AN OVERVIEW OF SYSTEMS AND SYSTEMS ANALYSIS

By
Dr. Robert Finkelstein
Robotic Technology Inc.

INTRODUCTION

Technology continues to evolve at an exponential rate, along with the growth in human population. Organizations of people and machines grow increasingly complex, along with the problems and opportunities they engender. Solutions to problems become counter-intuitive, and the best intentions of decision makers lead to disastrous consequences. Sometimes it seems that "up" becomes "down," and "in" becomes "out."

The Universe is a system, as are organizations: galactic clusters, galaxies, solar system, planet, societies, organizations, organisms, organs, molecules, atoms, leptons, hadrons, and perhaps even the quark – and fleas upon fleas upon fleas. Systems possess certain properties, many of which remain hidden. But a major characteristic of systems is that they possess emergent properties. These properties cannot be predicted, a priori, from the properties of the system's subsystems. A chaotic pile of wood and screws obscures the "sit-ability" of a potential chair which can be constructed from the seemingly disordered pile of parts. Even in physics, only the simple two-body problem (i.e., the motion of two bodies due to their mutual gravitational field) can be solved analytically for all conditions, while the three-body problem can be solved analytically only for certain configurations. Beyond that, the multi-body problem can be solved only approximately (and for relatively few objects) using simulations in powerful computers. If one cannot predict the behavior of a fairly basic system of rocks in the vacuum of space, under the influence (in the simplified problem) of a single (gravitational) force, then what of the ability to predict – and control – the behavior of individual humans and human organizations?

There have been a number of attempts to develop a general theory of systems, analogous to the general theory of relatively. The theory would explain the laws of systems common to all systems and be able to predict the behavior of systems based on those general laws. So far, this has failed. Nevertheless, there are some useful, discernable rules that govern systems in general, including those complex systems formed by Homo sapiens. It behooves the management professional and decision-maker to know the types and properties of systems to better manage people and organizations – and maybe even solve a few difficult problems.

The most rudimentary form of a science – one that is in its infancy – is one that essentially categorizes and establishes taxonomies. In the rudimentary science there is no unifying theory to tie together disparate observations in one grand explanation, nor is there an ability to make predictions based on the theory. Physics achieved its first overarching theory and powerful ability to predict in the late 17th century with Isaac Newton, but biology did not achieve explanatory power and predictability until the late 19th century with Darwin (evolution) and the late 20th century with Crick and Watson (DNA). Systems science is barely a science, but there are useful systems taxonomies – along with a few rules – that can help the manager to analyze problems and make decisions.

In particular, the notion of the cybernetic system – and its subset, the intelligent system – is extremely important as computers and intelligent systems become ubiquitous and people become one with the machine. If managers remain ignorant of the nature of these systems, they risk their organizations – and their jobs.

1.0 WHAT ARE SYSTEMS?

1.1 Definitions

"Systems which do not include certain parameters can be shown to be insensitive to changes in such parameters." ----- Anonymous

This section will attempt to elucidate the elusive notion of the "system" and describe its relevance to management and organizational control.

A *system*, in one definition, is simply a set of *variables* selected by an observer, where a *variable* may be defined as a measurable quantity which at every instant has a definite numerical value - a quantity which, for example, can be represented by a measuring device such as a ruler or a gas gauge (or, perhaps, a subjective evaluation). A simpler version of this definition is: **a system is anything that has parts**. This means that an observer may define a system to be whatever is convenient for a particular purpose (such as to solve a problem).

Once a system is defined, the system's subsystems (those entities which comprise the system) are implicitly, if not explicitly, defined, as is the system's environment (the immediate context in which the system is embedded – or the rest of the universe). Defining a system, as well as its internal subsystems and external environment, usually involves subjectivity on the part of the observer (or analyst) who is the definer. If a classroom is defined to be the system of interest, then its subsystems may be defined as walls, floors, ceiling, windows, door, heating and air conditioning, chairs, desks, blackboard, chalk, lights, students, and professor. But should the screws in the chairs be considered as subsystems – or even as sub-subsystems of the chairs? What about the students' gastro-intestinal tracts or the professor's bunions? Are they important to purpose of the system definition? If so, they should be included. If not, they should be ignored. (A professor's bunions, for example, may be important in determining whether a class should be taught standing or sitting; and the students' gastro-intestinal tracts may determine whether the class should be taught at lunchtime, or whether toilet facilities should be located conveniently near the classroom).

The system's variables are selected from a large of variables set because they are deemed important. It is impractical to include every conceivable variable to investigate a problem. Likewise, the definition of the environment – or context – of the defined system depends on variable that are important to the problem under consideration. Is the environment of the classroom the building in which the classroom is located – or the entire school or university? What about the gravitational effect of the moon or the planet Venus on the classroom, or the electromagnetic field from electric lines on the campus? As with any research, an initial selection of variables (i.e., choice of the system, subsystems, and environment) may have to be changed to reflect new information arising during the study.

With somewhat greater specificity, another definition declares that a system is a set of two or more interrelated elements – or subsystems – that satisfy three conditions: (1) the *behavior* of each element has an effect on the whole; (2) the behavior of the elements and their effects on the whole are *interdependent*; and (3) each subgroup of elements has an effect on the *behavior of the whole* and *none* has an *independent* effect on it. (The *behavior* of each element (or anything) in the above definition may be defined as any sequence of *states* that each element attains. And *state* of an element (or anything) may be defined as the set of numerical values which its *variables* (defined above) have at that instant.) But what does it mean for each element to have an "effect on the whole." The gravitational attraction of the planet Venus has an effect on the trajectory of a baseball, but it is negligible in determining the trajectory of the ball and can be ignored. So judgment must be used, once again, in determining which elements have a significant effect on the whole system and which can be ignored. Likewise, judgments must be made about the interdependence of the elements (subsystems).

A system is *different* than the sum of its parts and cannot be understood fully with analysis alone (i.e., the decomposition of the whole into its parts). This rule is often stated as: "a system is greater than the sum of its parts." (But sometimes a system can be less, in a functional sense, than its parts. For example, a committee of academics is generally inferior to a single academic.) One cannot infer the existence of a higher system from subsystems or lesser pre-existing systems. To a visiting Martian who has never seen a cow, for example, a cow carved into its constituent components – a mound of flesh and bones – implies nothing about the behavior and functioning essence of a live cow. Likewise, one cannot predict new system characteristics arising from a new unity created by the integration of individual components. Consequently, optimizing subsystems will, in general, not optimize the system (i.e., sub-optimization will occur). This is a common management error in corporations and politics.

So a system is a structure of subsystems, with every system being embedded in a larger system (and thereby becoming a subsystem). A system is a way of looking at the world. The properties of a system are not intrinsic to it, but are relational between it and an observer. The study of a system requires reification of the system, i.e., the treatment of the abstract relationships, perceived or defined by an observer, as if they were real.

In studying a system, synthesis precedes analysis. The system as a whole – its properties and behavior – must be studied first, then the properties and behavior of its components. In general, systems should be examined – or designed – teleologically (i.e.,) oriented toward output (in terms of goals, objectives, ideals), rather than deterministically, and quantitatively, oriented toward flows of matter and energy in the system. In other words, the researcher should first direct the examination of the system toward its ultimate purpose (what an organization, for example, is supposed to accomplish and how it is to accomplish it) and not focus initially – or exclusively – on the quantitative aspects of the system (how many employees, how much raw materials, how many square feet, how much revenue and profits, etc.).

The U.S. military has long engaged in systems synthesis and analysis. It regularly defines weapons systems, subsystems, and their environmental contexts (e.g., operational scenarios). As an example, consider the Army's Future Combat System (FCS), in which all conventional battlefield systems will be replaced by a *system of systems* consisting of a variety of robotic and manned ground and air vehicles. Depending on the needs of the moment, a system may consist of an individual vehicle or many vehicles or many vehicles and soldiers. All government and contractor participants in the FCS program must always contemplate and plan how their piece (subsystem) physically and functionally integrates with the whole, seamlessly, effectively, and efficiently.

It behooves the competent manager to know about systems, and the nature of the organization as a system. Without such knowledge, what seem to be solutions to problems grow into problems in search of yet more solutions. In complex systems, like organizations, causes often have non-linear effects and solutions to problems are counter-intuitive, while managers tend to think linearly and intuitively. The ecosystem is, at long last, recognized (if not well-understood) as a complex system in which seeming solutions (e.g., introducing toads, in an environment without toads, to eat mosquitoes) often lead to new problems (e.g., a plague of toads in an environment where there are no toad predators). The global weather system is likewise recognized as a complex system – and also not well understood. The organization must also be recognized as a complex system – perhaps as a kind of ecosystem – even if it is not well-understood.

1.2 Taxonomy

Systems may be categorized in a number of useful ways. Some **useful categories** of systems are (in no particular order):

- **Closed:** systems which have no input (of matter, energy, or information) from outside. Strictly speaking, real systems all have some input (connectivity) with the environment. A system can be considered closed if the input is not significant for the purpose of the observer (definer) of the system. A closed system is one whose behavior is entirely explainable from within. Systems which are closed to matter and energy are also known as *autark* (except they may be allowed the continual flow of sun energy). Systems which are closed information are called *independent*. Systems which are closed to organization from the outside are called *autonomous*. A closed system might include a rock or a chair in a museum display case or a self-contained ecosystem in a space station. Biological organisms are largely closed to organization, while open to matter and energy, because their organization is specified by their DNA at inception. The output of a system has nothing to do with whether a system is closed. Systems without output cannot be known by observing them from their outside.

- **Open:** systems in which the input of matter, energy, or information is significant for the purpose of the observer (definer) of the system; systems where a boundary is not closed. Open systems receive inputs and produce outputs, and change their behavior in response to conditions outside their boundaries. (Systems are usually open to some influences and closed to others. Because of their need to combat decay within, food intake makes biological organisms and societies open to matter and energy from their environment.

But this property says nothing about openness to information, which is needed for adaptation, learning, and manifestations of intelligent systems, or openness to organization, which social systems, such as organizations, require. The distinction between open and closed systems does not depend on whether or not a system has outputs. Systems without output are non-knowable by an external observer (e.g., black holes in the visible universe). Systems without inputs (closed systems) are not controllable. A live person is an open system, while a dead person, long entombed and decomposed or mummified, may be considered to be a closed system. The earth is an open system, receiving energy from the sun, while an isolated planetoid, traveling in vacuous space between the stars, may be considered to be a closed system. Open systems do not obey the second law of thermodynamics in which closed systems continuously decay, in a heat death, into increasing disorder. Open systems, however, can evolve from simplicity to complexity; life can originate from non-life, and humans can evolve from bacteria. (It is the lack of understanding of open systems, among other things, that leads those who believe in Creationism or Intelligent Design, which are belief systems and not science, into muddled assertions). Likewise, organizations, which are open systems, can evolve from small garage enterprises into billion-dollar global businesses.

- **Conceptual:** systems which consist of symbolic entities, such as words or numbers, or which are models or simulations of real or concrete systems; semiotic systems.

- **Concrete:** real systems which consist of non-random accumulations of matter and energy in a region in physical space-time and which are organized into interacting, interrelated subsystems or components.

- **Non-Living:** concrete systems which do not have the characteristics of living systems; the general case of concrete systems (of which living systems are a special case).

- **Living:** concrete systems which: are open systems; maintain a steady state of negentropy (despite entropic processes); have some complexity; have a structural and procedural template (e.g., deoxyribonucleic acid – DNA – or other program); largely composed of aqueous suspension of macromolecules, proteins, and other characteristic organic and non-living components; have a decider (a critical subsystem which controls the entire system, causing subsystems and components to interact); have subsystems which are integrated to form self-regulating, unitary systems with goals and purposes; are able to exist only in environments in which critical variables have values within a narrow range (e.g., temperature, pressure, radiation, atmospheric composition, etc.).

- **Simple:** systems in which there are few variables and where cause and effect are close in time and space, so that effects (such as system outputs) can be readily discerned from causes (such as system inputs).

- **Complex:** systems in which there are many variables and interconnections among variables (called *detail complexity*), or where cause and effect are not close in time and space and obvious interventions do not produce the expected outcomes (called *dynamic complexity*). Another definition is: complex systems are systems with the potential to evolve over time, with their subsystems having emergent properties that can be described only at higher levels than those of the subsystems (the whole system being more than the sum of its subsystem parts).

- **Cybernetic:** systems which have negative feedback and are therefore controllable; often consisting of organisms and machines (such as a car and driver, or homeowner and thermostat).

- **Hierarchical:** systems which have a form of organization resembling a pyramid, where each level is subordinate to the one above it. More specifically, a hierarchy is a partially-ordered structure of entities in which every entity but one is successor to at least one other entity; and every entity except the basic entities is a predecessor to at least one other entity. Hierarchical systems have advantages in nature and organizations, as we will discuss, along with some disadvantages.

- **Heterarchical:** systems which have the form of organization resembling a network or fishnet. Systems or subsystems in nature may be heterarchical (such as the neural network in the human brain). In heterarchical organizations, authority is usually determined by knowledge and function. Terrorist organizations tend to be heterarchical, and the U.S. military now emphasizes network centric (netcentric) warfare as the countermeasure to asymmetric threats.

- **Intelligent:** systems (i.e., organisms or machines) which are able to make an appropriate choice (or decision), where that which is *appropriate* depends on the system's purpose or function. There are three useful corollary definitions: (1) **reactive intelligence,** or **adaptation,** is based on an autonomic **sense-act** modality and it is the ability of the system to make an appropriate choice in response to an immediate environmental stimulus (i.e., a threat or opportunity) – for example, it is raining and the system is getting wet, so it seeks shelter; (2) **predictive intelligence**, or **learning**, is based on **memory** and it is the ability to make an appropriate choice for events that have not yet occurred but which are based on prior events – for example, it is very cloudy and the system infers that it will likely rain soon, so it decides to seek shelter before it rains; (3) **creative intelligence**, or **invention**, is based on learning and the ability to cognitively **model and simulate** and it is the ability to make appropriate choices about events which have **not yet been experienced** – for example, it takes too much time and energy for the system to seek shelter every time it rains or threatens to rain, so it invent an umbrella to shield it from the rain; the system can imagine that the umbrella, which never before existed, will protect it from the rain.

- **Adaptive:** systems which are able to maintain critical or the essential variables within physical (or physiological) limits (e.g., homeostasis); the ability of a system to achieve its purpose in a changing environment by modifying internal variables or structure – or the external environment – in order to make itself fit by adjusting to new or changed circumstances.

- **Learning:** systems which achieve growing success (e.g., improved behavior) in a fixed environment – learning takes place when the system's behavior increases the efficiency with which data, information, and knowledge is processed so that desirable states are reached, errors avoided, or a portion of the environment is controlled. Learning is a process of growing success in a fixed environment, e.g., riding a bicycle, acquiring linguistic skills, or cooking eggs Benedict. Learning is not the same as acquiring knowledge by receiving information, nor is it identical to adapting. Consciousness may or may not be involved in learning (even flatworms can learn).

- **Stable:** systems in which the tendency of their variables or components are to remain within defined and recognizable limits despite the impact of disturbances – where the system has the ability to return to equilibrium (or its original state) after having been displaced.

- **Dynamic:** systems which display motion, change, and process as, opposed to being *static*.

- **Self-Organizing:** systems which change their structure as a function of experience and environment; or alternatively, a system and its environment taken together which organize themselves on the basis of experience. (St Thomas Aquinas, constructing logical proofs of the existence of God, argued that since everything had to be organized an organizer was necessary – and today Intelligent Design believers are trying to displace evolution. But if systems can be self-organizing, there need not be a designer; it now seems likely that life itself came about through a self-organizing process whereby different chemicals came together in a more or less chance fashion and gradually organized themselves into living patterns.)

- **Autopoietic:** systems which produce themselves. An autopoietic system is an autonomous and self-maintaining unity which contains component-producing processes. The components, through their interaction, generate recursively the same network of processes which produced them. An autopoietic system is *operationally* closed and structurally state-determined, with no apparent inputs and outputs. A cell, an organism, and a corporation are examples of autopoietic systems.

- **Allopoietic**: systems which produce something other than themselves. An assembly line in an automobile factory is an example of an allopoietic system, producing automobiles, not the machines used in production or automobile factories.

- **Homeostatic:** systems in which essential variables are constant or remain within their critical (acceptable) values, even in the presence of unexpected disturbances (e.g., human body temperature or fluid content).

- **Metasystem:** a system which monitors or controls a subordinate system (i.e., one of lower ordinality). It audits, and perhaps alters, the subordinate system's essential variables and processes. For example, a corporate metasystem might change the focus of the company's business or its measures of success. (A board of directors is supposed to act as a metasystem, but often is enmeshed in the subordinate system and cannot perceive the needed changes). To some extent, the success of organizations – and societies – depends on the strength and nature of the meta-systems they establish. A thermostat regulating room temperature depends on a metasystem of humans setting preferred temperatures which the thermostat then maintains. Golfers obey the rules of golf – and people obey the rules of organizations and society in general – because of a metasystem involving human motivations, social controls (such as laws and morality), and incentives (such as pay and praise).

A **hierarchy of systems** (*not* necessarily mutually exclusive) has been defined as:

1. **Static systems** of structures or frameworks (where the framework is considered static even if elements move: e.g., atoms, molecules, crystals, bones, rooms, continents).
2. **Simple dynamic systems**, metaphorically clockworks (e.g., machines, solar system, galaxies).
3. **Cybernetic systems** (e.g., thermostats, homeostatic biological processes, robots).
4. **Open systems** (e.g., flame, cell, organisms, planet).
5. **Lower organism systems** (e.g., plant-like organisms with increasing functional differentiation).
6. **Animal systems** (e.g., animal-like organisms with increasing importance in information transfer).
7. **Human systems** (e.g., human-like organisms with increasing self-consciousness and the ability to produce and understand symbols).
8. **Socio-cultural systems** (e.g., populations of organisms; populations of humans in which there are symbol-determined communities (cultures)).
9. **Symbolic systems** (language, logic, mathematics, science, art, morality, etc.).

Since these categories are not mutually exclusive, a system can fall into more than one category. For example, a classroom with students may be considered to be any or all of the following types of systems: static, cybernetic, open, human, socio-cultural, and symbolic. It is not clear how useful this sort of taxonomy is in developing a general systems theory.

1.3 Systems Theory

Systems theory, like any other theory, attempts to explain seemingly disparate facts and phenomena in an integrative, general, all-encompassing way, and to predict facts and phenomena based on the theory. The theory tries to explain the nature of systems and their laws and properties, and to establish isomorphisms among systems. What are the common rules and properties of systems, regardless of the type of system (e.g., physical, chemical, biological, or social)?

Unfortunately, the theoretical basis of systems theory remains weak. It may be that there is no underlying basis for a general theory of systems after all, or that current tools or perceptions are insufficient to develop a suitable theory. Or it may be that the means of discourse, the language used to define and describe systems (especially complex systems) is lacking. The definition languages typically used to describe systems – natural language and mathematics – may have inadequate expressive power. The Theory of Hierarchical Definability (THD) contemplates a hierarchy of discourse, in ascending order of expressive power:

- Natural language (NL)
- Language of mathematical analysis, probability theory, and bivalent logic (C)
- Language of fuzzy logic without granulation (F)
- Language of fuzzy logic with granulation (G)
- Precisiated natural language (PNL)

While PNL is a fuzzy logic based language with maximal expressive power, THD as an approach is still in its infancy and has not been applied to the development of systems theory (although it is beginning to be applied to the subset of intelligent systems, to define, for example, what is meant by *intelligence* and how to measure intelligence).

While the *science* of systems, sometimes known as systemology, struggles to emerge, the discipline of systems *engineering* is progressing. Classical engineering focused primarily on product performance, rather than on totality of the system of which the product is a part. **Systems engineering**, for example, involves life cycle engineering, where the cycle includes: determining the need for a product; developing a conceptual preliminary product design; generating a detailed design and development of the product; producing the product; examining how the product is used, improving the product, then phaseout and transition to a new product. The cycle includes maintenance, training, and logistics/customer support – and quality control throughout the cycle.

There is no commonly accepted definition of *systems engineering* in the literature, but various definitions have been proffered:

- "The application of scientific and engineering efforts to (a) transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test, and evaluation; (b) integrate related technical parameters and ensure compatibility of all physical, functional, and program interfaces in a manner that optimizes the total system definition and design; and (3) integrate reliability, maintainability, safety, survivability, human engineering, and other such factors into the total engineering effort to meet cost, schedule, supportability, and technical performance objectives."

- "An interdisciplinary approach encompassing the entire technical effort to evolve and verify an integrated life-cycle balanced set of system, people, product, and process solutions that satisfy customer needs. Systems engineering encompasses (a) the technical efforts related to the development, manufacturing, verification, deployment, operations, support, disposal of, and user training for, system products and processes; (b) the definition and management of the system configuration; (c) the translation of the system definition into work breakdown structures; and (d) development of information for management decision making."

- "An interdisciplinary collaborative approach to derive, evolve, and verify a life-cycle balanced system solution which satisfies customer expectations and meets public acceptability."

In systems engineering, a process is typically designed to satisfy specific project needs. The process is usually represented by one of several process models of the system development life cycle, such as the **waterfall model** and **spiral model**, illustrated in **Figures 1 and 2**. The waterfall model was introduced in 1970 and, like the spiral process model, was used primarily in software development projects. It consists of the steps or phases shown in the figure. The waterfall model was transformed in 1986 into the spiral process model and introduced a risk-driven approach to systems development (where risks are evaluated before proceeding to the next phase). It includes prototypes, where the waterfall model does not. And it emphasizes an iterative approach to systems development, where it proceeds through the several phases each time a different prototype (of a product) is developed.

Systems engineering emphasizes the generation and evaluation of alternative solutions to problems (e.g., alternative technologies or subsystem designs). One approach for accomplish this is outlined as:

- Perform an **environmental scan**, which includes gathering data from a variety of paper, digital, and human sources. In addition to databases, the environmental scan may include surveys of customers or experts.

- One approach to generating inventive **alternative solutions** to technology problems is a method called **TRIZ**, which is an acronym for the Russian words *Teoriya Resheniya Izobretatelskikh Zadatch* (translation: "Theory of the Solution of Inventive Problems"). TRIZ, rapidly gaining adherents in the U.S., is a method for generating creative solutions. There are **five levels of solutions**:

    - ✓ **Level 1:** *Standard* (solutions by methods well-known within specialty);
    - ✓ **Level 2:** *Improvement* (improvement of an existing system, usually with some complication; methods from same industry);
    - ✓ **Level 3:** *Invention Inside Paradigm* (essential improvement of existing system; methods from other fields);
    - ✓ **Level 4:** *Invention Outside Paradigm* (creating new generation of a system; solution not in technology – in science);
    - ✓ **Level 5:** *Discovery* (pioneer invention of essentially new system; usually based on major discovery or new science). TRIZ abstracts the problem and solution sets, leading to a matrix displaying features needing improvement based on a set of parameters (such as weight, speed, complexity, reliability, etc.) and undesirable features. The cells of the matrix contain potential solution pathways based on certain inventive principles (such as segmentation, extraction, asymmetry, combining, universality, nesting, etc.).

WATERFALL PROCESS MODEL

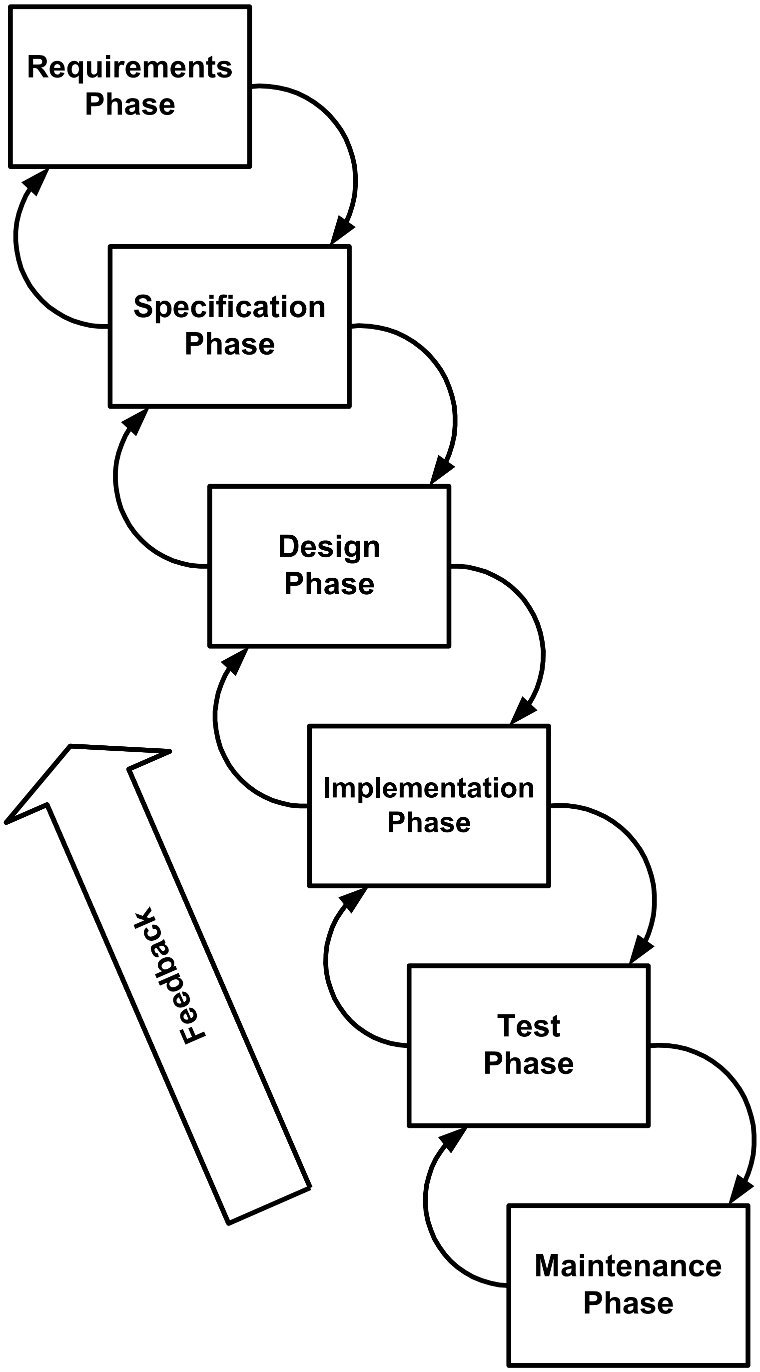


Figure 1: Waterfall Process Model

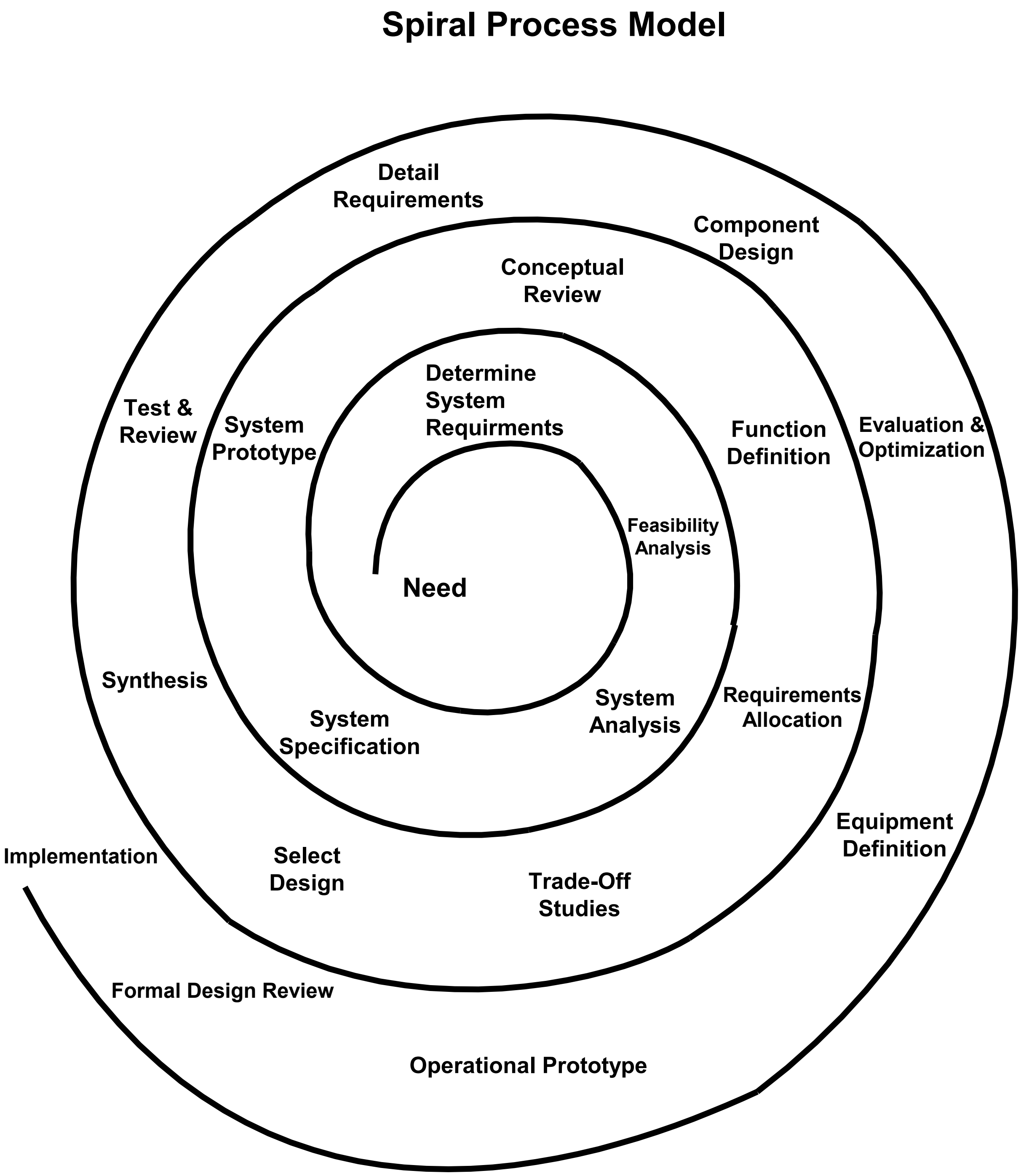


Figure 2: Spiral Process Model

- A system's technology **functional requirements and solution alternatives** can be generated and evaluated using the **Quality Function Deployment** method (QFD). The QFD method is often used for **structured product planning and development**. It specifies the customer's **functional requirements** (*wants* and *needs*) explicitly and with graphic clarity. It compares **requirements**, systematically and graphically, with **prospective technologies**, systems, components, or services able to satisfy the requirements. The QFD process constructs one or more matrices (*quality tables*), the first matrix being the **House of Quality** (HOQ), which represents the voice of the **customer**. As it is often depicted, the HOQ has several sections:

  - ✓ **Section A** contains **functional requirements** (the customer's wants and needs);
  - ✓ **Section B** contains the **relative importance** of the wants and needs (strategic goal setting for new system, product, or service and **rank ordering** of the wants and needs);
  - ✓ **Section C** contains a **high-level description** of the system, product, or service to be developed (as generated by the wants and needs);
  - ✓ **Section D** contains the **weighting** of relationship between each element of technical response and each want or need (functional requirement);
  - ✓ **Section E** contains the **assessments** of interrelationships between elements of technical response to the wants and needs; and
  - ✓ **Section F** contains the rank ordering of **technical responses**, based on rank ordering of customer wants and needs (Section B) and relationships (Section D). A sequence of matrices relates functional requirements, at various levels of detail, to potential solutions ("what vs. how") until the desired final step (such as production or procurement) is reached.

- The **Analytic Hierarchy Process** (AHP) is used to determine the **relative importance** (weights or priorities) of the **functional requirements** and **metrics** within the QFD process (and elsewhere in assessment process). It is used to **evaluate** (score or prioritize) **alternative systems**, subsystems, or technologies. The AHP simplifies decision process through problem structuring, decomposition and pairwise comparisons and can accommodate both **quantitative and subjective** inputs, merge them into single overall measure for ranking alternative choices (the underlying mathematics mostly involves solving for matrix eigenvalues). After defining metrics and submetrics, pairwise comparisons and a numerical scoring system are used to **weight** the metrics and submetrics, then **evaluate** and rank the **alternative technologies** or systems against the weighted metrics and submetrics.

- **Event Tree Modeling** (ETM) is a systematic way to **identify scenarios** which lead to a key event and **assess risks** associated with that event, such as the development and implementation of **alternative technologies**. ETM is often used if successful operation of component or system depends on a **discrete, chronological** set of events. The probability of occurrence of main events of the event tree is determined by using a **fault tree** or its complement - the **success tree.** It identifies various combinations of event successes and failures.

- **Event tree analysis** similar to **fault tree analysis**: both techniques use probabilistic reliability data of individual components and events along each path to compute likelihood of each outcome. But the **reasoning** is different: event trees use **inductive** reasoning, while fault trees use **deductive** reasoning.

- This process ultimately leads to the creation of a **Technology Roadmap**, grading the technologies according to their suitability for the desired application or product as a function of time.

The **benefits** of systems engineering include:

- More efficient (lower cost and time) of system design, development, production, operation, maintenance, and training; i.e., the life cycle cost of systems is lower.
  - ✓ The additional effort required by systems engineering up front is more than compensated by cost saving later in the system's life cycle.

- More effective systems which are better able to satisfy users' needs with better functionality, higher quality, and greater reliability.

- Greater transparency in the decision-making process and better risk mitigation.

Some think that clear distinctions should be made among the concepts of **systems analysis, systems engineering, systems theory,** and **general systems theory**. In this view, **systems analysis** usually taken to mean the study of a single phenomenon in a single discipline by modeling, simulation, or other mathematical method, often to optimize some function. It is undertaken to identify rational decisions about the design, selection, or operation of a system – identifying the most effective system for an application and the most efficient way of operating it. Systems analysis translates functional objectives and requirements into a system (e.g., of people and machines). Systems analysis creates a broad framework of the desired system, determining what can be designed without undertaking the design. **Systems engineering** is concerned with designing a system which incorporates the optimized technology and subsystems.

Systems theory is usually taken to mean the comparison of interpretations of different phenomena, often within a single disciplinary area, using systems concepts. While systems analysis seeks to predict phenomena, systems theory seeks to understand phenomena. **General systems theory**, by comparison, attempts to denote abstract isomorphisms of principles and patterns to explain widely differing phenomena in various disciplines and across many levels of complexity and organization.

In **systems management**, the manager is responsible for ordering and phasing the work of systems analysis and systems engineering, as well as monitoring the way systems analysts interpret the customer's needs, wants, and objectives and the way systems engineers interpret the systems analysts' specifications. The systems manager is also responsible for moving the completed system design from engineering to production; testing the system; developing supporting systems (such as training, documentation, and maintenance); and final use of the system. The systems manager must schedule, control, locate resources, coordinate activities, and push for the continued progress of the system. Systems management differs from other management in that it is typically more multi-disciplined and decentralized.

The search continues for basic principles and the systematic framework applicable to all systems, natural and artificial – the Rosetta stone of interdisciplinary relationships.

Proponents of systems theory have tended to over-hype and over-promise. Some systems approaches, such as *system dynamics*, have had some minimal success in simple cases. And the systems approach seems to work well for developing (some) complex technology. So proponents cling to the faith that a substantial theory will yet emerge from their labors. But reality is complex with many variables, especially for social systems. The efficacy of the systems approach as a practical set of rules and processes seems to be established, at least for some technology systems. But an underlying theory, with a powerful ability to explain and predict, remains elusive.

1.4 Operations Research

Some people confuse **operations research** with **systems analysis**. Operations research (or operational analysis) originated as a discipline during World War II as an approach to solving tactical and strategic military problems, such as optimizing the search for enemy submarines, or developing tactics to counter enemy artillery. It subsequently grew into a discipline encompassing a grab-bag of analytical tools and techniques, some of which pre-dated World War II by decades (such as inventory theory).

Operations research is concerned with research on operations, i.e., it is applied to problems about how to conduct or coordinate the activities in an organization, often involving the optimized allocation of scarce resources. The type of organization is irrelevant – military or civilian, including banks, supermarkets, factories, hospitals, clothing stores, etc. The highly applied nature of operations research became, in the view of some practitioners, too theoretical and impractical. A new discipline was formed, using the same analytical tools, known as management science. The professional society was split in two. After some years, the two societies merged once again into the Institute for Operations Research and Management Science (INFORMS).

Operations research (O.R.) employs a number of mathematical techniques, such probability and statistics, algebra, matrix algebra, and calculus. The analytical tools and techniques used in O.R. include: linear, non-linear, and dynamic programming ("programming" in this case refers to an optimization technique which may or may not be coded in a computer program); network analysis; game theory; queueing theory; inventory theory; Markov processes; modeling and simulation; reliability theory; decision analysis; search, detection, and attack models and analysis; Lanchester's theory of combat; and combat simulation and war gaming.

Some analysts believe that the distinction between systems analysis and operations research is unclear or insignificant, or that systems analysis is an extension of O.R. Others make a distinction based on the kinds of problems solved by the two fields. But both fields employ the same tools and techniques in attempting to find optimum solutions to problems. A useful distinction might be that systems analysis is a more encompassing approach to solving problems (or developing products) than O.R., which often uses the tools and techniques of O.R., among others, to derive solutions. For example, before applying queueing theory or inventory theory for a business, the systemic nature (framework) of the business should be discerned or defined through systems analysis.

2.0 COMPLEX SYSTEMS

2.1 The Nature of Complexity

A dictionary definition of a *complex* system is a system that consists of elaborately interconnected or interwoven parts. Because simple systems are also formed from parts, the notion of complexity stems from the way the parts are interconnected, structurally and behaviorally. Examples of **simple systems** include: a pendulum, an orbiting planet, a shoe, an ice cream cone, and a chair. Examples of **complex systems** include: an ant, a person, a brain, the weather, a rain forest, a desert, an ocean, a government, a family, a corporation, a computer, and the Internet. The key properties or attributes of complex systems include: the type of quantity of the system's elements (subsystems); the type of subsystem interactions and the strength (or importance) of the interactions; the formation and operation of the subsystems and their timescales; the diversity and variability of the subsystems; the nature of the system's environment and its demands on the system; and the activities of the system and its subsystems and their objectives. With **emergent complexity**, it is possible to have simple subsystems which comprise a complex system (e.g., any complex system formed from atoms). With emergent simplicity, it is possible to have a simple system (i.e., where the collective behavior is simple) which has complex subsystems (e.g., the behavior of a planet orbiting a star – the earth has complex subsystems, but its behavior as a collective system orbiting the sun (on a different scale than its subsystems) is simple. Likewise, a corporation's aggregate behavior may be that of a simple system, even if it has a multiplicity of complex subsystems (such as the brain of its lowliest janitor). On a large scale, the complex details within a system may be irrelevant. As always, the observer determines what is relevant.

Complexity depends on **emergent** properties or behavior. All physical systems are based on fundamental quarks and quanta and atoms. The emergent (collective) behavior of a system is not readily understood from the behavior of its parts, but this does not necessarily mean it is not contained in the behavior of its parts. Emergent properties cannot be studied using reductionism (taking the system apart and studying its in isolation), but they can be studied by examining the system's parts in the context of the whole system. For example, human memory cannot be studied by focusing on the behavior of a single neuronal synapse – unless the synapse's behavior is examined in the context of the behavior of many other synapses.

The complexity of a system is determined by the number of its elements, the heterogeneity in its parts, and the richness of the interactions among them. There are two types of complexity: *detail complexity* (where the system has many variables) and *dynamic complexity* (where cause and effect are not close in time and space and obvious interventions do not produce the expected outcomes. Models and simulations are useful in understanding and controlling dynamic complexity, but there are fundamental problems in trying to understand and control detail complexity; the tools are still relatively primitive. However, the biological brain, including the human brain, must deal successfully with detail complexity in order for the organism to survive. The human mind masters detail complexity mostly on the subconscious level.

2.2 Cybernetic Systems

Cybernetics (coined by Norbert Wiener from the Greek "kubernetes," or "steersman,") has been variously defined as:

- The science of communication and control in the animal and the machine
- The science of effective organization
- An experimental epistemology concerned with communication within an observer and between the observer and his environment
- A way of looking at things and as a language for expressing what one sees, especially focused on self-correcting systems
- A field of study generally including information and communications theory, computers and the nervous system, feedback loops, learning and self-reproducing machines, the relation between man and machine, and the impact of intelligent machines on society
- A system of people and machine interactions, designed for a purpose and containing negative feedback
- A means of understanding society through a study of messages and the communications facilities which belong to it; messages between man and machine, between machine and man, between machine and machine
- Away of perceiving the organism or a machine as more than matter and energy – but also as "message" or information

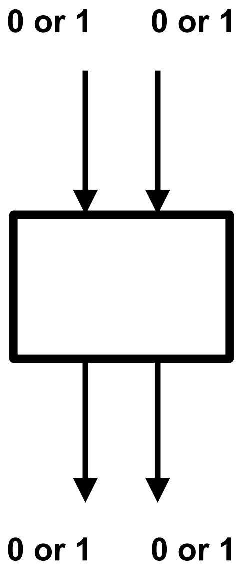
There is a strong relationship between cybernetics, management, and organizations. It has been said that **cybernetics is the science of control**, while **management is the profession of control**. Cybernetically-controlled systems are self-controlling and therefore self-managing. But in order for machine intelligence to serve a basis for providing organizational and socio-cybernetic control, the decision-making and consensus-building machinery in the organization must be redesigned to incorporate cybernetic principles and practices. For example, management by exception has long been used to filter out extraneous information so that managers can exercise control in a timely way. But if cybernetic systems are able to define and recognize exceptions, then nothing need be filtered from the system – only from the immediate decision process. The (seemingly) momentarily extraneous information, may, in fact, be important for the problem under consideration, or for a future problem. With the cybernetic system, the information remains available for retrieval whenever it is needed – and by whoever needs it.

Some of the viewpoints for the cybernetic systems approach to management may be compared with the conventional management view. These viewpoints, or values, are relevant to the design, implementation, and ultimate acceptance of the systems approach, by management.

Conventional Management Viewpoint	**Cybernetic Systems Viewpoint**
Management not suited to scientific approach	Management is suited to scientific approach
Decisions based primarily on institutional traditions and faith or intuition	Decisions based primarily on systems analysis and synthesis
Understanding through authority, tenacity, priority	Understanding through scientific method
Systems are linear and intuitive	Systems are nonlinear and counterintuitive
Sub-optimize total systems by optimizing subsystems	Optimize total systems
Basic assumptions are givens	Basic assumptions are open to question
Stability of systems is static, with no feedback	Stability of systems is dynamic, with feedback required
Specialization is needed to solve problems	Generalization is needed to solve problems
Business operations are uncertain, improbable, and immeasurable	Business operations are uncertain, improbable, but measurable
Deduction is emphasized	Induction is emphasized
Rules and regulations are used to control the system (e.g., the organization)	Metasystems use situational variables to control the system (e.g., the variety of the system is controlled by equivalent variety generated by the metasystem)
Expensive, high-variety systems can be controlled by cheap, low-variety controls	Low-variety controls require a reduction in variety in the system to be controlled
Chaos is more natural than order and must be continually suppressed	Order is more natural than chaos and can emerge from chaos

Ross Ashby and Stafford Beer noted that **variety**, in cybernetics, is the number of distinguishable states of a system (or sometimes the logarithm to the base two of that number; where the unit is the bit (binary digit). The Law of Requisite Variety states that control of a system requires that the variety of the controller be at least as great as the variety of that which is controlled (or, for a system as a whole, output variety must at least equal input variety). As an example of the enormous numbers involved, consider a seemingly simple system with just two inputs and outputs, where each input and output is able have a value of either 1 or 0. This (n-variety) situation generates 2^n input and 2^n output states or patterns (because each possible selection provides two alternative choices, 0 or 1). This system may be an organism or machine system where, for example, there are two sensors to receive input, such as a light sensor which may register light or not (a state of 1 or 0) and an acoustic sensor which may or may not register a sound (a state of 1 or 0). The output consists of two effectors: a feeler which moves or does not move (a state of 1 or 0) and a leg which moves or does not move (a state of 1 or 0). This simple system may be represented graphically by a box with two arrows showing input, each with a potential state of 1 or 0, and two arrows showing output, each also with a potential state of 1 or 0. This is illustrated in **Figure 3**. Thus there are 4 different binary input states: 00, 01, 10, and 11. Like wise, there are 4 different binary output states. This leads to 16 distinguishable states for the 4 input states and one of the output states. Thus, given 4 input states and 4 output states, there are 256 (16 x 16) possible states (for a variety of 256) for the system.

Figure 3: A Simple System Having 256 States



To see why such a large number of states can be generated by a seemingly simple system, consider, for example, the 4 input states and one output pattern (assume 00). The output pattern may or may not be registering a **connection** with any of the 4 input patterns. The lack of a connection between input and output can be indicated by a 0 and the existence of a connection can be indicated by a 1. (There are many kinds of system inputs which may not connect with an output, such as the connection between Jupiter's gravitational field on the rate of inflation in the U.S.). Thus the 16 distinguishable states generated by the 4 input states and the single output state of 00, are exhaustibly listed as:

Input State	**Distinguishable States**				**Output State**
00	0000	0000	1111	1111	00
01	0000	1111	0000	1111	00
10	0011	0011	0101	0011	00
11	0101	0101	0101	0101	00

The total interaction of the input and out put states generates the system's total variety (possible states) of 256:

$$\left(2^{2}\right)^{\left[2^{2}\right]} = 256$$

Even a modest hypothetical firm with, for example, only 300 employees or machines or customers or competitors can quickly generate states with inconceivable variety:

$$\left(2^{300}\right)^{\left[2^{300}\right]} = 3 \times 10^{92}$$

The number 10^{92} is greater than the estimated number of atoms in the universe. For real organizations, variety quickly gets out of hand.

But the design of an organization can represent a reduction in variety. An organization, like all systems, exists partly in the mind of an observer. The organizing process can be made to alter variety by changing the observer's point of view. The organization of a system is specified by the mapping between the states of a system and the parts of the system. Thus *organization* and *mapping* are two ways of looking at the same thing – the organization being noticed by the observer of the actual system, and the mapping by the mathematician representing the behavior of the system in mathematical or other symbolic form.

A system's control system must be able to proliferate variety because *only variety can destroy variety*. Requisite variety is needed to control the complexity of the system one is attempting to control. Living systems can become aware of threats and opportunities in the environment because they readily can detect, in a field of unimaginable variety, the appearance of something which ought not to be there, as well as being able to forecast where that something ought to be - and recognize that it is not there. If a control system (whether a machine or organism) has the ability to forecast, a high-variety decision is replaced by a decision of variety two (e.g., fight or flight). Thus can intelligent systems deal with complexity and survive and prosper.

Consider the conventional traffic light at an intersection. It has a clockwork mechanism which controls the timing and duration of the red and green lights. All day and night, the sequence of lights remains constant. Perhaps it is optimized for rush hour, when Main Street traffic far exceeds that of Maple Street and gets the longest green lights. But between rush hours, the traffic is equalized, and drivers stopped on Maple Street have an inordinate, impatient wait. And late at night, a lone driver at the intersection, with no other vehicles visible as far as the eye can see, may be tempted to break the law and run the red light. The variety of the traffic control system (the clockwork mechanism) is insufficient to control the variety in the system (the vehicular traffic at the intersection). Consequently, variety in the system to be controlled (drivers at the intersection) is reduced in order to control it (i.e., stop at the red light, for as long as it is red, however illogical and regardless of whether or not there is traffic on the cross street, or get an expensive traffic ticket, points on your license, increased insurance rates, and, perhaps, arrest and jail). Thus people are inconvenienced and their freedom reduced. It is control imposed by meat axe.

A traffic control system with greater variety would be a clock with multiple settings, which would adjust the timing and duration of the traffic light based on the time of day. So between rush hours, the duration of the red and green lights can be equalized for both streets at the intersection, and late at night the light can be set for blinking yellow, requiring drivers only to slow momentarily as the pass through an empty intersection. The variety of the traffic control system has increased and drivers are not as inconvenienced. But it is still short of sufficient variety. It does not account for days which are holidays, or special circumstances, such as higher traffic on one of the streets between rush hours because of a baseball game.

A higher variety traffic control system would be cybernetic, with sensors to detect the actual traffic – and traffic queued waiting for the light on Main and Maple Streets – 24 hours a day. Using queueing theory, the intersection could be optimized, for example, to minimize the total waiting time of drivers at the intersection (or to minimize the length of the queue on Main Street to avoid interfering with shoppers, or some other objective function). The variety of the traffic control system has been further increased by introducing sensors, processors, negative feedback, and an ability to optimize for various criteria. But it is still short of having full requisite variety. This is because control has been optimized for a system defined as the traffic at the intersection of Main and Maple. This may not be the appropriate definition of the system. If the definition of the system is actually *all* of the traffic at *all* of the intersections in downtown Smallville, then the system defined as an intersection is actually a subsystem. It is a system rule that optimizing a subsystem generally sub-optimizes the system. Thus if traffic flow is optimized at Main and Maple, it may jam up a block beyond at Main and Oak Streets. A higher variety system would include intelligent controls over all of the intersections.

But a citywide traffic control system may still lack requisite variety. With all traffic signals optimized across the entire city, there is still only so much physical space available for cars and trucks. Gridlock is still possible. The system may then be re-defined to be the movement of goods and people, and a higher-variety traffic control system may be one that includes provisions for public transit, telecommuting, dynamic signage, traffic information dissemination via TV, radio, and internet, and HOV lanes – in addition to sensor-based traffic signals.

The era of the corporate enterprise stamping out a single product or service suitable for everyone (one size fits all) is coming to a close. It is possible now, for example, to order a computer over the Internet or phone with every component customized for each customer. Soon it will be possible to do the same with clothing, furniture, and all manner of goods and services. Advances in cybernetic technology, especially robotics and machine intelligence, will allow organizations to provide individuals with customized goods and service at mass production efficiency and prices. The age of mass customization is arriving.

But organizations, and society at large, continue the attempt to control high-variety systems with control systems of insufficient variety. Instead of increasing the variety of the control system (albeit, a difficult problem), management or government instead reduces the variety of the system to be controlled – often with crude techniques (rules, threats, laws, and penalties) leading to inconvenient or inhumane results and reducing the freedom of stakeholders and citizens. Reducing variety is no different than reducing freedom and liberty.

2.3 Intelligent Systems

The organization might be designed as an intelligent system, but it is not entirely clear what intelligence is or how it is to be measured. There are many definitions of intelligence, but there is no accepted, purely objective, definition of intelligence for humans, organisms, machines, or organizations. Nevertheless, we offer a definition that, while somewhat subjective, seems useful:

Intelligence is the ability of a system (i.e., organism or machine) to make an *appropriate* choice (or decision). That which is "appropriate" depends on the system's purpose or function. And the intelligence need not be at the human level of cognition. Bacteria, snails, ants, sharks, crows, and dogs – and all organisms that survive the rigors of evolution – exhibit "appropriate" intelligence.

Various kinds of intelligence may also be defined. For example:

- **Reactive intelligence,** or **adaptation,** is based on an autonomic sense-act modality, and it is the ability to make an appropriate choice in response to an immediate environmental stimulus (i.e., a threat or opportunity). **Example:** It is raining and I am getting wet, so I seek shelter.

- **Predictive intelligence**, or **learning**, is based on **memory** and it is the ability to make an appropriate choice for events that have not yet occurred but which are based on prior events. **Example:** It is very cloudy and thus it will likely rain soon, so I should start to seek shelter before it rains.

- **Creative intelligence**, or **invention**, is based on learning and the ability to cognitively **model and simulate** and it is the ability to make appropriate choices about events which have **not yet been experienced. Example:** It takes too much time and energy to seek shelter every time it rains or threatens to rain, so I invent the umbrella. I can imagine that the umbrella, which never before existed, will protect me from the rain.

Humans consider themselves intelligent, a consequence of the brain which is, perhaps, the most complex known single structure. The average brain weighs about 1,350 gm (3 lbs) with the heaviest known brain at 2050 gm (4.5 lbs); it is about the size of a grapefruit. The human brain is composed of 100 billion cells, and there are 10 billion active neurons of 100 different types. A typical neuron has a body diameter of .01 cm (.004 in) and a length of up to a meter or more (several feet). The brain operates with a power of 10 watts, and can transmit information with a speed of 9 to 108 m/sec (30-360 ft/sec). Each human neuron is connected with as many as 10,000 others in a switchable network, providing about 10^{15} neuronal connections. The variety (number of distinguishable states) in the brain, based on raising the motor subsystem variety to the power of the sensor subsystem variety, is an unimaginably large number, expressed exponentially as:

$$\left[2^{10^{6}}\right]^{\left(2^{10^{7}}\right)}$$

Even small numbers of neurons as found in insect brains (perhaps a hundred thousand to a million in an ant brain), are capable of generating intelligence (or appropriate behavior) such that their possessors can survive and prosper for hundreds of millions of years. These tiny brains are sufficient to process a variety of sensor information and generate many kinds of appropriate behaviors. (Ants appear to make decisions and lay plans, individually and for the colony as a whole, without command centers. The sharing of information and food throughout the colony means that each individual ant out of millions knows at each moment, more or less, the state of the colony. Individual decisions become similar and harmonious mass action can take place.

The mind, emerging from the processes of the brain, is what the brain does. The mind is no longer considered an epiphenomenon (a phenomenon occurring in association with, but not caused by, a set of events) of the brain. There are a multitude of models of the mind, from the Freudian to the cybernetic, to the mind as an information processing system which may be duplicated in machines.

A system which is complex in *space* has many parts with high connectivity. A system which is complex in *time* has successive states which are highly varied and dependent on previous states in intricate and lawful ways. A human brain is complex in both space and time, while today's computers are complex only in time. Complexity in time can lead to behavior perceived by humans as intelligent - a thought, in one view, is a temporal sequence of spatially ordered events in the brain.

The origin of consciousness (or at least the perception of being conscious) remains a mystery. It may be an emergent phenomenon of a complex intelligent system, in which case intelligent machines may become conscious. Even if a conscious machine brain were to be designed, there remains the epistemological problem of other minds, of determining whether something other than oneself – an alien organism, a robot, or even another human – is really a conscious being rather than an unconscious automaton whose behavior replicates consciousness while arising from other mechanisms. In the behaviorist view, if a machine behaves as if it is conscious, then it is by definition.

Intelligence is a mechanism of survival, and all measures of intelligence (whether for organism, man, machine, or organization) involve an ability to make appropriate choices or decisions. The subjective word "appropriate," in relating intelligence to "appropriate" choice, implies that a system can be intelligent only in relation to the system’s purpose, function, goal, or environment. Intelligence provides an ability to cope with the unexpected and an ability to bring about the unexpected. It requires an ability to use information (where information, in one definition, is that which reduces uncertainty).

In one view, attributes of systems having higher (human-like) intelligence include:

- Mental attitude (beliefs, intentions, desires)
- Learning (ability to acquire new knowledge)
- Problem solving
- Understanding (implications of knowledge)
- Planning and predicting consequences of actions, comparing alternative actions
- Knowing one's limits of knowledge and abilities (meta-knowledge)
- Drawing distinctions between similar situations
- Synthesizing new concepts and ideas, acquiring and employing analogies, originality
- Generalizing
- Perceiving and modeling the external world
- Understanding and using language and symbolic tools

Some hold that the last attribute above – language – is the main determinant of intelligence; that every representation of knowledge is primarily an interpretation, not decision-making or expertise (the field of *hermeneutics* is the study of the methodological principles of interpretation). Symbolic manipulation (i.e., communication) creates second order reality; an advanced, intelligent system must be able to perceive second order reality (the meaning and values attributed to first order reality) as well as first order reality (the reality accessible to perceptual consensus, physical reality).

An intelligent machine can be built which "understands" human emotions without possessing emotion itself. That is, the system can have a model of human emotion and understand human motivation and behavior stemming from emotion without becoming emotional itself. While it may also be possible to design a machine that behaves emotionally, it is not clear that this would be desirable or useful. It would be useful, however, for an organizational control system to "understand" human emotion and motivation.

An intelligent system should possess meta-knowledge, i.e., it should have knowledge about what it knows without having to search exhaustively. For example, the system should know whether it has knowledge about France if it were asked to list the kings of France. While knowledge includes representations of facts, generalizations, and concepts, organized for future use. The use of knowledge is a form of cognition, so that all living organisms, in a sense, are engaged in cognitive processes.

A self-conscious system could become so through self-observation, an ability to describe itself, and, through interaction with its descriptions, an ability to describe itself describing itself, etc. In one view, a system is behaving as if it were conscious if it:

- Receives information about its environment
- Recalls and compares past experiences
- Evaluates the quality of its experiences
- Makes conceptual models of its environment
- Projects consequences of alternative future actions
- Chooses and implements actions which further its goals

A generic architecture for an intelligent system is shown in **Figure 4**.

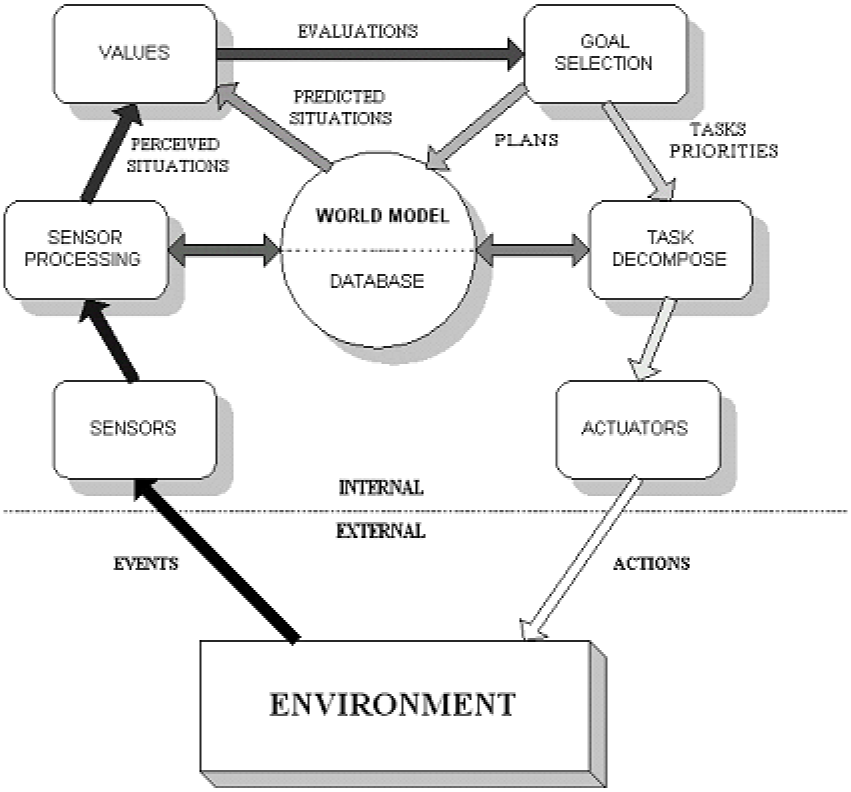


Figure 4: A Generic Intelligent System

As shown in the figure, the environment acts upon sensors in the intelligent system. The sensor data is processed into usable information and perceptions, which are then entered into a database and world model (which contains objects, entities, features, relationships, etc.). The perceived situation is compared with what was expected (predicted) by the world model and evaluated to determine the impact on the systems goals. If the situation causes the goals to change, the plans leading to the goal must also be changed. The plan to accomplish the goal is decomposed into simpler tasks, which ultimately leads to actuators (effectors) acting upon the environment. This process operates in any intelligent system, including ants, rats, people, and robots.

2.4 The Organization as a Complex, Intelligent System

Human organizations, being social systems, are inherently complex. They are ongoing, circular, systematic processes based on feedback processes and exhibit growth, differentiation, hierarchical order, control, and competition.

Most organizations are bad, in the sense of their adverse affect on people as well as their inability to function as intended. The criteria for a good organization must be defined explicitly for each case. There is no "good organization" in an absolute sense in that an organization may be good in one context and bad in another. The systems approach offers alternatives to conventional organizational structures and processes, and it provides another perspective of organizational problems.

The basic questions for any organization are: What is the organization supposed to do? What does it actually do? How does it do it? How should it do it?

Traditionally, a basic organization was defined as two or more people working together toward a common goal. In a trivial sense, an organization can be quite transitory, such as friends gathered for a barbecue. A more detailed definition sees the organization as the rational coordination of the activities of a number of people for the achievement of some common explicit purpose or goal, through division of labor and function, and through a hierarchy of authority and responsibility. In organizations with a pyramidal structure, which is the case for most current organizations, a small number of people at the top can control a large number of people below. The range of decisions at each level is defined and limited. Bureaucracy is effective and efficient in large organizations because the hierarchy facilitates coordination to carry out complex tasks. Also, the decomposition of tasks allows complex decisions to be made which are beyond the competence of any single individual. For some organizations, including corporations and terrorist groups, pyramidal structures are replaced by networks, which are loose, amorphic, and decentralized structures, with a manager's function being primarily to provide coordination and support rather than issuing commands and exercising authority and power.

Another model for an organizational structure alternative to the conventional hierarchy is the *democratic hierarchy*. In this systemic structure there are a multiplicity of management boards, where each manager has an associated management board which consists of the manager, the manager's immediate superior, and the manager's immediate subordinates. Thus a middle manager could serve on three boards. This structure provides some democracy to the hierarchy by allowing subordinates to have some control over their managers. Whether with boards or other entities, cybernetic insights suggest that the totality of the organization ought to be made up of groups that are quasi-independent domains, which are domains which are functionally between independent domains (decentralization) and no domains (centralization).

The organization is (or should be) an intelligent system – the *intelligent organization*. An intelligent organizational design has the potential for improving the productivity of all types of organizations, whether factories, banks, hospitals, or the knowledge-worker service sector of the national economy.

Organizations have always been intelligent to the extent that their individual human members are intelligent and perform appropriately, while the organizational design and processes allow subgroups and the organization as a whole to perform efficiently and effectively. But the conventional organization has not been designed explicitly as an intelligent system; it can lapse readily into inappropriate behavior. One concept of the intelligent organization is: *an organization that is designed explicitly as an intelligent system, where in carrying out the functions, goals, and objectives of the organization, autonomous machine processes assist or replace human thought and activity, such that the organization behaves intelligently (i.e., makes appropriate decisions and performs effectively and efficiently)*. Autonomous machines (or supervised autonomous machines) would permeate the intelligent organization at all levels in a hierarchy, or among all sub-units in a non-hierarchy. An intelligent organization would establish cognitive goals and programs and encourage purposive adaptation relevant to its goals.

In one view, an intelligent organization would be more democratic and egalitarian, permitting and valuing intelligent behavior from all members of the organization, not just those at the top of a bureaucratic pyramid. Businesses, nonprofits, and government agencies can become more productive and ready for the future through new organizational principles and architecture which allow their members to better express their collective intelligence and judgment, enhancing flexibility and innovation, and increasing the tiny fraction of individual human potential which is ordinarily used. The intelligent organization would allow its knowledge workers to apply their intelligence in a free, yet coordinated, way. With machines doing most of the routine work, workers will be able to concentrate on tasks requiring initiative, innovation, and flexibility.

The building blocks for intelligent organizations are becoming available, but there is not yet a framework, or a paradigm, in which to connect the elements and examine the potential consequences of such a system. The learning organization will require metanoia (in Senge's phrase) – a shift of mind. It will also require controlling structures for the members of the organization to generate new patterns of behavior. The computer-based technology of the learning organization will permit the integration of complex team interactions and complex business interactions.

Mechanistic Vs. Organic Organizations

The basic dichotomy in organizational frameworks is between the mechanistic (bureaucratic-like) and organic forms. In the **mechanistic** structure:

- Decomposition of tasks by specialization and individual roles are clearly defined and controlled by higher levels;
- Communication mostly flows down the hierarchy and is tightly controlled;
- Efficiency (doing things right) is emphasized over effectiveness (doing the right things);
- Knowledge concentrates toward the top of the hierarchy, and expertise of internal systems is more valued than cosmopolitan expertise;
- Strong emphasis on loyalty and obedience.

In the **organic** framework:

- Tasks are situationally defined - individuals have broad, imprecisely defined responsibilities in a structure that is more a layered network than a rigid hierarchy;
- Communication is occurs more laterally than vertically, involving consultation and advice;
- Effectiveness is emphasized over efficiency;
- Special knowledge and expertise is presumed to reside throughout the organization, and cosmopolitan expertise is more valued than internal expertise;

- Commitment to the organization's goals is more valued than loyalty and obedience.

Neither mechanistic nor organic systems are suitable for all organizations and conditions. The mechanistic is generally better (more efficient) under stable technology and markets. The organic is better when technology is changing rapidly and markets are unpredictable. Most organizations today fall along a continuum between the mechanistic-organic endpoints, and shift along a continuum over time. However, with exponential change becoming the norm for technology and markets, the organic form should predominate in the future. The pyramidal hierarchy is giving way to self-organizing systems. It is possible that a real-time control system can serve as a tool which, hierarchic itself, can reduce the need for a human authority hierarchy by decentralizing decision-making, responsibility, and authority.

Order vs. Chaos in Organizations

In organizations, as in other systems, order is more natural than chaos. Order is something systematic, a pattern. Patterns have no objective existence – they are perceived by an observer whose brain has imposed a structure on reality. In one view, management is the restoring of natural order to a system which has been disturbed, and which is trying to regain its equilibrium ... the cybernetic managerial structure as the focus of the natural order; a structure that flows to fit the changing “response surface” of the situation; a structure that is integral with the system and exemplifies its natural orderliness. An organization does not continuously threaten to lapse into a canonical state of chaos if it were not for the vigilance of the manager (chaos-order-chaos sequence), as in the typical entropic view. Rather, the organization’s canonical state is one of order; the manager helps restore order to a disturbed organization (an order-chaos-order sequence). Order and organization can even arise spontaneously out of disorder and chaos through a process of self-organization.

When systems are far from equilibrium, nonlinear relationships prevail and small inputs can yield large outputs; and the system (including an organization) may reorganize itself. All systems contain subsystems which are continuously changing states. As a result of positive feedback, a subsystem, or group of subsystems, might change so drastically that the existing organization is shattered and either disintegrates into chaos or becomes a more differentiated, higher-order organization.

Homeostasis, Heterostasis, and Adaptation

Feedback, an essential criterion of a cybernetic system, is also essential for organizational control. It is a method of controlling a system by reinserting into it the results of past performance; i.e., information about the results of a process which is used to change the process itself. Negative feedback reduces the error or deviation from a goals state. Thus negative feedback encourages the forces of growth (for good or ill).

A complex system, such as an organization, may have many component feedback subsystems for subordinate purposes, i.e., a hierarchy of feedback structures where the broadest purpose of interest determines the scope of the pertinent system. The feedback loop from the environment (or another system), which provides the system with reward or punishment in response to the system's behavior, is known as the *algedonic loop*. The algedonic (pain-pleasure) loop provides a means for two systems, which do not speak each other's language, to communicate with each other (such as a person with a machine or animal). An output pattern is made to associate with an input pattern, and convergence to a desired goal can be achieved by reinforcing the desired output for a given input. Reward or punishment, in a generic sense, can serve as a broad means of communications with a person, animal, or machine; algedonic loops are suited for simple adaptive neural networks. A system can be made to adapt to its environment through the algedonic loop. The ability to adapt is a fundamental measure of whether an organization (or any system) is intelligent.

Adaptation, in general, is a form of behavior which maintains a system's essential variables within physiological limits. An adaptive system modifies its internal structure as a function of experience such that, over a period of time, the systems behavior tends to become more appropriate relative to some criterion. This behavior or process of self-regulation is known a *homeostasis*. A homeostatic system attempts to continue functioning even when confronted by unexpected disturbances. In homeostasis, a system's essential variables have achieved steady state values compatible with the system's ability to function (where essential variables may be defined as those “closely related to survival and which are closely linked dynamically.”

A result of homeostasis is the tendency of complex systems, including, organizations, to run towards an equilibrial state. This happens because many parts of the complex system absorb each other's capacity to disrupt the whole. However, the ultimate equilibrial state, where entropy is maximized, is death. A dynamic, or moveable, equilibrium is needed by the system to adjust to continuous change and to avoid this ultimate stable state. So adaptation involves the ability of a system to move its stable state in response to environmental change. Although a homeostatic system moves its stable point when confronted with a shock, it takes a finite time to re-establish the stable point. If, in an organization, the relaxation time is longer than the time between the shocks, either violent oscillation or the terminal equilibrium of death ensues. It is necessary to make the relaxation time, or the response time, shorter than the time between the shocks, as well as providing the appropriate responses to the shocks. An intelligent organization should have this ability.

Homeostasis is a primary goal of all animal behavior, but a contrary view of homeostasis is that the primary goal of animals, including man, is the achievement of a maximal condition, not the achievement of a steady state condition. Animals are not homeostats; they are heterostats (a heterostat is defined to be a system that seeks a maximal condition - the condition itself will be termed heterostasis). In animals, the variable being maximized is neuronal polarization, which is equal to the amount of depolarization (pleasure) minus the amount of hyperpolarization (pain). In this view, the heterostatic nature of animals derives from the heterostatic nature of neurons. In psychological terms, neurons are hedonists and thus living systems they control are hedonists. Nervous systems are so structured that homeostasis is a necessary (but not sufficient) condition for the maintenance of heterostasis. This explains why organisms vigorously pursue homeostasis even while it is not their primary goal. If homeostasis is a subgoal, survival may not be a central concern of living systems as is usually assumed. In this view, survival is a consequence - a side benefit - of seeking pleasures such as food, drink, sex, warmth, etc. Evolution has established equivalence between survival value and sources of pleasure. It is a need for stimulation, not an abstract need to "understand," that drives humans to explore.

Work on adaptive neural networks, dating from the 1950's, focused on the top down rather than the bottom up. The process was always to contemplate the system goals, and then examine the network structure and mechanisms to achieve the goals. For a heterostatic system, the process is the opposite, where a goal is examined for the individual network elements and the behavior of the total system is analyzed in terms of the elemental goal. While both approaches could be equivalent, the perspectives are different. The heterostatic view is that the individual network elements are goal seeking systems. This view relates well to the organization as a system, where the individuals or subgroups are goal-seeking systems.

Complex forms of human behavior arise from the combinations of billions of interacting neurons and the complexity of their environments. Neurons, nervous systems, and organizations are heterostats, and while negative and positive feedback is essential to life's processes, it is positive feedback which dominates and provides the "spark of life." In the case of positive feedback (for example, excitation delivered to a neuron) not only does the input enhance the output, but also the input enhances the effectiveness of recently active positive feedback loops. In the case of negative feedback (for example, inhibition delivered to a neuron), not only does the input diminish the output, but also the input enhances the effectiveness of recently active inhibitory feedback loops. In this way, the heterostat not only accomplishes short-term modification in its behavior, but it also accomplishes long-term modifications, thus encoding causal relations and providing a basis for intelligence. The implications for organizational control are the use of positive feedback to enhance the process by which the positive feedback is provided to the organization.

However, some organizations are almost *open systems* in which outputs are isolated from, and have no influence on, inputs. Such open systems are not aware of their own performance – and past action does not control future action.

Self-Organizing Systems

Given the appropriate goals (i.e., to achieve stable equilibrium states), an organization would ideally be **self-organizing**. A self-organizing system organizes itself as it moves toward its stable equilibrial states. In one view, every isolated, determinate, dynamic system obeying unchanging laws is self-organizing. As a system moves from any state to an equilibrial state, it is essentially "rejecting" alternative states and "selecting" a certain state. Such a system, whether it is an organism, machine, or organization, is self-organizing. Self-organization is a characteristic of complex systems, such as organizations of people. One way of looking at self-organization is as non-interacting parts become interacting; there is new mapping between a system's parts and its states, including an ability to achieve new states. The self-organizing system changes its basic structure as a function of its experience and environment. The self-organizing system is an entity or subsystem (such as an organism or organization) coupled with its environment – they organize themselves together.

Therefore, strictly speaking, a system (such as a machine or organization) cannot itself be self-organizing. It appears to be self-organizing when coupled to another system (a meta-system) so that the original system is self-organizing as a subsystem of the new whole. But a system can be **self-authorizing**.

A self-authorizing system (or subsystem) can take self-initiated action on behalf of a larger system. It needs an internal model consisting of:

- A model of the system in which it is embedded;
- A goal-model with the desired final states (i.e., the larger system as it should be);
- A model of the transformation process to change the states of the larger system;
- A model of itself (the self-authorizing system), including a model of its current abilities, desired abilities, and transformation (so that it may alter its own abilities or states as well as those of the larger system);
- A model of the interactions between itself and the larger system, representing the range of actions and consequences;
- Dynamic constraints and timelines for actions, events, and results

Stability and Ultrastability

Research indicates that complex, dynamic systems remain stable until connectivity among its elements reaches a critical level and the system becomes suddenly unstable. Ultrastable systems, however, can resume a steady state after being disturbed in a way not foreseen by its designer. An ultrastable system has a double feedback loop between a regulator and environment, and between essential variables and the regulator. Regulatory functions are step functions, and they change values only when essential variables exceed their limits, thereby causing the system to alter its behavior in reaction to the environment. Sensory information, in a first feedback loop, causes an examination in a second feedback loop of the essential variables to determine whether they are within their critical boundaries. Variables which exceed their physiological (or survival) limits can cause new reactive behavior through the changes in step functions. Even though a system's (organization's) behavior is deterministic because it is state-determined, a large number of step function combinations and states can mean that the behavior is unpredictable in practice (which provides at least an illusion of free will). So stable systems can change the values of critical variables, while ultrastable systems can change the relationships among critical variables, or even define new critical variables.

Thus the first feedback loop provides stability to a system by reacting to frequent, small changes in the environment, while the second feedback loop provides ultrastability by reacting to infrequent, large changes in the environment. An organizational control system must be able to react and cause the organization to adapt to unexpected perturbations in its environment.

Organizational Problems and Counterintuitive Solutions

Organizations, and other social systems, are inherently insensitive to most policy changes that people select in an effort to alter the behavior of the system. For example, problems may be produced by feedback-loop dynamics of a larger system in which the smaller system is embedded as a subsystem. Social systems have a few sensitive influence points through which the behavior of the system can be changed. Sensitive points are not easily found, and attempting to control the system's behavior through them, by intuition, usually drives the system in the wrong direction. In social systems, there is usually a fundamental conflict between the short-term and long-term consequences of a policy change. Policies which cause improvement in the short run (which is visible and compels immediate action) often degrade the system in the long run.

An organization may have major problems which are known in and out of the organization. Decision-makers may know the problems, power structure, traditions of the organization, their own personal goals and welfare, and they can rationalize their policies and plans to solve the problems. Yet implementation of the policies can make the problems worse because of the counterintuitive nature of social problems. Greater efforts to solve a problem often make it worse. Organizational models, embedded in the organizational control system, can reveal counterintuitive solutions to organizational problems.

An intelligent organizational control system must be able to: identify problems (threats and opportunities) and relationships among problems, plan, evaluate decisions, make decisions, implement and control decisions and plans, compare results with expected results, and obtain sufficient information to accomplish these tasks. An organizational control system should:

- Predict decision outcomes using performance measures;
- Obtain information on actual performance;
- Compare actual with predicted performance;
- If the decision is deficient, correct the process for arriving at decisions and ameliorate the current consequences of the poor decision.

An organizational control system could be designed to facilitate interactive planning, including: participation by all members of the organization; coordination (simultaneous and interdependent) among organizational subunits; integration of each level's planning with planning at other levels; revision of old plans continuously as needed. The interactive planning process should include:

- Ends planning (what is wanted - goals, objectives, and ideals for short run, intermediate, and ultimate ends);
- Means planning (how to get there - causes of action, practices, programs and policies);
- Resource planning (types and amounts of resources - people, machines, money - and their allocation);
- Organizational planning (required organizational structures and processes);
- Implementation and control planning (how to implement decisions, control processes, alternatives plan).

Heuristics and Negative Heuristics

An organizational control system should have a **heuristic structure** in which its internal parameters can be changed when necessary through feedback. (A heuristic is also an aid to discovery, a rule of thumb, unproved or incapable of proof. It is a method of problem solving in which solutions are discovered by evaluation of the progress made toward the final solution. Heuristics are needed for the partial specification of goals because they can cope with proliferating variety.

In comparison, an **algorithm** is a specific rule, procedure, or technique for reaching a fully-specified goal or solving a problem. In one view, we tend to live our lives by heuristics, and try to control them by algorithms. Nature uses algorithms to specify heuristics, and that is how natural systems control unimaginable variety. For example, genetic material (DNA) is algorithmic, but organism structural development and behavior is mostly heuristic. Even a simple one-celled organism behaves according to the heuristic “move toward the light,” as opposed to having an algorithm specifying an exact path of motion and sequence of movements. Heuristics can organize a system to learn, to vary control strategies, to cause a system to evolve. A hierarchy of heuristic control is needed to guide the learning (through meta-rules or goals) of lower-order systems. The top of the hierarchy is reached when the ultimate criterion - survival - is achieved. Heuristic programming can lead to computers which are more intelligent than the programmer. (Neural networks use algorithms to specify heuristics).

Because it is easier to prevent a system from being stupid than making it smart, the organizational control system should also employ “negative heuristics.” Control knowledge in the form of negative heuristics (telling the system what not to do) to complement positive heuristics can prevent actions which do not contribute to achieving the system's goals. A few negative guidelines can eliminate a large number of inappropriate system states, plans, and actions.

With a cybernetic approach, knowledge about structures can be replaced to some extent by knowledge about function, about the behavior of a system (with dimly perceived subsystems) over an abstract set of states. But despite the apparent usefulness of cybernetics for organizational control, it has not had sufficient testing in real-world organizations and applications as yet.

One neurophysiological model of the organization, proposed by Stafford Beer, includes:

- **System One**, which contains highly autonomous operational divisions of the organization;
- **System Two**, a meta system which subsumes all Systems One and keeps the entire organization from oscillating wildly in response to the environment (and may be disbursed among several organizational elements);
- **System Three**, which allocates resources to System One, monitors output, coordinates among Systems One, Two, and Three, and governs the stability of the internal environment of the organization by absorbing the variety of System One (and it is the highest level of autonomic management);
- **System Four**, which primarily interfaces with the environment and contains the model of the organization (and may be a distributed, informal system);

- **System Five**, which controls the entire organization, interacting primarily with System Four and Three).

Intelligent organizational control systems can take many forms as long as they satisfy the functional requirements and constraints associated with complex, cybernetic systems, just as the brains of organisms can take many forms as long as they satisfy the requirements and constraints of (Earth) biology.

Organizational Applications

In an expansion of our previous definition of intelligence as the ability to make appropriate decisions, an intelligent organization may be defined as “an enterprise that establishes cognitive goals and programs, and encourages the collaborative and purposive adaptation, shaping, and selection of contexts relevant to its goals and competencies.”

The organization can become intelligent through the emergent behavior of its people and machines. (Emergent behavior may be manifested by the repetitive application of seemingly simple rules that lead to complex overall behavior.) The emergent behavior can be that of an ant and ant colony, or a person and an organization. Collective intelligence in insect societies, especially for certain of the ants, bees, and termites, is reasonably understood. Higher forms of intelligence arise from the synchronized interaction of simpler units of intelligence. This is true as well of “higher” forms of life, such as dolphins, wolves, apes, and humans. Social intelligence allows an individual organism to “analyze and respond correctly (intelligently) to possible behavioral responses of other members of the group.”

Collective intelligence is an advanced form of intelligence, a group intelligence in which individuals submerge their individual identity to the group's responses to the threats and opportunities in the environment. Communication among individuals is essential for collective intelligence, whether by pheromone, vision, sound, touch, or email. Information technology is now affecting the collective intelligence and evolution of the human species, possible leading to the emergence of a global intelligence, a system of individual and collective humans and machines. The further development (or enhanced “IQ”) of the collective intelligence of the organization (which has always existed at some level of intelligence) can be achieved well before the advent of the global brain.

Intelligent organizations would be flexible and adaptable not because they employ extra people, but because the people they employ would be able to switch jobs as demand for different tasks shifts. Architectures of intelligent organizations will be flexible, able to adapt to changing demands in the environment. Teams would be the basic building block of organizational intelligence, along with a requirement for the free flow of information. Individuals and teams would freely interconnect like nerve cells. Organizational structure would be a result of local adaptations, rather than conscious design of the human members of the organization.

In the intelligent organization, the power to decide and act would be distributed in netcentric configurations. As more information within an organization becomes available, newer and flatter management structures become possible. Organizations are no longer forced to choose between centralization, for tighter control, and decentralization, for faster decision making. Tightly coupled, real-time, communications links, sensors, databases, and computer decision aides make it possible to have centralized control with decentralized decision making.

In the intelligent organization, process teams will tend to replace functional departments, and employees will become more empowered as the organizational structure flattens. It is the organizational structure that establishes the line of communication within the organization and determines the decision making hierarchy.

In the **intelligent organization**:

- Shared databases will distribute widely information that otherwise would have had limited distribution;
- Expert systems will allow generalists to do the work of experts;
- Telecommunications networks will allow the organization to enjoy the simultaneous benefits of centralization and decentralization;
- Decision support tools, such as database access and modeling software, will allow all workers to make decisions, not just managers;
- High performance computing will allow organizational plans to be revised almost instantly instead of quarterly or yearly.

We were thrust from the forests in fairly recent history, carrying in our heads a brain composed of many parts accreted over the eons through Darwinian evolution. The Darwinian brain must now deal with social institutions, technologies, and values which are evolving with exponential, Lamarckian-type change. Without genetic engineering (which is a result of conscious evolution), our biological evolution is, for all practical purposes, at its end. Evolution is now in our hands.

The essence of intelligent behavior is control, and without the assistance of intelligent machines to help us with the flood of information and the complexity of problems, we stand a good chance of losing what tenuous control we still have over our organizations and institutions.
The tools of systems analysis can help us in this quintessential quest for control.