Part I

Systems: Advances in Systems Science and Thinking

Systems Engineering: A 21st Century Systems Methodology Derek K. Hitchins

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Systems Philosophy

Observe how system into system runs
what other planets circle other suns

Alexander Pope, 1688–1744

Emerging Systems Movement

The industrial revolution started in Britain in the late eighteenth, early nineteenth century, spreading rapidly through Europe and the northern US. Two centuries later, the industrial revolution is still sweeping around the world, with populous nations such as China and India emerging as major economic players on the World Scene, in swift succession to Japan and other South East Asian nations. So significant has the industrial revolution been that it has been likened to the previous ‘ages’ in human social development: Stone Age, Bronze Age, Iron Age, and now, perhaps, the Machine Age? And like those successive Ages, the advances in tools, methods and artifacts have fuelled a social revolution that has not always enhanced the human condition and quality of life.

The industrial revolution emerged from the European Renaissance, and owes much to the iconic figure of René Descartes, of ‘*cogito ergo sum*’ fame. His name is enshrined in the term Cartesian Reductionism — the concept he espoused, of breaking down big things into smaller, and hence more understandable things. If it was possible to understand and explain the smaller parts, then the whole could also be explained by bringing together the various part-explanations.

The ideas and practices of Cartesian Reductionism pervade our everyday lives, our buildings and engineered artifacts, even the way we are taught. Whenever we list, prioritize, disassemble, disaggregate, decompose, etc., we pay implicit homage to René Descartes and Cartesian Reduction. And, it has a great track record. Many of our greatest achievements have relied on reductionism.

At the start of the twentieth century, scientists began to notice that not everything was amenable to the reductionist approach. Some things, systems, seemed to function and operate only as wholes. They certainly might have discernable parts, but the parts did not explain the whole. Or, looked

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at in another light, the parts seemed to be mutually interdependent and to adapt to each other, such that looking at any part on its own was not only impractical, but also irrational. Such things, systems, were dubbed 'complex,' or 'complexes.'

Systems were defined: a system is an organized or complex whole: an assemblage or combination of things or parts forming a complex or unitary whole (Kast and Rosenzweig, 1970). The definition may not, in retrospect, offer much insight into the nature of systems, but it did serve to indicate, on the one hand, the essential integrity of systems, and on the other the basis for the integration of scientific knowledge across a broad spectrum.

A movement grew, notably among scientists of all persuasions outside of the 'hard' sciences, that came to be referred to as the systems movement, that regarded the whole system from a functionalist perspective (q.v.). Wholes were fairly evident: a whole person, a whole personality, a whole team, a whole organization, a whole army, a whole economy, or a whole nation. And the natural world seemed intent on creating wholes: whole atoms and molecules; whole animals and plants; whole civilizations; whole planets; and so on. True, many of these wholes subsequently decayed, but they were replaced by other wholes . . . .

To understand any part of these wholes, it was seen as vital to view the part operating in concert with, and continually adapting to, the other interacting parts making up the whole; a part could not rationally considered out of context, excised, sans interactions. To understand the operation of the heart, it was vital to see it functioning in a live body, responding to stimuli from other bodily systems, adapting to demands from the whole body, growing, aging, and so on.

This systems approach, as it came to be called, proved highly successful, and it was widely adopted in organizational and management research, economics, psychology, anthropology, sociology, political science, geography, jurisprudence, linguistics and many more. So much so, that a new age was declared: the Systems Age. In this bright new age, dynamic Systems Age thinking was compared with static Machine Age thinking (Ackoff, 1981, see Table 1.1):

A classic example concerned a mythical Martian arriving on Earth and finding a mechanical clock. He might open the clock, take it apart, reassemble it and hence find out how it worked. However, he would gain no idea of the concept of time in this process.

Table 1.1 Machine Age vs System Age paradigms (Ackoff, 1981).

Machine Age procedure	Systems Age procedure
■ Decompose that which is to be explained (decomposition) ■ Explain the behavior or properties of the contained parts separately ■ Aggregate these explanations into an explanation of the whole	■ Identify a containing system of which the thing to be explained is part ■ Explain the behavior or properties of the containing whole ■ Then explain the behavior of the thing to be explained in terms of its roles and functions within its containing whole.
Machine Age analysis	**Systems Age synthesis**
■ Analysis focuses on structure; it reveals how things work ■ Analysis yields knowledge ■ Analysis enables description ■ Analysis looks into things	■ Synthesis focuses on function; it reveals why things operate as they do ■ Synthesis yields understanding ■ Synthesis enables explanation ■ Synthesis looks out of things

Or, consider a proposed new university department, dedicated perhaps to research into medieval French literature. Its containing system, the university as a whole, is dedicated to research, to developing new knowledge, and to the dissemination of that new knowledge both to students and for the enlightenment of all. It may be funded, or it may have to engage in research and in teaching for reward. So, the proposed new department has to be seen in the context of the whole. In what degree will it contribute to the research goals of the university, over and above those already targeted by existing departments? How will it contribute to the dissemination of knowledge? How will it be funded and/or earn reward? In what degree will it interact synergistically with existing departments, so as to enhance the capability of the university as a whole? By thinking about the proposed new department in terms of its contribution to the whole, it becomes possible to understand the essential role, purpose and value of the new department as it will help to achieve the goals and objectives of its containing system, the university.

Systems Age thinking spread even into systems design: parts were no longer to be designed like static pieces of a jigsaw puzzle; instead they were to be designed to fit, and even adapt to, each other so as to work together harmoniously as well as efficiently and effectively. Since some designs and combinations of parts could prove more effective than others, the idea of 'best,' or 'optimum' design solution emerged in parallel.

The Nature of Systems

Systems may be real, tangible wholes, or they may be concepts. They are comprised of parts, which may be arranged in some way. A fundamental idea about systems is that they possess some degree of order, i.e., that there is discernable pattern or configuration, which leads to notions of structure and architecture. Yet many systems are thought of as 'doing' things, i.e., functioning in some way — which is suggestive of action, activity, process, etc. One of the simplest, yet curiously compelling, definitions of a system is a 'dent in the fabric of entropy.'

'Systems' must, in truth, be one of the most overworked words in the English language:

- Washing powder manufacturers promote their 'washing system'.
- Gamblers frequenting the Las Vegas casinos may have their pet 'gambling system'.
- Some industries declare themselves to be 'systems companies'.
- In Linnaeus' seminal work, nature was divided into three kingdoms: mineral, vegetable and animal. Linnaeus used five ranks: class, order, genus, species, and variety. (Or, more generally: kingdom, phylum, class, order, family, genus, species and form.) This is a biological 'classification system'.
- People who try to do things in an unorthodox way are described as 'trying to buck the system,' where the system seems to be 'the way things are,' or — for the more paranoid — the way 'they' make things happen. Whoever 'they' are . . . .
- At least one aerospace company declares that systems are everything on an aircraft other than airframe and engines, so includes avionics systems, cabin-entertainment systems, coffee- and team-making systems, air conditioning systems, toilet flushing systems, luggage loading and unloading systems, etc., etc., all of which are needed for the transport aircraft to be considered a 'whole.'
- Some engineers working in, e.g., aerospace companies declare themselves to be systems engineers; in the light of the previous bullet, that title does not seem to be too specific in its meaning and implications.

Despite this overtaxing of the word, 'system' retains its sense of order and completeness. Systems have been around since before the solar system. Artificial systems have clearly existed for millennia before we humans thought about them.

The ancient Egyptians had a system for building the Great Pyramid in only twenty years using only some 4000 men. How do we know? Well, by deduction — without a high degree of purposeful effort from organized teams of dedicated people, so much work could not have been achieved with such precision in so short a time to a clear and evident design plan. Consider: the only technology they had was the rope. The lever had not been invented, nor had the wheel. And, on the motivation front, the builders were not paid in money, because that had not been invented in 2650BC, either. So, there had to be some kind of system for enthusing and motivating the builders to work in such hot, desert conditions year in, year out . . . there was organization, motivation, competition, reward, supply chains of food and beer (water was too tainted to drink), leadership, control, direction, supervision . . . .

Civilizations are systems, too, of course — large, diffuse ones perhaps, with uncertain boundaries, and apparently with a limited lifetime, since they all inevitably pass away — *sic transit gloria mundi*, and all that!

Causality and Teleology

Cracks in the bastions of Cartesian Reduction appeared early in the twentieth century. Teleology — purposeful, goal-seeking behavior — was a problem. A goal-seeking system responds differently to events until it produces a particular state or outcome: the system has a choice of behavior.

In a mechanistic world, the idea was to decompose parts to find more basic components, with which to explain how things worked. Decomposing a goal-seeking system failed to reveal any component as the root of the goal-seeking behavior. Yet, such purposeful behavior was all around in organisms. Causality proved similarly problematic. Causality was unidirectional. One gene corresponded to one deficiency in an organism, for instance: one bacterium caused one disease. Only, it didn't . . . at least, not always.

The notion of individual units acting on their own in unidirectional causality proved inadequate to explain observed phenomena. Evidently, groups of things worked together in some way, so that the behavior of the whole could exhibit purpose, could be multi-causal . . .

Consider, too, DNA — the so-called blueprint of life. DNA is a complex woven, folded molecule, comprised of nucleotides. Despite its complexity, it is nonetheless an inert molecule. There is nothing in the DNA that indicates whether the 'owner' is alive or dead; the DNA of a 100-million-year-old extinct dinosaur is indistinguishable in this respect from that of a live modern human. To some, the notion that the very essence of life is itself lifeless is curious, even bizarre . . . which came first, the organism or the DNA?

Then there are soldier ants, with enormous colonies made up from hundreds of thousands of ants. How can the whole colony act as one in its pursuit of food, its setting up of a bivouac within a net of living, interconnected ants, its overpowering of prey many times the size and power of any ant, its ability to cross rivers . . . yet each ant is blind and can carry out only a very few functions? There seems to be only one way to understand the army of soldier ants — as a whole, as some kind of extended, unified organism.

Animals in groups presented real problems, too. How did hives of honeybees know when to swarm? How do flocks of birds and shoals of fish wheel, whirl and dance as a single entity?

Humans in groups have been the source of commentary for many years before systems ideas emerged. *E pluribus unum*, (out of the many, one) was the motto on the first Great Seal of the US, which signified the coming together of the 13 states: it a system concept of wholeness. Similarly, there is the well-known Aesop fable: the Bundle of Sticks. A man had sons who were always quarreling. One day he brought a faggot of sticks and asked each of the sons if he could break the faggot. None could. He then untied the bundle and gave individual sticks to each brother, who broke each stick easily. The moral was evident: united we stand: divided we fall.

Benjamin Franklin is similarly reputed to have remarked to John Hancock, at the Signing of the Declaration of Independence, 4th July 1776: ‘We must indeed all hang together, or, most assuredly we shall all hang separately.’ The words are different; the sentiment remains the same. All these ideas are expressions of the power of cooperation, coordination and complementation that seem to underlie the concept of the system as a whole being in some way greater than the sum of its parts.

Emergence

Cartesian Reductionism could not explain why some wholes possess capabilities, have properties, and behave in ways that were not evident from examination of their parts in isolation. This observation was labeled ‘emergence,’ and some wholes were observed to possess or exhibit properties, capabilities and behaviors not exclusively attributable to any of their rationally separable parts.

It was evident, for example, that the human brain was made from many different neurons, each of which was of itself relatively simple, being able to adopt a very few discrete states. Yet, somehow, the combined effect of all these simple, interconnected, interactive neurons was to create self-awareness, which astonished — and still astonishes — any scientist who cared to think about it. How could that be?

There were many examples of this initially mysterious emergence, once people began to look. How could bringing together two odorless gases, nitrogen and hydrogen, result in ammonia, with its pungent odor? How could a film, made up as it was of a series of still frames, present apparent motion to a cinema audience?

Life and the Second Law

The Second Law of Thermodynamics is a central tenet of classical physics. It can be stated in a number of different ways:

- The processes most likely to occur in an isolated system are those in which the entropy either increases or remains constant; or,
- the entropy of an isolated system not at equilibrium will tend to increase over time, approaching a maximum value.

Whichever way it might be stated, the conclusion may be drawn that entropy (disorder) will pervade all systems eventually. Using the Second Law as a guide, astronomers have concluded that the Sun will cease to shine in another five billion years or so, and the Universe will eventually become cold and inert. Current research suggests they may not be right, but the principles expressed by the Second Law seem sound enough for all that.

Only . . . life and living things seem to confound the Second Law. Living things create order in their being, in their growth, in their ability to organize, categorize, form groups, etc., etc. Similarly, civilizations seem to confound the Second Law, and on a smaller scale so do companies, organizations and societies. Indeed life is itself an apparent anomaly, inconsistent with the Second Law.

Of course, the Second Law is not really being confounded — it refers specifically to an isolated system. Life does not occur as isolated systems. For a system to be isolated, it has to be alone and receive no inputs. Living things — plants, animals, organizations and civilizations — receive inflows and emit outflows. So, an animal ingests food, negative entropy, and converts the food into parts that it can use to replace and rebuild its own internal parts. Hence, by ingesting negative entropy, the entropy of the whole can reduce, rather than increase.

Entropy and Work in Human Organizations

A more pragmatic view of entropy and the Second Law indicates that the ability of a system to do external work reduces with increasing entropy. This indication is compatible with the observation that disorganized companies do not produce much output, even though the people inside the organization might be working feverishly; streamlining the organization can improve its performance.

Government departments are often organized using committee structures. There are high-level committees, and then a number of intermediate-level committees with perhaps the committee chairmen also sitting as delegates on the higher-level committee. Lower-level committees are set up similarly, providing delegates to intermediate level committees. Additionally, there are cross-connections, with delegates and representatives operating laterally and diagonally across the committee structure. Such committee structures are found in such contentious areas as defense ministries and departments, where difficult choices have to made about costly defense projects such as new fleets of ships, aircraft, tanks, missiles,etc.

It has been observed, somewhat cynically no doubt, that the committee structure has two characteristics: (a) it ensures that no one person can be made responsible for any mistakes; (b) the net outcome from so much work done by such committee structures is to decide whether, or not, to implement some proposed major project. Logically — perhaps even rationally — the same decision that took perhaps years of reporting, vigorous debate and heated counter-debate, could be taken instantaneously on the turn of a coin. For, after all, the final decision is simply to proceed, or not to proceed with the project. The high-entropy system, which may expend copious amounts of internal energy operating and maintaining itself, is capable of very little external work. And, it really would be cynical, would it not, to suggest that, on the evidence, spinning a coin might have a better chance of success in choosing the right project . . . .

Of course, the many participants in such complex committee structures will argue that it is necessary to give everyone their say, that each advocate or opponent has a valid contribution to make, that it is important to give everyone a voice . . . and so on. There is copious evidence to show, however, that the ability of any group of people to make a cogent decision is inverse to the number of people involved in the process; beyond a handful, perhaps, five or six only, it becomes increasingly difficult and eventually impossible to make any sensible, consensus-based decision in any reasonable time.

Entropy Cycling

While the Second Law suggests that entropy inexorably increases over time, this is not what we observe with natural and many artificial systems. Instead we see systems being created, growing, becoming more complex perhaps, and then collapsing only to be supplanted by newer or resurgent systems.

The weather is a global system, always in a dynamic state, as the atmosphere is churned by the rotation of the earth and differential heating from the Sun at poles and equator, and by day and night. We see periods of calm interspersed with periods of turbulence, dry with wet, hot with cold, in a never-ending panorama. The entropy of the weather system seems to both reduce, as clear patterns of anticyclones, cyclones and ridges form, and then to increase again as the various patterns disperse — only to reform again, although never in quite the same way.

Life appears to be an example of entropic cycling, too. In the natural world, plants grow, are eaten, so animals survive and grow, then age and die. Animal and plant remains decay into nutrients for more plants, and the cycle continues — seemingly forever.

In the real world, it seems that we are not dealing with closed systems, with increasing entropy, but with open systems and entropic cycling, which we may perceive as birth–death–birth cycles.

General Systems Theory and Open Systems

In the middle of the 20th century, an attempt was made to develop a General Systems Theory. A Society for General Systems Research was founded in 1954, with the following principal contributors:

- Ludwig von Bertalanffy, a biologist
- Kenneth Boulding, an economist
- Ralph Gerard, a physiologist
- A. Rapoport, a biomathematician

Their General Systems Theory had four aims (Checkland, 1981):

1. to investigate the isomorphs of concepts, laws and models in various fields, and to help in useful transfers from one field to another;
2. to encourage the development of adequate theoretical models in areas that lack them;
3. to eliminate the duplication of efforts in different fields;
4. to promote the unity of science through improving communications between specialists.

The general theory envisaged by the four contributors has not really emerged, although their work has been highly influential. Some specialists, in particular, were scathing — but then, that was to be expected. Much of the work was mathematical in nature and has not stood the test of time so well as some of the many models that were created. Today, systems people use many of these models unaware of their origins . . . .

Boulding's Classification of Systems

Kenneth Boulding attempted one of the more difficult tasks — a coherent classification of systems. In Table 1.2, the first three levels are appropriate to physics, astronomy and the related 'hard' sciences; at these levels, a system is essentially regarded as closed, having no significant contact with its

Table 1.2 Boulding's classification of systems (von Bertalanffy, 1968).

Level	Characteristics	Example
Structures	Static	Bridges
Clockworks	Predetermined motion	Solar system
Controls	Closed-loop control	Thermostat
Open	Self-maintaining	Biological cells
Lower organisms	Growth, reproduction	Plants
Animals	Brain, learning	Birds
Man	Knowledge, symbolism	Humans
Social	Communication, value	Families
Transcendental	Unknowable	God

environment, and not adapting to that environment. The next three levels, four to six, are the concern of biologists, botanists and zoologists, and address open systems, those that are in contact with, and adaptive to, their environment. Levels seven to nine, also open systems, concern themselves with human and social systems, the arts, humanities and religion. Then, of course, there are the sciences that cross the layers: sociology, sociobiology, ecology, anthropology, psychology, organization, linguistics, and many more.

Categorizing systems is notoriously difficult. Even providing examples may be fraught. For instance, there are many systems engineers who deny that the solar system is a system at all, because a system has to be 'manmade and purposeful' (*sic*.) Boulding's Classification has stood the test of time, and it certainly provides a basis for discussion and much head scratching.

Parallels and Isomorphisms

Bertalanffy suggested that the many and various fields of modern science exhibit a continual evolution towards a parallelism of ideas, which allows for the identification of isomorphisms within and between the various separate scientific disciplines. Such isomorphisms offer the basis to formulate and develop principles that are applicable to systems in general. 'So has arisen systems theory — the attempt to develop the scientific principles to aid us in our struggle with dynamic systems with highly interactive parts.' (Ashby, 1964)

Isomorphisms had been observed increasingly between the various hard scientific disciplines. An elementary example concerns simple harmonic motion (SHM) and resonance. Physicists described SHM mathematically, observing that the acceleration of a particle obeying SHM was directly proportional to its distance from the point of zero displacement, and directed towards that point. They talked of resonant columns of air vibrating longitudinally, plates vibrating when a violin bow was pulled across the edge, and so on.

Electronics scientists and engineers regarded resonance somewhat differently, as caused by the exchange of energy between a capacitor and an inductor. Such resonance could be induced, usefully, by broadcasting a collection of radio waves of different wavelengths, so that the capacitor and inductor combination resonated only at the wavelength of a particular component of the broadcast spectrum, so enabling a radio to be tuned to a particular broadcast.

Mechanical engineers thought about vibration in much the same way, except that it was generally undesirable, and structures could be developed which did not vibrate at certain frequencies.

A notable failure in this respect was the catastrophe of the Tacoma Narrows suspension bridge, which was driven into resonance by a strong wind; so violent did the resonance become that the bridge collapsed into the river below.

Despite the many and various ways of looking at SHM and resonance, the underlying mechanisms were mathematically the same; and there were many other ‘behavioral isomorphs,’ as these phenomena came to be known. Behavior parallels (and convergent evolution) were observed in animals, even of quite different species. It became apparent, too, that some complex systems might be described by their behavior without necessarily having to delve into the depths of the systems design, structure, processes, etc. Here, then, was a potential way of managing complexity . . . .

The Concept of the Open System

Bertalanffy’s concept of an open system was a masterstroke; clearing the way for a singular theory of systems that could apply to soft, open systems, as well as closed, hard systems. An open system is in contact with its environment, receives inflows and emits outflows. It is able to adapt to its environment, yet may retain a steady state. Essentially, therefore, it is internally dynamic, which suggests that stability is conceptually different from that proposed for closed systems in physics.

The following equations (Bertalanffy, 1950) show some general systems mathematics which may seem rather obvious, once stated, but which show the developing nature of systems theory at the time. Equation (1.1) states, in essence, if the sum of all the elements arriving at a system equals the sum of all the elements leaving the system, then the system will neither increase nor decrease.

$$\frac{\partial Q_i}{\partial t} = T_i + P_i \tag{1.1}$$

where: $Q_i =$ is a measure of the ith element of a system; $T_i =$ the velocity of transport of Q_i at that point in space; $P_i =$ the rate of production or destruction of Q_i at a certain point in space.

A system defined by Equation (1.1) may have three types of solution: first there may be an unlimited growth in the system, Q; second, a time-independent state may be reached; and third, there may be periodic solutions.

In the case where a time-independent solution is reached:

$$T_i + P_i = 0 \tag{1.2}$$

In these two simple equation can be seen both the conservation laws of physics and the open systems (dynamic) stability of organisms. To an electronics engineer, for example, these equations may be redolent of Kirchoff’s Laws used in circuit analysis, concerning the conservation of energy and the conservation of charge. These laws simply state that the algebraic sum of the currents flowing into a node is zero — total charge in, equals total charge out — and that the algebraic sum of the voltage ‘drops’ around a closed circuit is also zero.

However, it was perhaps more the general ideas and models emanating from GST that most influenced the fledgling disciplines of systems science and systems engineering.

Understanding Open System Behavior

The following nine characteristics seemed to define all open systems (after Katz and Kahn, 1966):

1. Importation of energy. Open systems import some form of energy from the external environment. This is evident for open systems since they invoke dynamic interactions between the parts, which therefore do work and expend energy. Less obviously, perhaps, this is also true for the personality, which is dependent on external stimulus.
2. The throughput. Open systems transform the energy that is available to them.
3. The output. Open systems export some product into the environment, whether it is the invention of an inquiring mind, or a bridge constructed by an engineering firm. At a more basic level, open systems export waste which has arisen as the result of metabolism, i.e., as the result of transforming energy.
4. Systems as cycles of events. Energy exchanges with the external environment and within the open system itself have a cyclic nature. Breathing, heartbeat, peristalsis, the hunger–eating–digestion–metabolism–excretion cycle, etc., are well known examples from the body. Consider, too, a manufacturing organization. It takes in parts from suppliers, as needed, machines, assembles, etc., in a series of processes, sells the product for money, uses the money to buy in new parts, and to sustain, enhance and perhaps expand the internal machinery, processes. Like the body, the whole is characterized by a continuing series of interconnected (peristaltic?) processes.
5. Negative entropy. To survive, open systems must ‘ingest’ negative entropy. This may come in the form of food, new staff, new organization, even new concepts and beliefs . . . .
6. Information input, negative feedback, and the coding/categorization process. All open systems receive information, which they categorize both to reduce perceived complexity, and to identify that which is relevant. Open systems generally receive negative feedback, of a form that allows them to correct deviations from some course. (Research subsequent to this work suggests that control in many systems does not depend primarily on negative feedback, but instead on the opposition of forces, as in agonistic and antagonistic muscles and processes. Negative feedback, where it occurs, may act as incremental control.)
7. The steady-state and dynamic homeostasis. Importing energy to arrest increases in entropy can result in a steady-state condition, or quasi-stability, which may be dynamic in nature. Body temperature is a good example. Le Chatelier’s Principle (q.v.) can be seen in operation: changing any element within the open system causes other elements to rearrange themselves so as to oppose the change, and to restore the body as near to its previous state as possible.
8. Differentiation. Open systems move in the direction of differentiation and elaboration.
9. Equifinality. Open systems can reach the same final state from differing initial conditions by a variety of paths. (Von Bertalanffy suggested the principle of equifinality; it has not emerged as a universal truth, however.)

Since whole humans were whole systems too, it was possible to regard humans individually and in social groups and societies as exhibiting behavior. Comparing human behavior with the nine characteristics above, humans evidently exhibited additional characteristics, which were the source of intense study. Freud and Jung were foremost in this field of endeavor. It also became evident with research that groups of humans did not behave as individuals. Jung observed, for instance:

> It is a notorious fact that the morality of society as a whole is in inverse ratio to its size; for, the greater the aggregation of individuals, the more the individual factors are blotted out, and with them morality, which rests entirely on the moral sense of the individual and the freedom necessary for this. Hence every man is, in a certain sense, unconsciously

> a worse man when he is in society than when acting alone, for he is carried by society and to that extent relieved of his individual responsibility. Any large company composed of wholly admirable persons has the morality and intelligence of an unwieldy, stupid and violent animal. The bigger the organization, the more unavoidable is its immorality and blind stupidity . . . the greatest infamy on the part of . . . a man's . . . group will not disturb him so long as his fellows steadfastly believe in the exalted morality of their social organization. (Jung, 1917)

As this extract shows, Jung was acutely aware of the ways in which groups of people could behave, and that such group behavior could be, was likely to be, significantly different from the behavior of individuals. We recognize in his words the ideas of 'group think,' mob behavior, 'risky shift,' and of the typical excuse of the hard-nosed businessman: 'business is business; no room for sentiment in business.' Jung's insights make it evident that there was rather more to understanding social systems than had been thought previously, and in particular that, while a social system might be in equilibrium or homeostasis, it could at the same time evolve and adapt when stimulated.

Jung introduced the notion of types: introvert and extrovert, which have become everyday terms. He identified the introverted thinking type and the introverted feeling type, together considered introverted rational types. He also identified the introverted sensation type and the introverted intuition type, together the introverted irrational types. Extrovert types were similarly characterized, creating a total of some sixteen types in all. His seminal work was taken up by others and can be seen today in psychological tests such as the Myers–Briggs Type Indicator (Briggs, 1990), much used in industry as part of recruit selection testing.

Both Freud and Jung might be described as early systems thinkers: in their different ways they were trying to understand the whole human intellect, and both saw the need to view the parts only in the context of the whole. Each developed models of the intellect, Freud with his ego, super ego and id, Jung with his conscious, subconscious, collective unconscious, archetypes, etc. While the work of both emphasized the individual, Jung in particular seemed to recognize that the social group might be considered to have a collective intellect, too.

Developing systems theory encompassed and incorporated the ideas of psychology, group psychology, social anthropology, etc., and deployed them into organizational and management theory, to address the behavior of whole social systems, of whole socioeconomic systems, and whole sociotechnical systems. This last was of particular importance, since organizations, businesses and industries were generally sociotechnical systems, with their people-content forming teams, groups and divisions, and using machines which may also form social entities, such as distributed computer systems, sequential processing machines, etc. It had become evident, notably with the advent of mass production and its adverse effects on many of the factory workers, that technological devices interacted with their human operators/users, each affecting the behavior of the other, such that the conception and design of either the human team or the technology on its own was unlikely to afford success; instead, the whole had to be conceived and designed as one.

Gestalt and Holism

Aristotle said:

> The whole is more than the sum of its parts.
> The part is more than the fraction of the whole.
>
> Composition Laws (Hall, 1989)

The world, it seemed, would not be ready for such a profound systems concept for a further 2000 years; not, that is until Gestalt – a German word with no clear English translation, but meaning something like 'form,' or 'shape.' The Gestalt movement started early in the twentieth century: Gestalt psychology was launched in 1912 by Max Wertheimer, who published a paper on the visual illusion of movement created by presenting a series of still photographs of a galloping horse. The central tenet of Gestalt thinking was that the whole was greater than the sum of the parts.

A more current view might be that a Gestalt entity is a physical, biological, psychological, or symbolic configuration or pattern of elements, so unified as a whole that its properties cannot be derived from a simple summation of its parts. From this perspective, the whole is different from, not necessarily greater than, the sum of the parts. . . .

The Gestalt notion is contained within contemporary ideas of holism:

- Holism: the theory that the fundamental principle of the universe is the creation of wholes, i.e., complete and self-contained systems from the atom and the cell by evolution to the most complex forms of life and mind;
- Holism: the theory that a complex entity, system, etc., is more than merely the sum of its parts (*Chambers Dictionary*).

Gestalt has left a legacy, often overlooked, but nonetheless deeply embedded in today's systems thinking. Contemporary systems engineering, for instance, seems to owe more in practice to Gestalt than to operations research, since ideas of holism and emergence are firmly embedded, whereas mathematical optimization might be proposed by academics, but seems to be of little interest to engineers. Without optimization, however, requisite emergent properties may not be fully exhibited . . . .

Indivisibility

Whole system behavior was seen as indivisible; it was possible to observe and understand the behavior of any part only in the active, dynamic context of the whole and, therefore, the other parts too. It was not possible to observe and understand the part in isolation.

This was, of course, the antithesis of Cartesian Reductionism. Checkland put it as follows:

> Some view a system as being like a bag of pool balls: you can put your hand in the bag, pull out a ball, observe it, understand it, replace it in the bag, and nothing has changed. That is a reductionist view. On the other hand, a system may be seen as more like a privet hedge: if you try to remove a complete branch, you will have to rip it out from the complex growth, damaging both the branch and the hedge in the process; and, you will never be able to replace it. That is a complex, open systems view.

Interaction dynamics

It became clear with time and research that emergence was not really mysterious. As the example above of the mixing of hydrogen and nitrogen gases showed, emergence was not confined to complex systems either. Emergence comes about from the dynamic interactions between the various parts of a whole, or system.

For the two gases, the interaction concerns itself with outer electrons orbiting the ammonia molecule, and as chemists had known for some time, it was the pattern of electrons orbiting in the outer shells that gave a substance many of its chemical and physical properties.

The appearance of motion from a series of cine-stills is caused by interactions between the eyes and the brain, specifically between the retinal image and the visual cortex. The retina forms an image in such a way that it takes time for the image to form, and time to decay and disappear, while being overwritten by a succeeding visual image. The visual cortex has evolved the ability to integrate, or smooth out, this otherwise ‘jerky’ sequence that we would ‘see.’ It is also true that the optic nerve, which employs a sophisticated digital code, lacks the capacity to send to the brain sufficient information for us to ‘see’ the full visual images that we appear to see.

The problem is alleviated in part by having only the central point of vision transmitted in detail; so-called foveal vision. Even this is insufficient, apparently, and the brain also possesses the remarkable facility for ‘filling in’ parts of the scene from memory. The subjective result is that we observe a seamless, jerk-free moving picture. However, the processing takes time: it has been estimated, for instance, that a top-class tennis player has already received and played the ball by the time his/her brain forms an image of the ball traversing the net. So, while he/she may think they are watching the ball, in truth they have anticipated its trajectory and base their reactions on this anticipation and on years of training and practice. Now, that is interaction dynamics and emergent behavior!

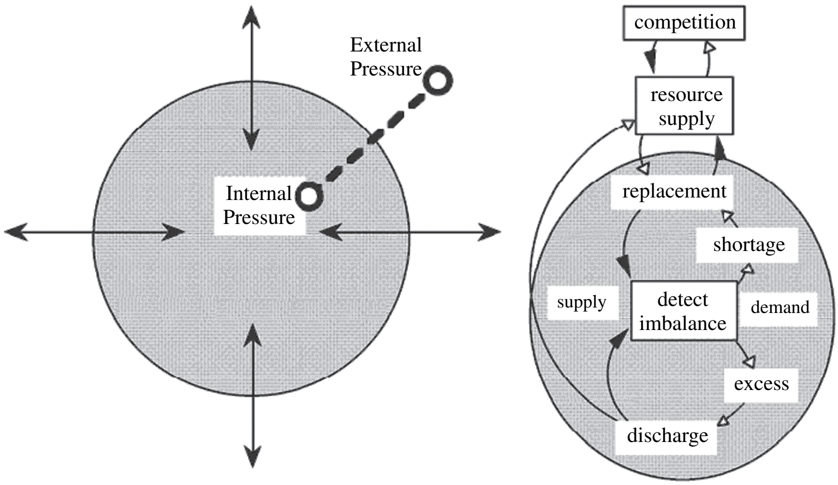
Emergent behavior is not always beneficial. It appears that part of the human brain is dedicated to identifying pattern and sequence. We become so good at observing and detecting pattern and sequence that we can sometimes ‘see’ what is not there. Police witnesses have been found to subconsciously create sequences of what happened, and in what order, during the commission of some crime or the build-up to some incident. Different, unconnected witnesses may tell the same story, but it may not be so. Our brains have the ability to ‘fill in the blanks’ in a supposed sequence of events or activities, to the point where we will be absolutely convinced that our version of events is correct. (This phenomenon has been observed since the advent of time-stamped CCTV, which has allowed investigators to build an unassailable timeline of events, against which to test observers’ reports.)

Stability and Steady-state

Stability in closed systems is a well-understood phenomenon. Generally, stability is indicated by a minimization of potential energy. Stability in open systems is more complex. Many open systems rest at relatively high levels of potential energy — a horse sleeps standing up, for instance, a candle flame stabilizes with the flame at a particular length, and a factory stabilizes when it has significant throughput. The reason for the difference, of course, is because open systems maintain themselves through internal processes and interactions, and these do work and expend energy.

The weight of a person is a balance between energy intake, internal energy transformation, energy expenditure, work and disposal of waste substances. If the energy intake, in the form of food, exceeds the rate of energy expenditure and waste disposal, then the body will convert some of the excess energy into fat, or stored energy, and weight will increase. This is a simple, obvious example of Equation (1.1) in action.

So, stability (homeostasis) in open systems is more a matter of dynamic balance than of minimum energy. An alternative, and perhaps more fruitful, way to look at open system stability is as the



If Pressure Differential > Threshold then Net Outflow

If Pressure Differential ≤ Threshold then Net Inflow

Flow rates = f{Threshold ~ Pressure differential}

Figure 1.1 Homeostatic concepts. At left, a cell maintains its volume by osmosis, with outflows and inflows through the cell membrane being ‘driven’ by the pressure difference between the cell and its environment. Analogously, at right, a commercial enterprise senses the difference between supply and demand (the analog of pressure differential) and uses that difference to vary inflow and outflow rates of resources: manpower, machinery, materials, money and information.

maintenance of a steady state: see Figure 1.1. Such maintenance will, in general, be dynamic, varying about some mean. If open systems are regarded as cycles of events, then this notion of steady state starts to make more sense. Cyclic events for the human body would include sensing hunger, eating and digestion including peristalsis – the waves of involuntary muscle contractions which break food up into boluses, and transport food, waste and matter through, and out from, the alimentary canal.

A person at rest, under anesthetic perhaps, appears to be motionless and inactive. If it were possible to open up the flesh, however, we would see inside a ferment of activity as the various subsystems and their organs interact dynamically and rhythmically. These cycles of events are analogous to the flow of materials through a manufacturing organization, payments through an accounting system, students through a university, and designs through a systems design team . . . and the feet of a swan swimming, apparently serenely, upstream against a strong current.

The Systems Approach

The systems approach, in which it became the practice to understand the part only in the context of the whole, interacting with, and adapting to, its environment, entered into almost every sphere of scientific endeavor, including the social sciences, and the life sciences — it had its roots, of course, in biology where there was no alternative. Management and organization sciences, in particular, adopted the systems approach.

It came to the attention of the engineering fraternities, too, who had been experiencing difficulties in applying their engineering practices to systems that included people — sociotechnical systems. The systems approach offered ways of understanding and addressing human activity systems and sociotechnical systems that had not previously existed.

The systems approach was seen as a way of addressing complex problems and issues. Ackoff (1981) suggested that there were three ways in which problems could be addressed:

1. Problems could be *resolved*. To resolve a problem is to find an answer that is 'good enough,' one which satisfices.
2. Problems could be *dissolved*. To dissolve a problem is to change the situation in some way such that the problem disappears, to 'move the goalposts.'
3. Problems could be *solved*. To solve a problem is find the correct answer, as in solving an equation.

In general, most people resolved problems, often by dealing more with the symptoms than by getting to the roots of the problem: sometimes they had to make decisions in absence of full knowledge. Satisficing was not seen as bad, more pragmatic. Sometimes satisficing resulted in more knowledge about the real problem, enabling further satisficing and more knowledge, so homing in on a complete solution to a problem.

Some people, however, were good at dissolving problems, making them go away. Politicians are often thought of as working in this way, and it can prove smarter, less confrontational and less expensive than other methods. However, it also can come at a delayed or hidden cost, as when the UK attempted to appease Hitler before World War II. Appeasement, in that context, was an attempt to move the goalposts, and it did not work. In the TV film, *Star Trek II: the Wrath of Khan*, the iconic Captain Kirk told of an examination he and his colleagues had faced at Starfleet Academy; the examination, concerned with the space vessel Kobyashi Maru, was known to have no solution. Kirk managed to surreptitiously reprogram the exercise computer simulation so that he could pass; that is, he moved the goalposts. Hence, in some circles, Kobyashi Maru is synonymous with dissolving the problem.

Some systems engineers chose the third route — they sought the best solution, the optimum, to a complex problem by so balancing the interacting components and coupled processes of a complex solution system that it gave the best results in its environment. This was a management task and, potentially at least, a mathematical task . . . as well as requiring understanding of just how emergent properties, capabilities and behaviors could be synthesized and realized.

Systems Thinking

Systems thinking is thinking, scientifically, about phenomena, events, situations, etc., from a systems perspective, i.e., using systems methods, systems theory and systems tools. Systems thinking, then, looks at wholes, and at parts of wholes in the context of their respective whole. It looks at wholes as open systems, interacting with other systems in their environment. Instead of thinking in the abstract sense, systems thinking has developed into dynamic modeling of open systems, often using smart simulation programs (Roberts *et al*., 1983, Richmond, 1992).

Because systems ideas are applicable to all kinds of systems, and are hence not limited by particular physical/structural/procedural constraints, systems thinking has evolved as modeling, particularly, the *behavior* of systems. This offers the opportunity to take maximum advantage of behavioral isomorphs. It also affords the ability to manage complexity, so that highly complex phenomena, situations, organizations, etc., may be modeled with some degree of confidence.

Like any form of computer simulation, behavior modeling is not infallible. This issue is alleviated, in some degree, by the way in which behavior modeling and systems thinking are used. In general, these methods are not used to provide specific numerical answers to complex mathematical problems. Instead, they are used to model the interactions between various systems-of-interest to explore likely outcomes from such interactions in some future environment. The models assume, too, that each system and its interactions affect other systems in the model and surrounding the model, so that the whole behaves dynamically and generally nonlinearly — like the real world.

In this way, models are used as experimental laboratories, to explore what might happen in some future situation, to explore the 'what ifs' . . . to see if there are likely to be any counterintuitive effects (Forrester, 1971) from unexpected interactions.

Systems thinking has been fuelled and enabled by the development of systems dynamics tools, of which there are many now available on the market. One such is STELLA™, which stands for: Systems Thinking and Experimental Learning Laboratory Approach: the title typifies the approach.

Functionalism and the Organismic Analogy

Functionalism is the principal theoretical perspective in sociology and many other social sciences. It is balanced on twin pillars: the potential application of the scientific method to the social world; and, development of an analogy between the individual organism and society. The concept of considering society as a system, and therefore subject to scientific investigation, might be viewed as a functionalist concept.

The analogy between the organism and society points functionalists to the bases for a social system to exist. A functionalist view would consider that every society must undertake, perform, or be capable of, certain basic functions for that society to survive and flourish, just as the organs of the body perform functions, which are necessary for the body's survival.

For a society to exist, for example, it must be able to overcome shocks and traumas and yet return to a state of normality, homeostasis or equilibrium; for the various elements of a society to function harmoniously, there will have to rules of behavior, codes of conduct, etc., which encourage cooperative interaction, and which discourage conflict. There will need to be organs of society that deal with members who do not observe the rules, such as the ability to impose sanctions on the one hand, and the provision of schools, colleges, etc., on the other hand.

The organismic analogy

The organismic analogy (Rapoport and Horvath, 1959) became central to the systems approach. The analogy does not state that all open systems, such as civilizations, societies, industries, enterprises, etc., are organisms. It does state, however, that in many ways they *behave* as organisms, in that they have a life cycle: a conception, a beginning, a development, maturity, and eventually a collapse. Bertalanffy noted that the collapse was often spectacular, or implosive, as for instance in the collapse of the Soviet Union, or the sudden collapse of seemingly invulnerable industries.

The organismic analogy suggested that, in viewing a system as made up from interacting, adapting subsystems, it was necessary to see these subsystems as complementary in some way, and as performing quite different functions on behalf of the whole system. As in society, there was a need to be able to impose sanctions on individuals who misbehaved, so in the human body there was a need for an immune system to suppress pathogens, and so in modern radar there was a need to detect and isolate defects and failures, and to undertake repairs.

The last example shows that systems thinking could be applied equally to technological systems, and that in so doing the technological system could be perceived differently: not so much as a collection of boxes; more as a synthesis of subsystems each of which performed different functions that interacted with those of other subsystems and which contributed to the performance, effectiveness, efficiency, stability and longevity of the whole. Viewing technological systems in this fashion was radically different from the engineer's view of technological systems and, in particular, allowed and encouraged the human users, operators, maintainers, etc., to be part of the whole system — which became a sociotechnical system in consequence.

The machine metaphor

It had been the practice to consider organisms as essentially biological machines. For the human body, the heart was a pump, the brain was a processor, the eyes were a camera, the kidneys were a filtration unit, and so on.

Bertalanffy (1968) had identified a number of difficulties with this metaphor, which he believed rendered it invalid. First, there was the problem for the origin of the machine. Whereas Descartes depended upon his Blind Watchmaker to build his 'biological machine,' machines did not create themselves in nature.

Second was the problem of regulation. While it was true that machines could regulate themselves, could a brain or an embryo be programmed for regulation after disturbances of an indefinite, possibly immense, number? It seemed not.

Third was the continuous exchange of components. Life, von Bertalanffy proposed, is a machine, composed of fuel, spending itself continually, yet maintaining itself. This creates a paradox: a machine-like structure of the organism cannot be the ultimate reason for the order of life processes because the machine itself is maintained in an ordered flow of processes. The order, then, must lie in the overall process itself.

Although engineers and some scientists still cling to the machine metaphor, the organismic analogy, or organic metaphor, has been widely recognized and employed, and can be seen at work in many aspects of systems engineering.

Mechanistic Control Concepts

Cybernetics offers a control view of the world that is neither particularly mechanistic nor organismic. The cybernetic model involves some input 'signal' which is amplified to drive a mechanism. Information from the mechanism output is fed back to, and differenced with, the input signal. In this way, the actual output is driven to meet the desired output as determined by the input signal.

The cybernetic model can, in principle, be used not only for machinery, but also for control of many different kinds. Management methods have included cybernetic concepts for the control of workers, although it generally proved unacceptable to the workforce, and hence to the management, since the workforce would be alienated by, and invariably rebel against, close control.

Organismic Control Concepts

Control in organisms generally works in two ways. The basic control strategy seems to be to form two opposing influences, such that that which is to be controlled finds itself balanced between the two. Limbs in the body are moved under the control of opposing sets of muscles: agonistic and antagonistic. Growing embryonic buds are directed in their growth pattern by chemical or nutrient gradients. Levels of glucose in the blood are regulated by the metabolism of glycogen on the one hand and by insulin on the other; and so on. Le Chatelier's Principle applies:

> When a constraint is applied to a physical system in equilibrium then, so far as it can, the system will adjust itself so as to oppose the constraint.

In so doing, the physical system seeks to restore equilibrium. Le Chatelier's Principle was first expressed in relation to chemistry and the behavior of interacting solutions, but it clearly has wider implications, addressing physical systems in general, as well as organismic systems. The principle evidently applies to social systems, for example. Note however, that Le Chatelier's Principle says nothing about the manner, direction, linearity or speed, etc., of this 'adjustment.'

Feedback regulation can also be found in organisms, where it may act incrementally, as fine control superimposed on the first method of control, i.e., through balancing influences. A well-known example of regulation is that of homeothermy, the maintenance of constant body temperature. For humans, the understanding is that as environmental temperature rises, there comes a point at which the body starts to perspire; the perspiration evaporates into the surrounding atmosphere, taking with it the latent heat of vaporization, and so cooling the skin and, possibly, reducing the rate of perspiration.

This well-known explanation falls short of explaining how the body maintains temperature when the environmental temperature falls. To appreciate this, it is important to understand that, as a warm-blooded, or endothermic, animal, humans metabolize food to provide energy, some of which inevitably emerges in the form of heat. This would raise the core body temperature, except for the conduction and convection of heat from the core of the body towards the surface, where it is lost to the environment. There is, therefore, a continual flow of heat energy from the core to the outside world in the steady state.

Should the external temperature fall, the consequent fall in skin temperature encourages the surface capillaries to close up, diverting blood flow away from the skin surface. The outer layers of skin, devoid of blood, insulate the core of the body, reducing the flow of heat energy so that the core body temperature remains effectively constant. While body temperature is higher than that of the surrounding environment, core body temperature is regulated in a manner analogous to that of a bath, in which the taps are running to raise the level of water, with the outlet left unplugged. As the water level rises, so does the head of water over the outlet, so the rate of outflow increases. If the bath is deep enough, a point of equilibrium will be reached at which the inflow from the taps equals the outflow through the plughole. This equilibrium, like that of core body temperature, is regulated without feedback.

From this perspective, the body's sweat evaporation-cooling mechanism specifically addresses the situation where the environment is warmer, such that heat loss from blood circulating near the skin's surface is insufficient to accommodate core body metabolic heat generation. (Sweating is not the only solution; dogs, for example, do not sweat, but pant instead.)

This greatly simplified description of homeothermy in humans illustrates that control and regulation in organisms and analogous open systems is not primarily of the cybernetic, feedback variety, but more generally of the opposing influences variety, with opposing influences acting differentially on coupled, cyclic processes.

Basic Percepts, Concepts and Precepts

Emergence and hierarchy

Whole systems exhibit emergent properties, where the whole is greater than the sum of the parts. If a subsystem could be a whole system, then it, too, may exhibit emergent properties. So, a hierarchical structure of systems within systems within systems is perceivable, in which levels of hierarchy are determined by emergence at each level.

This is distinct from the more general use of the term ‘hierarchy,’ as for instance in management structures or military rank structures. In systems, where a number of complementary systems come together and interact such that they form a coherent whole with emergent properties, then a level of hierarchy is established. Should that coherent whole interact with a number of complementary wholes, and should they then form a set with emergent properties, then a ‘higher’ level of hierarchy would be identified, and so on.

This concept is consistent with both the natural and the human activity worlds. Subsystems in the body interact to synthesize a whole human with emergence. Several humans can come together to form a team or a family, and the team/family can exhibit emergent properties: a team/family is, in this respect, different from a group of people, because the members of a team/family interact with each other. Such cooperative and coordinated interactions ‘bind’ the members of the team/family into a coherent whole that is capable of more than the sum of the separate individuals. Several teams can come together to synthesize a department with emergent properties, and so on.

The concept works for technological systems, too. The complementary parts of radar system might be: a transmitter subsystem, a receiver subsystem, an antenna subsystem, a power supply subsystem, an intra-communication subsystem, an operator/user control and display subsystem, and an operator or user. Without the user, the radar would, to use the Zen metaphor, make the ‘sound of one hand clapping.’ Individually and separately, none of subsystems can detect, locate or track a target at distance: brought together to interact in just the right ways, the whole radar system has these emergent capabilities; moreover, the nature and degree of interactions results in different capabilities.

By seeing the whole radar within its containing system, i.e., one hierarchy level higher, it is possible to establish just what the radar systems emergent properties should be. For instance, if the radar were to be one of a set of radars forming a sensor network to detect ships crossing some boundary, then there would be a potential risk of each radar transmitter interfering with the receivers of other radars within line of sight. This would mean either restrictions to the transmitter power, or the use of spread spectrum transmissions and receiver correlation, or simply, overall network frequency management, such that adjacent transmitters always worked on different frequencies. Only by looking at the next hierarchy level up, is it possible to determine just what the current whole systems emergent properties should be . . . .

(And, of course, a true systems engineer might question whether radar was the right solution to the problem in the first place — hence: ‘just what is the problem, and might there be other, better solutions?’ has become the byword of the professional systems engineer.)

Systems as comprised of interacting parts, themselves systems

Systems can be envisaged as made up from parts, themselves having the characteristics of systems, where the parts mutually interact and adapt to each other ‘symbiotically.’ So, the human body is made up of sensor systems, a cardiovascular system, a pulmonary system, and so on. A company might be made up from a production department, a research department, an administrative department, a sales and marketing department, and so on. In each case, these rationally separable parts cannot exist in isolation, are mutually interdependent, and are definable and comprehensible only in the context of the whole system, and of their interactions with other departments.

The associated concept of containment indicates that a whole system may ‘contain’ a number of complementary, cooperative, coordinated, interacting parts, themselves systems, or subsystems. Each subsystem could, in its turn, contain a number of mutually interacting sub-subsystems, and so on down to elementary particle level.

Interacting subsystems would, generally, mutually adapt to the inflow that each gave the other. Human activity systems do this all the time, of course, but it is possible to create technological parts that do not adapt to inflows — they process inflows, of course, but need not, in any way adapt to them. This led some to believe that subsystems could be created as building blocks, and could be mixed and matched. However, it is rare indeed that a piece of technology forms a subsystem; in the more general case, a subsystem would be found to be a person, or perhaps a group of people, using either one-on-one tools or machines, or perhaps using a distributed machine, such that the subsystem was in reality sociotechnical, not technological. Sociotechnical subsystems interact and adapt, because of the human element at their focus.

A classic example of this is the ubiquitous fighter aircraft. Without its human crew, it is a lifeless composite of metal, plastic, fuel, oils, gases, lubricants and chemicals. With its human crew it can take off, fly, detect, locate, identify, choose to intercept, intercept, warn, deter, return, land and report. Or, it can change its mind and . . . intercept, kill, return, land and report. So, all the higher functions, the decision-making, the prosecution of mission, the achievement of purpose, are in the hands of the human crew, but are enabled and supported by the live, active, interactive technology. It is the complete fighter, operational with its crew, that is a subsystem in an air defense system – not the sleek-but-inert fighter, leaking quietly in a hangar. The properties, capabilities and behaviors of the fighter emerge only when it is crewed by experienced experts: in that state, and only in that state, of wholeness, it is adaptable and flexible.

Variety in whole systems

Since the parts of a whole must complement each other, interact, cooperate and coordinate, it follows that the parts must be different from each other. Variety is therefore an important ingredient of whole systems: variety in subsystems, variety in interactions, variety in processes, etc. It is possible, in principle, to identify the minimum variety required of any whole, open system such that it can achieve homeostasis. This notion of variety suggests that the whole is made up from a necessary and sufficient set with minimum variety, and tends to emphasize the coupled process view of open system stability/homeostasis. That there is a minimum, or requisite, variety within an open system suggests that there might be adequate variety and even excess variety, too . . . .

Potential synthesis of open systems with desired emergent properties: systems engineering

With the (limited) understanding of emergence came the notion that it should be possible to synthesize systems with desired emergent properties: this was the driver for systems engineering. There are two convergent models of open system synthesis: in one model, the whole system is synthesized by bringing together suitable subsystems and causing the subsystems to interact; in the second model, the whole open system is seen as being formed from coupled processes; drawing in resources and energy, operating upon the resources, expending energy internally, pushing out product and waste, repairing and defending, etc., all of which is necessary for homeostasis. The two models converge where the various interlinked processes from inflow to outflow are executed by suitable subsystems. Processes operate, as it were, 'across' the hierarchy to create emergence.

Putting the two models together, there is an evident relationship between emergence, complexity and highly dynamic interaction between the parts of a whole system. The key to achieving desired emergence is to identify the essential pattern of coupled processes in system design that would result in emergence, and to ensure in any subsequent creative activities that the links in the pattern are not disturbed or distorted. This realization militates against the employment of Cartesian Reductionist practices during the creative phases of systems engineering, where such practices would address parts of the whole system in isolation, would treat such parts as independent, and would disregard the essential coupling and interaction pathways and routes through the design and operation of the whole.

So, a central tenet of systems and of systems engineering was identified as synthesis, as opposed to Cartesian Reductionism. However, it was not, and is not, entirely clear how to go about synthesizing highly interactive, adaptive systems. Nor is it clear what approach should be used. There seem to be two schools:

1. *Hard Systems School*. To create a new system that can be introduced into some problematic situation to neutralize/solve the problem, or . . .
2. *Soft Systems School*. To look for the symptoms of dysfunction in existing, dysfunctional systems, and to seek to repair, diminish, or work around, the dysfunctions so as to suppress the symptoms. The result is not so much a new system, as one that has been 'mended,' 'repaired,' 'enhanced,' 'improved,' etc.

The first school was characterized by the concept of 'hard' system solutions, i.e., solutions that had a clear singular purpose and which could be 'manufactured' *in vitro*, as it were, delivered and set to work. While recognizing the importance of interaction and process, this school emphasized functional, structural and architectural aspects of potential solutions systems, and that such systems would be delivered as a packaged, whole, 'turnkey' solution. Solution systems were conceived, created, delivered, supported, and eventually replaced after they had effectively 'died.'

The second school, on the other hand, applied itself *in vivo*, investigating problematic situations hands-on, seeking to understand the nature of the dysfunctions, and to recommend palliatives that would improve the situation. This second school viewed systems as complex, highly interactive and adaptive, and without any singular clear purpose. Such systems were described as 'messy,' or 'soft,' and were not necessarily amenable to revolution, more likely perhaps, evolution.

Soft systems approaches included 'action research,' in which systems consultants immersed themselves in the dysfunctional system, looking for causes of dysfunction and ways that might repair damaged or missing processes, interactions, etc. Often the systems concerned were large organizations which had formed internal disjoints, omitted necessary internal communications and interactions, or were even at war between internal parts. It was not for some external consultant to redesign the organization; rather, the external consultant might be able to recommend ways to ameliorate the issue or problematic situation. Solutions were conceived, proposed, adopted (or not), results assessed. There was no sense in which the ‘solution system’ had a life cycle, as such.

Both schools considered that they were systems engineering. And both were undoubtedly correct, although neither recognized the claims of the other. However, a more abstracted view might suggest that, rather than soft and hard as opposites, it was possible to perceive a spectrum from soft to hard, from higher entropy to lower entropy. Problem situations may start out as messy, unclear, lacking objectives, etc., but solutions may include not only repair of dysfunction by reconnection and adjustment, but might also include repair of dysfunctions by introducing new (e.g., sociotechnical) solution system as interacting components of some whole. The sense of this viewpoint becomes clear when the solution system turns out to be a modification, an upgrade, a retraining program, a streamlined process, a reconfiguration, etc.

Problem space and solution space

Systems engineering, both schools, were/are in the business of solving problems. Indeed, it was generally necessary to identify the seat of the real problem, since customers were often too close to the problem to see clearly. The concept of a ‘problem space’ emerged, a model of the wider system surrounding and encompassing the perceived problem, or at least the symptoms that led to a belief that a problem existed.

A problem space might be a diagrammatic ‘universe of discourse’ showing participating parties, interactions, coupled processes, disjoints, conflicts, omissions, etc. Of itself, it offered no solution, but sought to encompass and highlight the extent of the situation that engendered symptoms of dysfunction.

Consequent upon the concept of problem space, there emerged the concept of ‘solution space.’ A solution space showed the ‘universe of discourse’ in which the solution system would find itself, interacting with surrounding systems and the environment, and potentially adapting to both.

For soft systems, the solution space was similar to the problem space, in that the same participants might be present, but now there would be a changed pattern of interactions and coupled processes, such that the previous symptoms of dysfunction no longer appeared, homeostasis was restored, and so on. Soft systems approaches were seen as potentially progressive, in that making changes would alter the situation, perhaps making some aspects better, but potentially introducing unforeseen problems. So, there might be a number of successive ‘solutions,’ each taking account of the results from predecessors. This is satisficing, homing in on the ideal solution to a complex problem, but always mindful that such problems are dynamic and constantly changing: so, sometimes it would be impossible to keep up with the dynamics of the (complex) problem.

For hard systems, the solution space was also similar to the problem space except for the addition of the newly created hard solution system, which was seen in its ‘operational’ environment, interacting with other systems in that environment, all mutually adapting to each other. This was seen as something of a ‘big bang’ approach, one in which problems were hopefully eliminated at a single stroke, i.e., this is a form of solving. In practice, it was found that, in the time taken to create the big bang hard solution, the problem that it was designed to solve may have morphed, or even disappeared, such that the solution system was less than ideal for the new situation at delivery.

Further, it proved difficult to anticipate how future systems in the solution space would interact with, and adapt to, the newcomer . . . .

Hard systems engineering was attractive to engineering and aerospace organizations and to the military. It promised creative, innovative ready-made, turnkey solutions to problems. There was and is a tendency to exclude, submerge, or overlook the role of the human in the solution system where possible, perhaps because the human operator, user, supervisor, etc., is not possessed of a clearly understood transfer function.

Much of hard systems engineering took to creating complex, technological and expensive solution systems, comprised largely of interacting artifacts, with humans seen almost as ‘plug-ins,’ i.e., outside of ‘the system,’ and acting as an operator or user. Lip service was paid to the users with the development of MMI, the man–machine interface, HFE, human factors engineering, and ergonomics. For systems such as command and control, emergency services, air traffic management, etc., in which teams of people worked in harmony, using technological support systems, hard systems engineering proved less than satisfactory, so for these kinds of sociotechnical solution system, systems engineering developed along a pathway intermediate between the two schools, soft and hard. The variability and adaptability inherent in people was reduced by training them to perform particular tasks in particular ways, and by forming them into teams, such that the behavior of the team could be sensibly described and relied upon.

Soft systems, on the other hand, was attractive to management and organizational interests, and so found its home more in academia and in consultancy organizations, some of which applied the basic ideas with varying success, while others developed patent snake oil medicines for improving corporate health.

Evolving adaptive systems

Natural systems are able to adapt to changing situations, changing environments, changing climate, etc., provided the changes are neither too rapid nor too extreme. Human activity systems also display a degree of adaptability, and the ability to evolve. If adaptive systems could be designed and created, they would be able to track changing problem situations, operate successfully in changing environments and situations, and hence offer increased utility and longevity.

There are, potentially, a number of ways in which adaptive systems might be synthesized. If it is possible to perceive a problem space, understand the nature of a problem within that space, conceive, test, evaluate and the create/introduce a remedy into the problem space that neutralizes the problem, then it should feasible to incorporate all those facilities and capabilities into a complex system, such that the system can sense problems, can solve/resolve them, and can reconfigure itself, reconstruct itself, etc., continually so as to be at its most effective in addressing the contemporary problem. We might call such a system intelligent, since it would be able to change its behavior according to situation and experience.

An approach that offers promise is one based on so-called genetic methods. In this, some future system is generated using so-called genes: for a military system, there might be a gene that ‘codes for’ a particular kind of tank, another for a truck, another for a command and control system, another for a communication link, an infantry platoon, and so on. Using such genes it is possible to synthesize a force, with capability, within a computer simulation, so that there might be, say, genes coding for platoons, for tanks, and so on. The simulation would also contain representations of the environment — in this case, territory, perhaps — and of course an enemy.

The simulation would proceed by causing the two opposing forces to engage, perhaps as intelligent cellular automata, moving over, and making use of, the terrain, with force elements on both sides being threatened and damaged as the engagement proceeded until there was a victor. The simulation would then be run repeatedly, each time with a different pattern of genes, corresponding to a different force mix. Again, the combat results would be recorded. By choosing the various combinations of genes as a random pattern, a wide variety of potential force structures and tactics could be simulated, and the results for each structure/tactic combination recorded. Eventually, the ‘best’ combination would present itself. This combination would then be used as the ‘seed’ for a further round of simulated combats, i.e., as the initial force configuration, disposition, resources, communications, vehicle speeds, etc. In this way it is possible to progressively generate a force structure that should be able to successfully combat the chosen enemy on the chosen terrain to best effect.

If it were now supposed that this genetic design capability was ‘built-in’ to a combat force, such that the force could run simulations and determine ideal configurations and combat tactics before engagements, then the force would become an adaptive system. If this could be achieved for a fighting force, then it could be achieved, too, for a business, an enterprise or an industry.

Readers will have seen the flaw in the above argument, i.e., that the force structure would have been tuned to a particular enemy over a particular terrain. Trying out the evolved fighting force against different foes over different terrains, and so engendering a broader capability, would ameliorate this concern. In addition, the design of the fighting force might be frozen, and the tables turned, such that the enemy force is the one being evolved, using the same genetic approach. This should result in a more capable enemy force. The tables could then be turned yet again, and the friendly fighting force evolved once more to combat and overcome this new, improved enemy, in a kind of auto-ratcheting capability design system (Hitchins, 2003).

Such methods for developing sophisticated system designs are not without their flaws, but they afford great potential if employed with care.

Self-organized criticality

Some systems drive themselves to a critical state, one in which they are on the edge of collapse or disaster, but in which they seem rarely to go across the edge, and if they do they possess the ability to withdraw to safety and regroup.

As an example, consider ancient Egypt. During the Old Kingdom, the River Nile inundated its banks annually, providing rich black silt for farming. Food was plentiful and the population prospered and grew, until a point was reached at which the food supply was just able to meet the needs of the population. This was a state of self-organized criticality: if the inundation of the Nile should be either significantly greater or smaller than usual, the crop yields for that year would reduce and famine would ensue. If, as a result of famine, some of the population died, then the situation would repair itself — for a while, that is, until the population rose again. So, the population teetered ‘on the edge of chaos,’ as the situation is popularly described.

Such situations are common, and were epitomized by the sandpile experiment (Bak and Chen, 1991), conducted as part of an investigation into the frequency–size pattern of earthquakes. In the experiment, grains of sand were dropped on to a horizontal, circular plate positioned on a chemical balance. Successive grains formed a pile, which rose into a cone, until a point was reached at which adding another grain caused an avalanche to occur. As further grains were added, the cone grew again until further avalanches occurred. So, in the steady state, the height of the cone had a critical value; as it grew above the critical value, avalanches occurred which could bring it below the critical value, whereupon it would rise again to and above that critical value. In the jargon of chaos theory, the critical value was a simple attractor. In systems-speak, homeostasis was established.

The use of the chemical balance made it possible to calculate how many grains fell during each avalanche; some avalanches were comprised of only a few grains, others of many grains. As expected, there were more small avalanches and fewer large avalanches. Surprisingly, there was a clear mathematical relationship between the number of grains of sand in an avalanche, and the frequency of such avalanches. The relationship formed a power curve, of the form:

$$y = ax^b \tag{1.3}$$

Weak chaos

So, on a graph plot of log (grains of sand per avalanche) against log (frequency of avalanches with that number of grains) the result is a straight line. This phenomenon is sometimes called 'weak chaos,' and we are familiar with it in connection with earthquakes, where the Richter scale for the magnitude of earthquakes is logarithmic, such that a magnitude six earthquake is ten times more powerful than a magnitude five, while a magnitude seven earthquake is ten times more powerful than a magnitude six earthquake, and so on. It is found that the frequency of magnitude five earthquakes is greater than that of the more severe magnitude six earthquake, and again that the frequency of these is greater than the magnitude seven earthquakes.

This unexpected mathematical relationship was found to apply in many different, unrelated spheres: stock exchange price movements; distances between cars on a busy motorway; noise in an electrical conductor; meteors entering the Earth's atmosphere; deaths in wars; and many, many more. As the last instance shows, this rule applied both to natural and to human systems. It appears to be that rare thing — a universal rule that applies to whole systems, and is not explained by looking at parts of the whole.

System precepts

From the foregoing fundamental precepts, or tenets, emerge as central to sound systems thinking, systems practice, and systems engineering:

1. *Holism*. A system is a whole. An open system is a whole. The whole is different from, and may be greater than, the sum of its rationally separable parts.
2. *Organicism*. A whole (system) may be an organism, or may be analogous to an organism, in that the many interacting parts behave as a unified whole. The rationally separable parts exist in virtual symbiosis, each depending upon, and being defined by, the sum of the other interacting parts
3. *Synthesis*. It is possible to form a whole from open, interacting parts such that the whole may exhibit desired, or requisite, emergent properties, capabilities and behaviors. This is a functionalist viewpoint, or *Weltanschauung*, and is the *raison d'être* of systems engineering
4. *Variety*. The parts of a subsystem are complementary: they cooperate and coordinate their various actions. The parts are therefore mutually different, i.e., they exhibit variety, and so too must their interactions and interconnections to complement each other. There is a minimum variety of parts for any system to exist and continue to exist.
5. *Emergence*. Emergent properties, capabilities and behaviors derive from interactions between the parts, and are traceable therefore principally to coupled processes, rather than to structure. Emergence arises only when the parts of a whole interact, or conversely when the coupled

processes flowing through the system are active. An open system, therefore, is only a whole while it is both complete and internally dynamic.

6. *System*. A system is an open set of complementary interacting parts, with properties, capabilities and behaviors emerging, both from the parts and from their interactions, to synthesize a unified whole. The definition encompasses the first five precepts: holism, organicism, synthesis, variety and emergence.
7. *Homeostasis*. Stability in open systems occurs at high, rather than low, energy. Stability is a dynamic steady state, brought about when inflows balance outflows. Homeostasis is necessary in a variety of parameters in complex systems, including energy, resources, waste, material inflow, product outflows, and many, many more.
8. *Viability*. The viability of open systems depends in part on achieving and maintaining homeostasis, but also on their ability to neutralize threats from without and within, to adapt and change with circumstance, and to maintain synergy — cooperation and coordination between the parts, to act as a unified whole in achieving some desired external effect.
9. *Purpose*. Manmade systems are viewed as having purpose, one perhaps that they were designed to achieve, or one that they have adopted. It is 'helpful' to consider the human element of systems as having purpose, or intent, and to consider the technological/artifact element of systems as serving that human purpose. So, the parts within a whole may be purposive, i.e., an observer might attribute purpose to them. The parts contribute to the objectives and purpose of the whole, but the purpose of the parts need not aggregate to the purpose of the whole.
10. *Behavior*. Open systems exhibit behavior, i.e., they respond to stimulus. Since open systems are interconnected and interact with other open systems, they are constantly stimulated and exhibiting behavior. Where the behavior of a system is consistent and predictable, the system may be usefully described by its behavior, so diminishing the need to describe the internals of the system; this is a direct means of reducing perceived complexity. Intelligence is marked by the ability of a system to change its behavior according to situation, e.g., it may not respond to the same stimulus in the same way every time, as would a machine or a simple organism.
11. *Isomorphs*. Different systems may exhibit the same behavior, i.e., they respond identically to the same stimulus, although they may be comprised of different parts. Clearly true of many physical systems, it may also be true of some natural systems at some times.
12. *Ideals — the Ideal System*. A concept exists in systems thinking and in systems engineering of the ideal system: it is the best that planners and designers can conceptualize (Hall, 1989). The ideal system can become a yardstick against which to compare options and alternatives, or against which to measure that which is realized.
13. *Values*. Value in artificial systems is often related to utility; the more useful a system, the more it is valued. The value of a subsystem or part of a whole may be judged in the degree with which it contributes to its containing system's objectives in concert with the other subsystems and parts. The value of a subsystem or part may also be judged by the degree in which it complements the other subsystems, particularly where, without such complementation, the other subsystems and the whole would not exist.

From the foregoing, we observe, engineers notwithstanding, that the solar system is indeed a system, organisms are systems, a complete set of ideas can be a system, a series of strategically placed stepping-stones across a river can be a system. We can also see that it is possible to create artificial, or human activity systems in which the whole is greater than the sum of the parts, which has important implications:

- systems can be created that exceed the capability implicit in their technology, or implicit in the sum capabilities of individuals, or both;
- systems can be created that proffer greater value than the sum cost of their parts would indicate;
- systems can be created that may proffer the desired value at less than the sum cost of their separate parts would indicate.

Not everything is a system, however, since not everything is a whole. As we have seen, a fighter aircraft sans crew is not a whole. Similarly, software sans processor is not a whole, simply a set of instructions; a computer without its software is similarly not a whole, simply a machine without instructions. A marriage is not a whole, by definition, unless it joins together complementary man and woman into a single union.

Assignment

Soft and hard systems schools both purport to explore problems and afford system solutions. Compare and contrast their approaches and propose in which kind of situation and problem these might be most appropriate. What do you think might be the flaws, limitations and constraints of each method in addressing complex issues and problems, and how might these be ameliorated?