dynamics as a Tool for Engagement

System dynamics is a powerful methodology for understanding the dynamics of complex systems. It offers a rigorous tool for engagement with systems, a modelling and simulation technique for analyzing and testing assumptions about a system's behavior, and a means of policy and strategy development for active interventions. It is thus effective in guiding efforts of system analysis, as well as synthesis and design.

System dynamics was originally developed by Jay Forrester and his group at the Alfred Sloan School of Management at MIT. It was first applied to industrial and corporate issues, but quickly expanded to address broader social issues as well. Key milestones included urban, health, then world dynamics, culminating in an impactful Club of Rome report *The Limits to Growth*. The report addressed issues that today are at the heart of the world's sustainability agenda. Modelling of these issues was further developed, to great effect, by Donella Meadows, one of the report's original authors. Over the years, the methodology has been continuously refined by the contributions of numerous practitioners and researchers, and system dynamics groups are now established in centers around the world. An active System Dynamics Society supports, promotes and offers a lively platform for further developments.

The system dynamics methodology enhances understanding of a system's behavior over time by delineating interdependencies between components, highlighting cause and effect relationships, and identifying circular feedback structures that dominate behavior. The procedure involves defining an appropriate system boundary, defining the system's key variables, mapping the causal relationships between variables, simulating behavior over time, and exploring significant "what if?" questions. Identification of operating feedback loops—positive feedback loops which amplify a gain, and negative feedback loops which reduce it—help pinpoint leverage points in the system that are critical to bringing about desired change.

Feedback loops and their combined, interacting operations result in archetypal structures which affect a similar kind of pattern of behavior: increase, decrease, remain level, or fluctuate over time. Because of their critical effect in driving a system's behavior, ignoring or disconnecting important loops can have a distorting and even seriously adverse effect on the whole system. Such critical systemic disconnects could be responsible for many of the sustainability-ills that now beset our planet. Think, for example, about the effects of decoupling forces in the economy from biospheric processes, upon which the economy ultimately depends. Or more specifically, imagine the effects of ignoring the link between the increasing use of fossil fuels and the long-term impacts of accumulating greenhouse gases in the atmosphere.

A brief description of the application of system dynamics in three very different consulting assignments can be found in the Appendix.

11. Ethical and Practical Implications of the Systems Approach

The implications of the switch from the mechanistic, reductionist perspective to a system view of the world are profound. The switch is akin to the difference between walking on a straight, hard, paved surface, to surfing the waves of a heaving sea. This difference forces acknowledgement of a variable, dynamic, and interdependent reality, and it implies the need for a deep transformation in values and attitudes, as well as actions in the world. Recognition of the fundamentally interdependent nature of reality is key, along with the realization that treating a system as though it were a simple clockwork mechanism is only likely to lead to unintended, even adverse, results. In the context of an underlying reality of interconnectedness and interdependence, a narrow, mechanistic view is inadequate. It is strategically defective, morally lacking and, in the long run, it is bound to prove ineffective. It is not the systems way.

Adopting the systems perspective has both practical and ethical consequences. For example:

- Recognition of the complex, dynamic, forever-evolving nature of reality suggests the need for becoming more accepting of uncertainty, fostering confidence and a level of comfort with the unknown, and relinquishing an obsessive impulse to control.

- The inescapable reality of change implies the need for agility and resourceful adjustments in configurations of continuing response. At the same time, the inexorable fact of complexity calls for respecting complexity for what it is, avoiding trivializing it with over-simplifications, and mistrusting the quick fix. The inevitable presence of uncertainty suggests, in turn, the wisdom of a modicum of detachment and a measure of humor, especially in the face of trials and adversity.

- The pattern of interactions and causal relationships that are disclosed by competent systems mapping highlight the structures and mechanisms that drive a system's behavior, bringing to light the leverage points that are crucial for initiating effective interventions. The important insight that it is a system's inner structure that drives its behavior, opens the door to proactive design as the means of reshaping and reconfiguring structures, in an effort to ensure preferred outcomes. Systems mapping makes the usually invisible apparent, and when carried out as a collaborative effort by key stakeholders, it can greatly facilitate the synthesis and implementation of initiatives for change.

- Accepting a reality of irreducible networks of interactions and interdependencies puts emphasis on the significance of otherness, and the necessary balance between individual components and the whole context of which they are a part. The networks of interactions and the mutual dependencies that these imply compel an appreciation of inclusive, nurturing relationships, and highlight the role of collaboration and coalition formation in evolution. Essential interdependencies also alert us to the indispensable role of empathy, reciprocity, and compassion in healthy interactions.

Integration, synthesis, tolerance, inclusiveness, creativity, and adaptive, hybrid strategies are the hallmarks of systems-appropriate behavior. Together, these aspects combine to project a qualitative stance that is fundamentally distinct from the fragmentation, separation, exclusion, alienation, and short-sighted strategies that are the typical result of the reductionist, mechanistic approach.

The qualitative aspects that are implied by taking the systems perspective have far reaching implications to all spheres of human activity. Although starting to spread more briskly in recent decades, they are still fragile, and they have yet to impact the centers of mainstream thinking. They are consistent, however, with deep insights of many wisdom traditions that acknowledge the plurality in unity, promote inclusiveness, and highlight the fundamental prerogatives of moral obligations. They are echoed in the Jewish concept of "Tikun Olam", or repairing the world; in the Taoist precept of harmony and becoming one with the rhythms of the universe; in the Christian precept that the "meek will inherit the earth"; in the Jains principles of harmlessness and non-violence; and in Buddhist doctrines that betray deep intuitions about the systems nature of reality.

Think, for example, of the basic Buddhist tenets of non-independent existence, non-permanence, non-dogma, and non-attachment. Contemplate, as well, the concept of Bodhisattvas presented as idealized beings who embrace a genuine concern for all, and who embody an authentic, all-inclusive empathy deep in their soul.

Attitudes, values, world views, and the mindsets that drive behavior are of critical importance. Invariably, they affect the choices we make and the quality of our actions in the world. They can manifest in a greedy, egocentric, predatory, and domineering orientation or, conversely, they can find expression in a nurturing, self-restrained, inclusive, and empathetic disposition that acknowledges the mystery underlying existence and honors the larger system of which we are a part.

From the viewpoint of sustainability, systems thinking offers a welcomed hope. Because of the intrinsically systemic nature of the many sustainability-related issues that confront us today, mastering systems thinking, along with systems-based design skills, is essential for tackling—perhaps even eliminating—these vexing challenges. The requirement for thinking in systems may sound simple, even obvious. Yet all too often, in the conduct of personal, social, and global affairs, it is largely ignored. Ultimately, embracing and internalizing the inherent systems characteristics of our home-world may inspire the conscious abandonment of a mindset that separates humans (we) from nature (it) and sees the biosphere as an object that is there to dominate and exploit. This is the kind of collective transformation that is required in order to bring about a more whole, creative, healthy, harmonious, and joyful way of being, and a better world.

Further Readings

- Ashby, W. R., An Introduction to Cybernetics, Methuen – University Paperbacks (1964), (first published 1956).
- Ashby, W. R., Design for a Brain, Chapman and Hall – Science Paperbacks (1966), (first published 1952).
- Bateson, G., Steps to an Ecology of Mind, Ballantine Books (1972).
- Beer, S., Cybernetics and Management, English University Press (1971), (first ed. 1959).
- Beer, S., Platform for Change, John Wiley & Sons (1975).
- Ben-Eli, U. M., Amplifying Regulation and Variety Increase in Evolving Systems, Progress in Cybernetics and Systems Research, Vol. VII, Richler, F. and Hanika, F., Hemisphere Publishing Corporation, (1979), and Journal of Cybernetics, Vol. 9, pp. 285-296, (1979)
- Bertalanffy, L. von, General System Theory, George Braziller (1969).
- Forrester, J. W., Principles of Systems, Wright-Allen Press (1968).
- Fuller, R. B., Synergetics, Macmillan (1975).
- Hock, D., Birth of the Chaordic Age, Brrett-Koeler Publishers (1999)
- Kuhn, T. S., The Structure of Scientific Revolutions, University of Chicago Press, 2nd ed. (1970).
- Laszlo, E., The Systems View of the World, Braziller (1972).
- Meadows, D. H., Meadows, D., Randers, J., Beyond the Limits: Confronting Global Collapse, Envisioning a Sustainable Future, Chelsea Green Publishing Company (1992).
- Meadows, D. H., Thinking in Systems, Chelsea Green Publishing Company (2008).
- McCulloch, W. S., Embodiments of Mind, M.I.T. Press (1970), (1st ed. 1965).
- Pask, G., An Introduction to Cybernetics, Hutchingson & Co (1972), (first published 1961).
- Rapparort, R., Pigs for the Ancestors, Yale University Press (1968).
- Yovits, M. C. and Cameron, S., eds., Self-Organizing Systems, Pergamon Press (1960)., pp. 31-48.
- Wiener, N., Cybernetics, M.I.T. Press (1965), (first published 1948).

Appendix: System Dynamics, Three Illustrative Cases

The power of using system dynamics modelling lies in the possibility of bringing to light hidden or counterintuitive aspects that would otherwise be ignored. To illustrate, I shall use a few cases from my own consulting experience, with assignments involving policy and strategy development in health care, regional planning, and nuclear waste management. These cases were developed in environments that were alien, and even antagonistic, to system concepts. The following stories briefly illustrate the effects of utilizing the system dynamics methodology and are meant to convey a qualitative impression rather than a detailed account of the steps and techniques of the modelling process itself.

1. Health Care

This case involves a leading academic medical center in New York, renowned for its excellent, advanced services and first-class medical education. At the time, hospitals in the United States were reimbursed at a fixed level for each patient-day, according to a classification based on multiple criteria, including the type of services offered, their levels of intensity, and the category of institution, whether a teaching hospital, community hospital, urban or rural hospital, and the like. Health care costs were escalating nation-wide, and there was a strong pressure by government and insurers to reduce costs.

Management of the medical center came up with an innovative concept for reorganizing its services in attempt to reduce the average cost of stay per medical episode. The average length of stay at the hospital was just over ten days, mostly representing serious medical cases. The hospital rarely had an empty bed, and at any given time, it could rely on a long, constant queue of patients awaiting admission.

The idea was to construct a simpler medical facility, more like a hotel than a hospital, to which patients could be transferred towards the tail-end of their stay. At that stage, patients would be convalescing, and would not require the same level of intensity of services and nursing care. In addition, patients could move to the new facility, named appropriately "Co-operative Care," together with a care-partner, a paying family member perhaps, thus further reducing the need for constant nursing supervision. At the new facility, patients and care partners could also receive instructions about the patient's condition and adjust to new, routine life-requirements before being released.

The accompanied economic argument was quite straightforward. Assuming that, on average, three out of every ten days would be spent at the lower intensity and, therefore, lower cost facility, an incremental savings could occur. The average cost of a typical hospitalization episode would thus be reduced. Even better, since the hospital would still be paid at a predetermined, fixed per-patient-day level, established by its category as an intensive medical center, an actual gain could be registered. The concept looked great all around. The size of the new facility was defined, architectural plans were completed, financing was secured, and management was ready to move forward with all the necessary preparations.

The center boasted a forward-thinking strategic planning department—at the time, an unusual capacity for institutions of this kind—and I was retained to assist in the planning. Some reflection and basic system mapping quickly revealed that there was a fundamental flaw in the concept, a flaw that was not immediately apparent given the simple, "linear" assumptions that were made. The point is as follows: every time a patient would be transferred to the lower cost facility, an empty bed would become available at the main hospital. Given the long waiting list, it would be immediately filled with a new patient. The place handled cases requiring highly intensive care, and the first few days following admission typically represented above-average costs because of sophisticated diagnostic procedures and frequent surgical work. Furthermore, the hospital boasted a very active and expensive open-heart surgery program, which because of its prestige had a strong claim on available beds. Instead of lowering the average intensity and cost across the board, the ultimate impact of the new program could be exactly the opposite. If followed as planned, it would actually accelerate the throughput of patients, increase overall intensity of service, and drive costs through the roof.

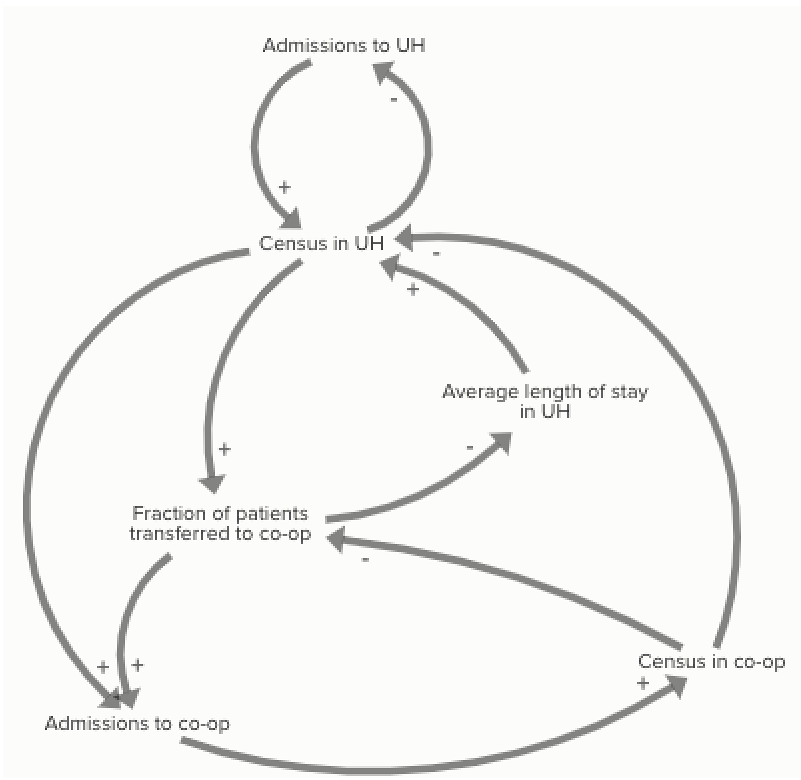

Figure 2: A simplified model highlighting some important cause and effect relationships regarding the policy of creating a co-operative care unit

At first, management resisted this view. To some, it seemed too "intellectual" and unnecessarily complicated. Some, however, were sufficiently intrigued to allow for a full-blown development of a system dynamics model. The model mimicked operations of the hospital, mapping the kind of loops that affected the flow of patients between the two facilities, and the factors affecting occupancy balance and intensification of services. A couple of examples of such mapping, at low resolution, are shown in the figures. The full model was developed in great detail, accounting for each medical service, the flow of patients throughout, the impact of demands on intensification, and subsequent demands on resources. It was computerized and allowed for the examination of conditions under a number of different assumptions.

Management embraced the results. The original concept was modified to use the new facility as an admission facility as well. More careful controls were introduced for optimizing patient mix, and the model's predictions with respect to increased capacity needs in radiology, laboratory services, and surgical rooms were used to guide further planning. Model results helped calibrate operations of the new program, which was later hailed as an important innovation in health care.

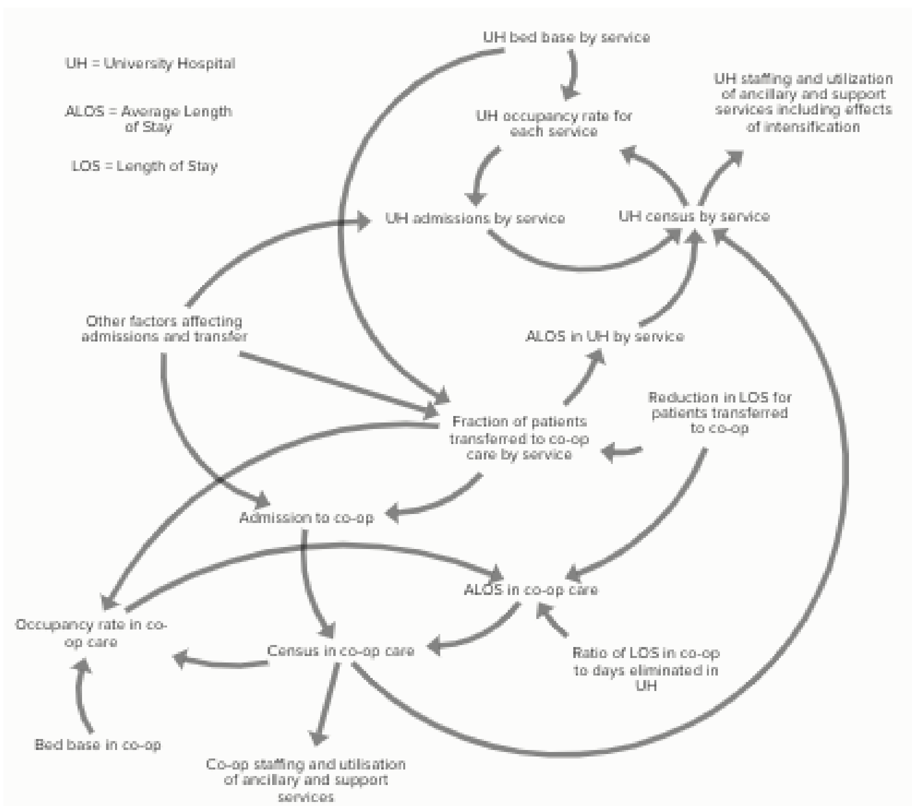

Figure 3: A model of factors affecting occupancy balance and intensification of services in the hospital

2. Great Lakes Water Level Fluctuations

This case involved work with the International Joint Commission, a joint American-Canadian organization whose work is focused on the Great Lakes region. It is a high-level commission, with American commissioners appointed by the U.S. president and Canadian commissioners by the Canadian prime minister. The commission was originally established to settle issues of water disputes between the two countries, and over the years the range of issues that came under its purview expanded. It dealt with questions of water quality and was instrumental in returning the lakes to pristine health. The work of the commission is supported by a team of Canadian and

American scientists, and it has been closely involved with the U.S. Army Corps of Engineers, which in the U.S. is responsible for issues related to waterbodies and waterways.

In the mid-'80s, an unusual increase in precipitation during two consecutive years caused water levels in the lakes to rise. This coincided with a sequence of violent storm events, resulting in major destruction along the coastline. Lake Shore Drive in Chicago was flooded, and great damage was inflicted on waterfront properties in both countries. Governments turned to the commission for advice about how to handle water-level fluctuations. A major study was launched, dominated by the Corps of Engineers. The underlying perspective was simple: the lakes were misbehaving and should therefore be contained. Thus, massive protective walls, new canals, and other engineering works were viewed as the appropriate solution. Members of the scientific advisory staff were becoming increasingly uncomfortable with this narrow, single minded approach, and I was invited to help think through an appropriate approach to the water level study. This was a case of large-scale regional planning, which surely called for a comprehensive system perspective. Despite strong resistance by the leading engineers, enough support was mounting among members of the staff and the Canadian co-chair of the study. It led to the formation of a system study group, which I was asked to lead.

A quick mapping focused on the primary components that drove the whole system, and therefore would be essential parts of an appropriate policy. Even at an early stage, interactions revealed situations in which following a strict engineering-only approach would result in unintended adverse consequences. For example, constructing protective measures to contain fluctuation would prevent wetland flooding, which would then inhibit all of the important environmental services that wetlands provide. Also, protecting shoreline with structures following damage inflicted by storms could create a false sense of security. Shoreline development would then intensify, which would increase vulnerability to possible impacts of potentially stronger storms in the future.

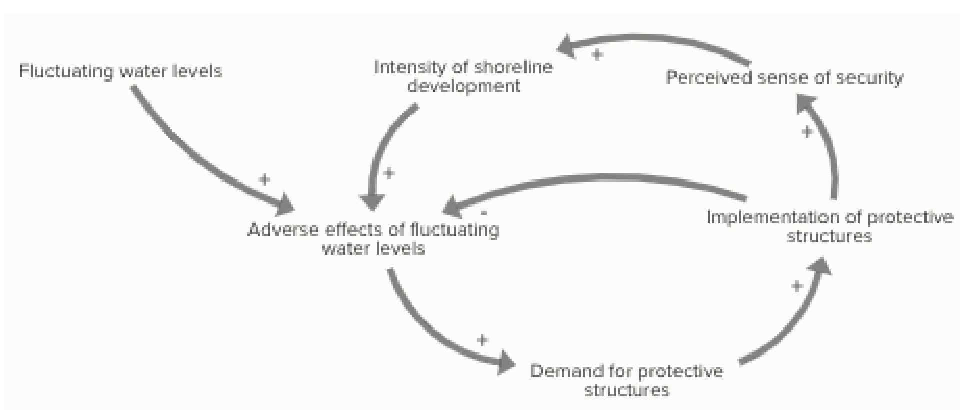

Figure 4: This model explains how protective structures can bring about a false sense of security that encourages shoreline development, which leads to increased future vulnerability

The concept of vulnerability drove the development of the model, which was offered as a tool for assisting the development of government policy. The model integrated three main clusters of variables: those related to hydrological aspects of water level fluctuations; ecological variables; and various aspects of human activity, including governance and other characteristics. For some typical mapping examples, see the figures below. The model was developed to a level of resolution sufficient to facilitate a well-informed discussion. It drove the crafting of a hybrid long-term strategy that included consideration of land use management, insurance policy, appropriate physical measures, and more. These became central in the commission's final report to governments.

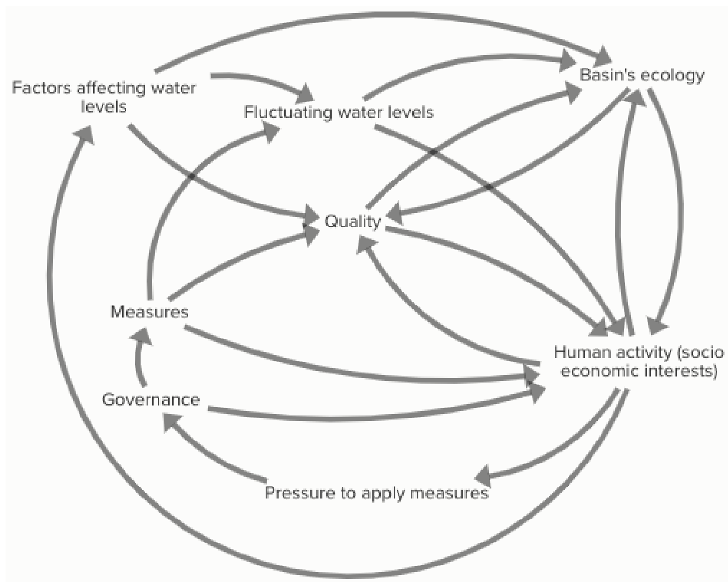

Figure 5: A systems overview depicting interacting primary components, including governance as a key element related to human activities near the Great Lakes

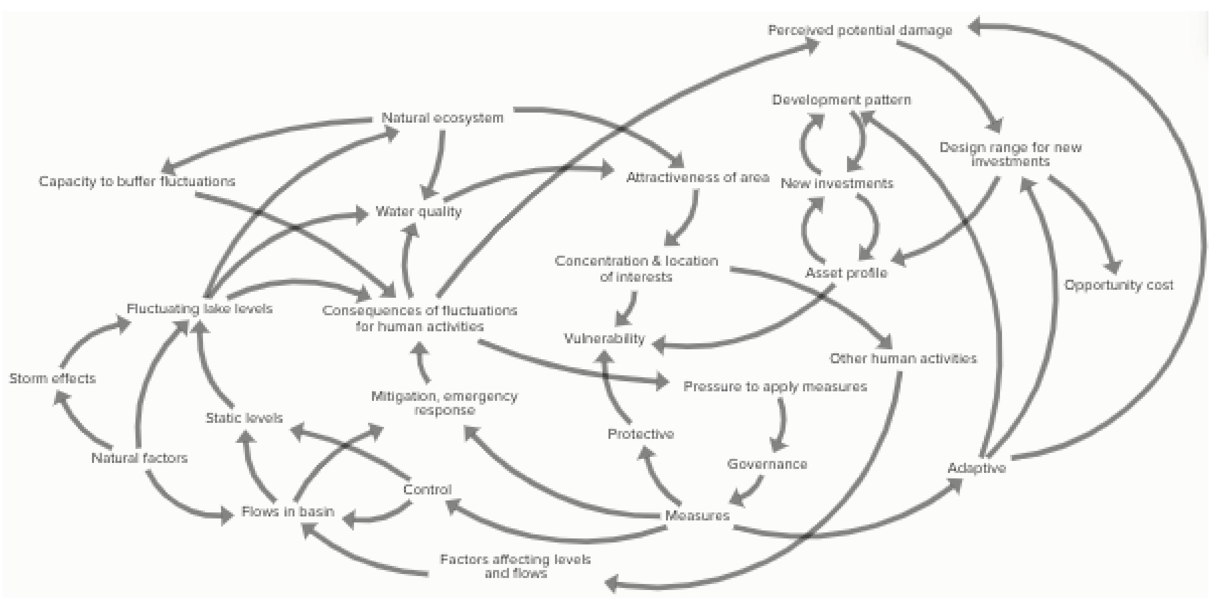

Figure 6: Detailed overview emphasizing the central role of vulnerability

3. Nuclear Waste Management

This last example involved issues related to the management of nuclear waste in Canada. Canada boasts large uranium deposits and it developed an active nuclear industry. Several provinces generate significant amounts of electricity from nuclear technology, and Canadian reactors are sold around the world. Over the years, the country accumulated large amounts of nuclear waste that have been stored in temporary facilities, often near the reactors themselves. The material is extremely toxic, and the toxicity remains active for tens of thousands of years. As in other countries that generate energy from nuclear fission, the government was seeking a permanent solution for handling this waste.

The Nuclear Waste Management Organization was then formed, and it was tasked with evaluating possible solutions and recommending an approach for addressing the issue of nuclear waste. Once the recommendation was accepted, the organization would become the implementing body to handle and manage the waste. Halfway through its work, the organization formed a special task force that was asked to develop a rigorous evaluation methodology, apply it to available options, and recommend the one that looked the best. Most ideas at the time involved techno-engineering solutions, ranging from the straightforward to the wild. I was invited to chair this task force, and the use of the systems dynamic methodology as a key element in the study was accepted from the start.

From the outset, the model identified four main clusters of variables, the interactions of which would ultimately drive a preferred management approach. These four clusters covered the political and economic landscape, factors related to alternative approaches, variables related to public acceptability, and those related to potential host communities. These were developed to higher resolution levels, as proven necessary for synthesizing an optimal strategy for the long-term handling of nuclear waste. The figures below depict the general logic.

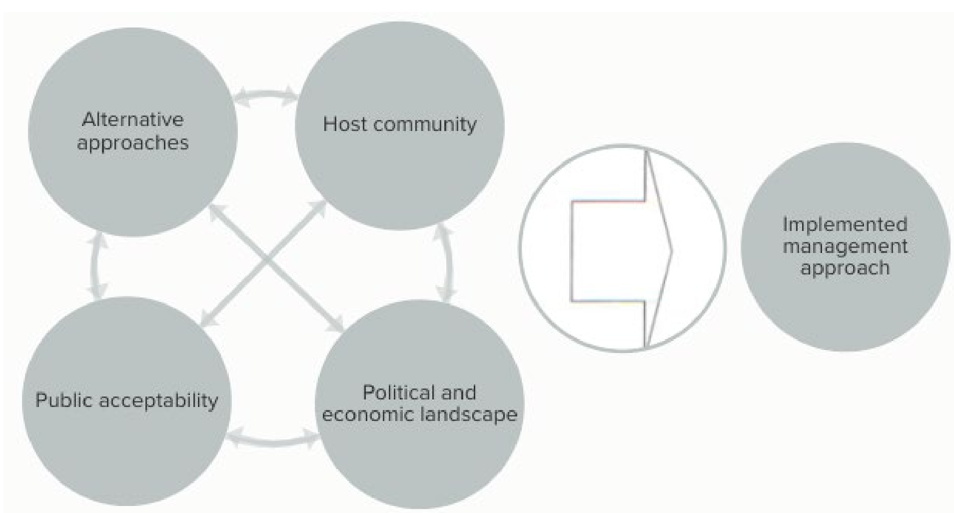

Figure 7: Four main clusters of factors that would inform the implemented management approach

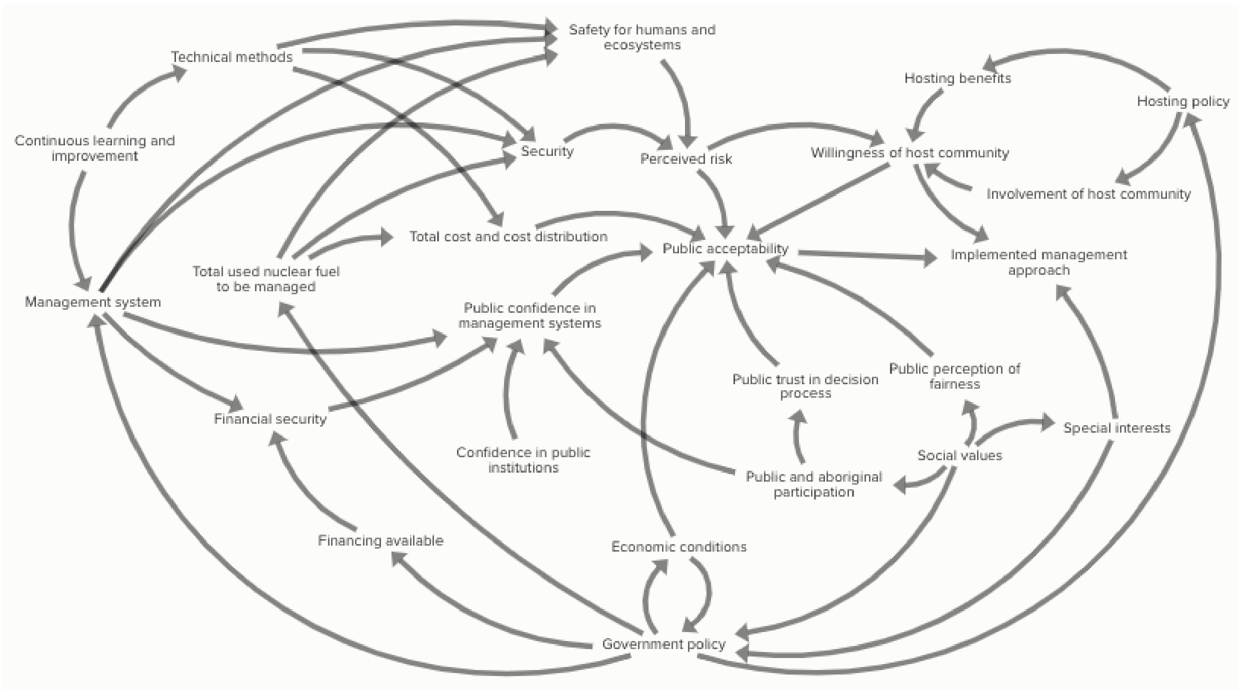

Figure 8: A systems perspective of factors leading to implementation of a management approach

A formal, system-based assessment methodology was then applied to evaluating different options. The integrated results highlighted the need to follow a hybrid, adaptive management approach. Ultimately, the approach included extensive public engagement and direct involvement of host communities and was fully adopted by both industry and government. The Nuclear Waste Management Organization was expanded, funded, and give the task to manage the process. It is deeply involved in implementation today.

Note the different ways in which system mapping and modelling were employed. In the health care example, the methodology was used to model, in considerable details, the actual operations of the hospital, and compute specific values for various variables under different conditions. In both the water level study and the nuclear waste management case, system dynamics mapping was used to establish the overall conceptual context and encourage a comprehensive, systemic perspective in framing the discussion, leading to richer more effective management strategies.

Acknowledgements

Understanding Systems was written as an introductory component for The Sustainability Laboratory's *System Thinking and Systems Modelling* course. The course, part of The Sustainability Laboratory's Global Sustainability Fellows (GSF) program, includes four additional modules introducing system dynamics, with step by step instructions for systems modelling. The systems modelling parts were developed in collaboration with members of Loop Consulting, who themselves are alumni of the GSF program. The online course is available at: https://loopsconsulting.kumu.io/systems-thinking-and-systems-modelling

The course as a whole was developed with a generous grant from the Foundation for Advancement of Systems-Oriented Management Education, at the University of St. Gallen, Switzerland.

The three modelling cases presented in the Appendix were developed in collaboration with Tom Bergan, Gary Hirsh, and Don Seville, respectively.

A Sustainability Laboratory Publication

First published 2018
New edition 2019

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