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Advances in Systems Science

> *In everything that relates to science, I am a whole*
> *Encyclopaedia behind the rest of the world*
>
> Charles Lamb, 1775–1834,
> *The Old and the New Schoolmaster*

System Theory, System Science

Systems science was recognized from the 1960s, and has been described both as the science of complex systems and as the science of wholes; that is, the science of how wholes form, how they stabilize, how they behave, how they function, how they are structured, how they remain viable, how they decay, fall apart, reconfigure, become moribund, etc.

Systems theory and science address self-organizing systems, autopoietic (self-reproducing) systems, multi-agent systems, closed and open systems, feedback systems, and many more. Systems science investigates how systems behave as a whole, without necessarily having to explain behavior in reductionist terms, e.g., by basing it on the behavior of the rationally separable parts.

Bak and Chen's sandpile experiment (described in Chapter 1) typifies the issue. If the sandpile is regarded, using a physical model, as a pile of tiny spheres placed upon each other to form a cone, then the weakly chaotic, dynamic behavior of the whole will not be observed in such a static model. If the human brain is regarded as an accumulation of neurons, then no basis for the emergence of intelligence and self-awareness will be evident in the model. If the army of soldier ants is regarded as an accumulation of ants, then no basis for the rich behavior of the whole (army) may be detected.

It may be possible to find explanations for whole system behavior at the level of the constituent parts. Weak chaos is exhibited in situations where a flow or stream in a channel is inhibited, such that there is a build-up of particles/force elements into a line or queue, which then releases, only for another build-up to accumulate. This offers an explanation for earthquakes where two tectonic plates rub past each other; snags occur, building up tensions and increasing forces until the snag eventually gives way, with the resulting earthquake, tremors and release of tension. Some snags 'rub off;' for others, there is a greater build-up of tension, and occasionally there is a major snag, and a major earthquake as the snag releases, the plates start to slide relative to each other, and perhaps grate roughly together, giving aftershocks.

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Similarly, when electrons flow in a conductor, some electrons can become impeded by the ions forming the metal lattice structure of the conductor. Temporary queues of electrons can build up behind an ion, only to release and flow on. This gives rise to noise in the conductor; the so-called $1/f$ noise to indicate that noise amplitude varies inversely with frequency.

Entering a school just as the signal is given for the children to go home is analogous to the electrons in the conductor. Children rush towards the exit, heads down or looking and chatting sideways, until one of them find the path blocked by an adult going in the opposite direction. The child cannot proceed as there are children streaming homewards to left and right. Another child finds their way blocked by the first child, and so on, until the mini-queue of children builds and disperses into the streams to either side; and, the process repeats.

It is possible, too, to find explanations at the level of the individual of how a flock of starlings returning from a city center to roost can present such dazzling displays of coordinated behavior: they swoop, wheel, change shape, divide, re-form, yet all the time behave like a single organism before diving unexpectedly into the darkness beneath to their covert roosting site. What triggers the starlings to come together, and to form this 'super organism' is not clear, although the motive for the flock, once formed, may well be protection against predation. Shoals of fish behave similarly in the face of predation. Goldfish, and other animals, display a slightly different pattern of behavior, in which the shoal moves around with individuals moving seemingly at random as they search for food, but periodically all sinking to the bottom in synchronism, usually pointing in the same direction, apparently for a rest. Ant colonies also exhibit rhythm, coming to a rest every 28 minutes; individual ants do not behave in this way — only when many ants are interacting does such behavior of the whole colony emerge.

Systems science purports to address all kinds of wholes. As von Bertalanffy demonstrated, systems theory is founded in well-established laws and phenomena. So, the queues of electrons and of children in the examples of weak chaos would all, of necessity, conform to the conservation laws and to the rules of queues. Systems science not only includes the physical sciences, but also the life sciences; it is, therefore, an inclusive science, investigating the natural, social and physical domains — wherever, systems are to be found, natural, and artificial.

Conservation Laws and Transport Phenomena

The physical conservation laws are significant to the understanding of systems behavior and to the development of system theory, owing to the high degree of interactivity within and between complex systems. The high interactivity between parts of a complex system is implicated in the generation of, and variability in, emergent properties, capabilities and behaviors. In physics, the continuous random motion of particles gives rise to the net macroscopic transport of matter by molecular diffusion; of energy, by thermal conduction; and of momentum by viscosity.

Dynamic simulation models developed as the basis for systems thinking are generally designed so that conservation is 'built-in' to the program. As a simple example, see Figure 2.1, which illustrates homeostasis and conservation of matter using the analogy of a bath with taps left on and plug left out. In the figure, which uses the simple STELLA™ notation, there is a header tank, which receives water in spurts (inflow) from an external pumped source (not shown). The header feeds water out to the bath, which has a drain arranged such that the rate of outflow is proportional to the level of water in the bath.

Graph 2.1 shows the result of running the simulation: the zigzag line shows the level of water in the header tank as the water spurts in and flows out. The rising line shows the level in the bath,

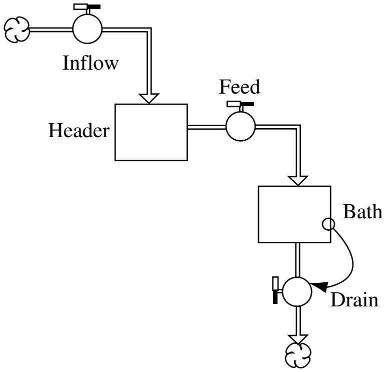
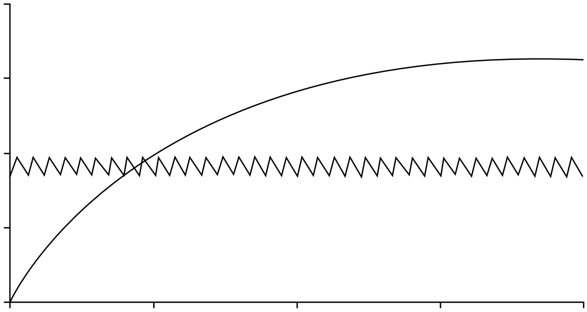


Figure 2.1 Conservation of matter — the Bath analogy.



Graph 2.1 Homeostasis — the Bath analogy.

rising to reach a steady level. This is analogous to the manner in which homeostasis develops in, say, the human body. Food is taken in periodically, at mealtimes and during snacks. Peaks and troughs of energy in the body are smoothed out by converting some of the food intake into glycogen, largely in the liver, to be released over time and as needed, so that the level of, e.g., glucose in the blood remains within sensible limits. The body mass, as shown by the other line on the graph, rises to some mean level, after which it will vary about the mean with the varying balance of food intake, work done and energy outflow.

So, the header tank is crudely analogous to the action of the liver, in that it smoothes out peaks and troughs in resource and energy inflows, and the bath is analogous to the body of the open system, stabilizing at high energy levels, rather than low, and with stability being a homeostatic balance between opposing influences, inflow and outflow, i.e., without regulation via feedback.

Queuing Phenomena

The formation, behavior and dispersion of queues can prove invaluable in understanding behavior of whole systems; particularly where intrachanges between parts of the system, or interchanges between systems are comprised of discrete entities. Queues might be formed of people in a supermarket, signals in a communication channel, assemblies in an assembly plant, patients in doctors' surgery . . . the behavior of the queue transcends the nature of the discrete elements forming the queue. When people form into parallel queues, in particular, they are likely to leave the system if the queue is too long (customer impatience), or jump between queues if they observe that another queue is moving faster than theirs. Queues can form in parallel, in series, or in any combination of parallel and serial.

Queuing theory and queuing simulation, of which a simple example is shown in Figure 2.2, are invaluable tools for understanding the behavior of complex systems. The model could represent parts being inspected (Service A) in a factory prior to assembly (Service B), or, triage arrangements in a hospital emergency room, or any number of situations and processes.

In this instance, it represents part of a recruiting office. Service Channel A might be the process of applicants providing their background and experience to an interviewer — technicians in Q1 and operators in Q2. Those who forget to bring their résumés might find themselves having to rejoin Q1 through Re-queue, after having retrieved or reconstructed the missing document. Service Channel B might be the final interview, with those applicants who failed returning to the general population . . . . The time taken to pass though each service channel would not be fixed; rather it would be distributed in some way. So, the time taken by each new recruit to pass through the whole process might vary significantly, as shown in the figure.

By simulating the end-to-end process, including the insertion of distribution patterns for arrivals and service times, it is possible to develop a statistical 'behavior profile' for the queuing system, indicating the mean time taken for an operator or a technician to go through the system, with and without the feedback loops, and with differing presumptions. This is systems thinking, and although the example might concern a recruiting office, the technique and tools are widely applicable. Note, that the model of Figure 2.2 is a 'closed' systems model, as opposed to a model of a phenomenon, i.e., there are no outflows or inflows to or from any unspecified external parties as there were in Figure 2.1. Note, too that the model shows feedback control, with the accumulated number of

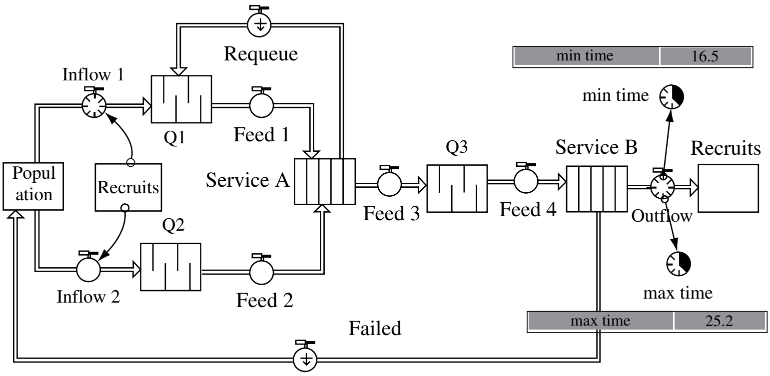


Figure 2.2 Model of parallel and single queues. Q1 and Q2 are queues of discrete entities forming at Service Channel A (a conveyor in the STELLA™ notation, analogous to a factory conveyer belt.) On passing through this channel, the entities form/join a third queue, Q3, for Service Channel B. Some entities are sent back from service Channel A to rejoin the back of Q1. Some entities are sent back from Service Channel B to rejoin Q2. The resulting flow of entities through the system over time can be calculated, but it is simpler and more effective to simulate the behavior of the queuing system, as in this example.

recruits being fed back to close the taps, Inflow 1 and Inflow 2, when sufficient recruits have been interviewed.

Queuing is ubiquitous. It occurs wherever there are flows of entities, whatever those entities might be. We can say with certainty, for example, that the 2.5-tonne stones being laid in ancient Egypt on the Great Pyramid of Khufu, at a rate of one every two minutes, will have formed queues en route from the quarry to the pyramid, with more queues forming as stones were dragged, raised, or ‘magically elevated’ up its sides. We can even work out the likely statistical patterns, lengths and queuing times, and be positive about our estimates. Queuing behavior applies equally to people in a supermarket; automobile parts in a global lean-volume manufacturing and supply chain, and digital words in a data stream.

Chaotic Phenomena

Lepidoptera Lorenzii?

Edward Lorenz is credited with the initial identification of what turned out to be chaotic behavior and strange attractors.

At the time, he was studying the weather using a fairly primitive computer, by today’s standards. Line printouts took a long time, so he would suspend a run and record the readouts to only three decimal places, although the computer stored to six decimal places — he didn’t think it important. Whenever he restarted, he found that he didn’t get exactly the same results. They were tantalizingly close, and the same graphical sequences seemed to emerge, but they were never precisely the same. The model replicates his three original equations:

$$\mathrm{d}x/\mathrm{d}t = -10x + 10y \tag{2.1}$$

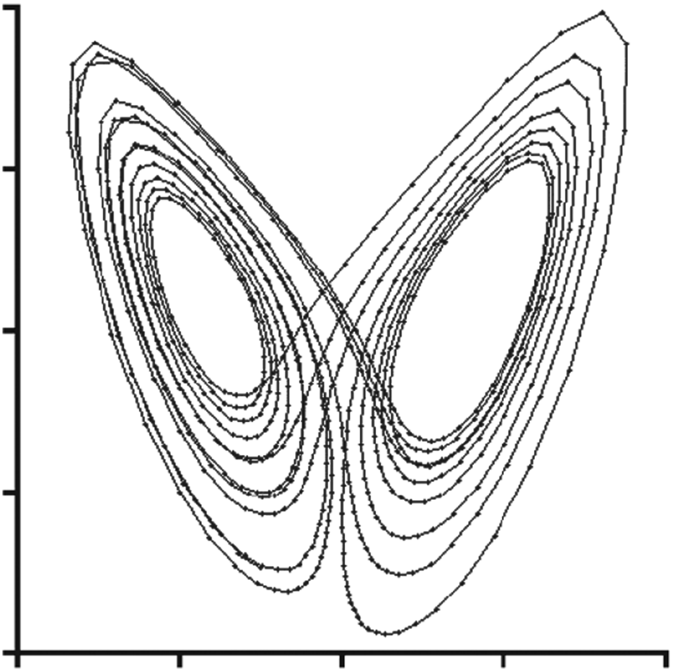
$$\mathrm{d}y/\mathrm{d}t = 28x - y - xz \tag{2.2}$$

$$\mathrm{d}z/\mathrm{d}t = -8z/3 - xy \tag{2.3}$$

Graph 2.2 shows a phase-plane chart of x vs y, which illustrates the now-famous Lorenz, or strange, attractor, looking suspiciously like a butterfly. It illustrates how the weather progresses: the graph space might be described as ‘climate, ‘ in that the instantaneous weather as represented by each dot can vary extensively, but always stays within overall bounds, which correspond to the limits of climate. No matter how extreme the weather might be, it is always ‘attracted’ back to this curious pattern. Each dot (plot) is a small progression from the previous dot: the weather is not random. Were it so, each dot would owe nothing to any other dot, and each dot could appear anywhere within and without the climate envelope of the graph.

Generating chaos

This is true for chaotic phenomena in general; they are bounded, and while each event in a chaotic series of events may not be simply predictable, the overall pattern of events is bounded. There is, moreover, an underlying order to the seeming disorder. Chaotic phenomena exhibit ‘no-go’ zones: areas/spaces in their phase-space where they will never go. So, chaotic phenomena are, it seems, more amenable in some respects than random phenomena.



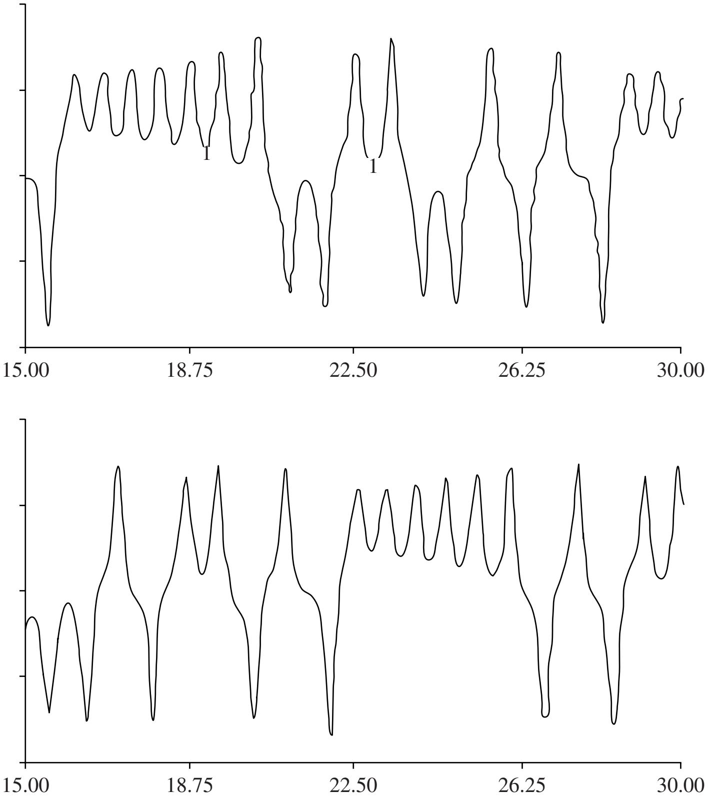
Graph 2.2 Lorenz's butterfly, or strange attractor. STELLA™ simulation.

Chaos is associated with events or processes where the output from some process becomes the input to the next, same process repeated. For example, if a video camera is set up on a tripod, pointing directly at a TV screen, and if the camera output is shown on the screen, then the camera is taking a picture of its own output. If the process is started off in the dark, nothing happens. However, if a match is struck then the camera picks up the light from the match, shows it on the TV, and the TV picture is seen by the camera . . . remove the match and the process is now self-sustaining. Waves of complex patterns sweep across the TV screen as each 'circuit' of the repeated process experiences the nonlinearity in the amplifiers, displays, camera, etc. The displayed patterns are 2-D chaotic, ever changing, never repeating, but nonetheless similar over time.

It is this repeated process, coupled with nonlinearity, and continuous/continual flow, that seems to characterize the generation of chaos. Chaos can be associated with linear behavior, too: Hyperion, one of Saturn's moons, rotates linearly about its planet, but at the same time it tumbles chaotically about its axis, so that its direction of pointing is unpredictable.

Figure 2.3 shows how easy it is to generate chaotic behavior. The model could not be simpler, consisting as it does of only three simple reservoirs, systems A, B and C. The chaotic behavior emerges from the nature of the interchanges, which are discrete rather than analogue, see Graph 2.4.

How could such behavior arise in the real world: three prisoners locked up in a tiny cell; three divisions in an organization coordinating and cooperating their activities; three stars tumbling about each other in close proximity under their mutual gravitational attraction? As this simple model shows, complex behavior can potentially emerge from the simplest of open interacting



Graph 2.3 Lorenz weather simulation patterns. Note that the graphs run from 15 to 30 time units; from zero to 15, the two graph runs appeared identical, although the upper graph started with a value of $x = 1$, while the lower started with $x = 1.0001$, a difference of only 0.01%. Note, too, the repetition of patterns, hinting that the patterns might coincide — but they never do. (STELLA™ simulation)

systems. Mathematically, perhaps the most complex entity is the Mandelbrot Set, named for Benoit Mandelbrot, which derives from iteration of the simplest of equations:

$$z^2 + C = z$$

The recognition of chaos and its sources might have been expected to cause a major stir amongst the ranks of both physicists and engineers. Generally, this does not seem to have been the case, however. Other than being in denial, one reason may be that chaos, while easy enough to observe in simulations and stellar motion, may nonetheless be difficult to observe in human activities. It has long been suspected, for instance, that projects experience chaotic behavior, particularly as they fall behind schedule and the various personnel seek to coordinate and cooperate more intensively in an effort to recoup lost time. Although coupling may be increased during this frantic effort, proving that chaos is implicated has not been possible to date.

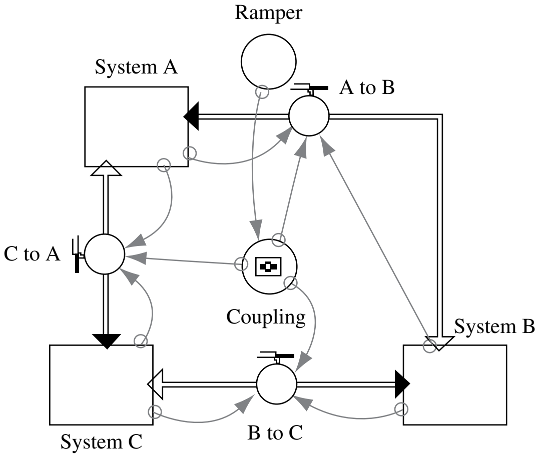
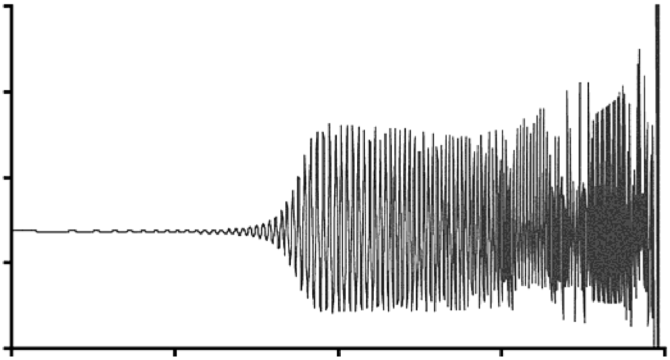


Figure 2.3 Simple, coupled reservoir model, representing three systems, A, B and C, mutually interacting. The degree of coupling between the three can be altered, i.e., how much of the contents of each reservoir can be interchanged at any moment. (STELLA simulation model).



Graph 2.4 Stability–chaos–breakdown. The graph shows the behavior of the model in Figure 2.3 as the coupling is progressively increased. At first, there is little change, then chaos ensues; finally, at the end the whole goes unstable. (STELLA™ simulation).

Another reason may be that chaos in everyday experience may not be so neatly expressed as the deterministic chaos of the simulation model or the weather model. Everyday chaos may be ‘noisy;’ i.e., parameters that would contribute to a chaotic model are constantly changing and adapting, so that any chaotic behavior which may emerge does not appear to fit neatly into anticipated patterns.

Despite these concerns, chaos and chaotic effects are real enough and are undoubtedly present in, and contributing to, uncertainties in human affairs. Instead of being concerned with avoiding the presumed harmful effect of chaos, scientists and engineers are now moving in the direction of harnessing the potential value of chaos in the design of military tactics, security coding devices, communication systems, graphical design programs and many more.

Self-similarity

Investigations into chaotic phenomena observed that many systems contained replicas of themselves on smaller scales. This is self-similarity; for instance, our solar system has a number of planets orbiting the sun, while several of the planets themselves have orbiting satellites. In the natural world, self-similarity in plants has been widely observed, notably in the design of fern fronds, where each branch is of the same form, though smaller, than the whole frond. This continues, with each branch from the frond being of the same form again, but of course much smaller still. It is thought that this observation may cast light on the genetic mechanisms that govern the development of the plant from the spore. Self-similarity is evident in the human activities, too. An army might have three divisions. Each division might have three brigades. Each brigade might have three battalions. Each battalion might have three companies. (In human affairs, the fractal chain is not infinite.) Similarly, the corporation might have three groups. Each group might have three divisions. Each division might have three departments, and so on through sections and teams.

For self-similarity to be meaningful in human activity terms, each of the self-similar entities forms a unified whole: so, a company is a unified whole, so is a team, an army, a division or a platoon. This is not to suggest, however, that our human propensity to form self-similar organizations is associated with chaos; on the contrary, it seems more likely to be based on some innate desire to manage and control a limited number of subordinate groups. A manager is more likely to be comfortable managing three groups under his control than ten groups. In the military, the talk would be of ‘span of control,’ and the issue would be both of the number and of the diversity of units under direct control of one individual.

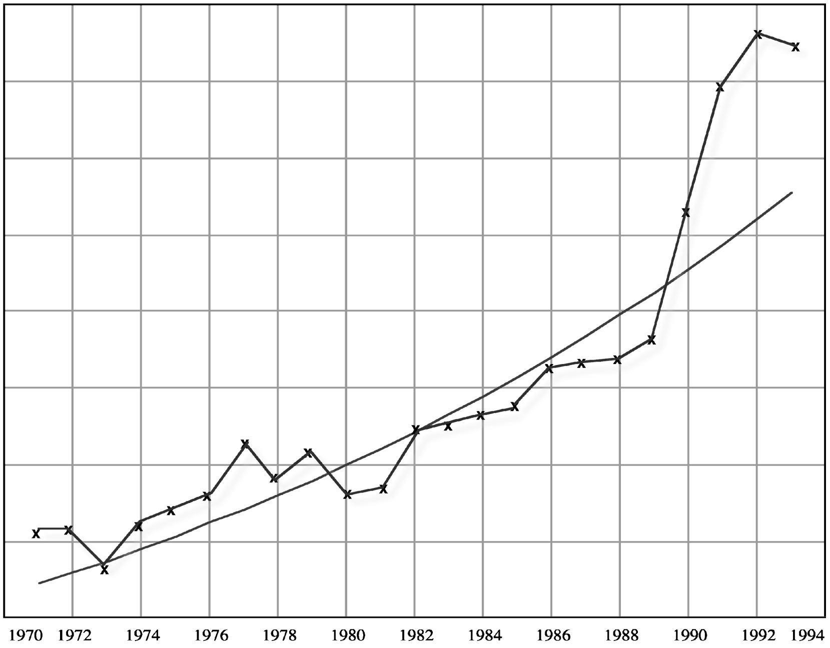
Fractals

Fractals are part of the chaos scene. Benoit Mandelbrot described fractals so: as you get closer to straight line, the smaller section you can see remains straight. As you get closer to an irregular coastline, the smaller section you can see remains irregular. Fractals are all those things that, as you get closer, remain the same, but that are not straight lines.

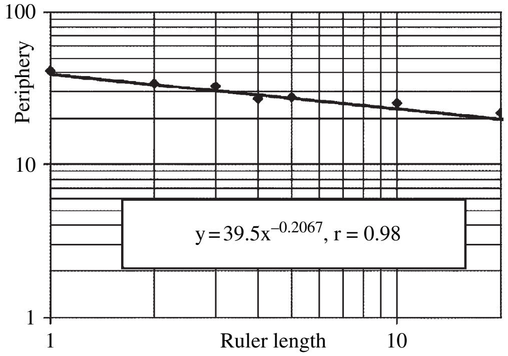
These are phenomena where the behavior may be described as being of the form $y = ax^b$ where b is a non-integer, so is ‘fractional’ — hence fractal. Many physical phenomena are linear ($y = mx + c$) as in distance traveled at constant velocity or square law ($y = ax^2$), as in distance fallen from rest under the influence of gravity. To observe phenomena with fractional indices was novel, but once observed, examples cropped up in unexpected places.

Graph 2.5 shows the reported crime statistics over some 25 years for a county in England. The annual figures show a seemingly erratic nature, allowing politicians of either flavor to successively deplore rising crime, or to state that their policies were clearly working, as witness the sudden dramatic fall in reported crime . . . .

The result of applying one method of identifying fractals is shown in Graph 2.6, and it tells a different story. The method used was to measure the ‘bumpiness’ of Graph 2.5; this involves using rulers of different length (hence y-axis, ruler length), and using the full length of each ruler to see how many lengths made up the overall length (hence x-axis, periphery). A small ruler would be able to go in and out of the various peaks and troughs, while a large ruler would miss them out. The straight-line ‘goodness of fit’ factor of 0.98 is sufficient to indicate that the reported crime statistics may be reasonably considered as fractal. This suggests that the reported crime statistics vary somewhat chaotically, without seeming influence from politicians or policemen, although



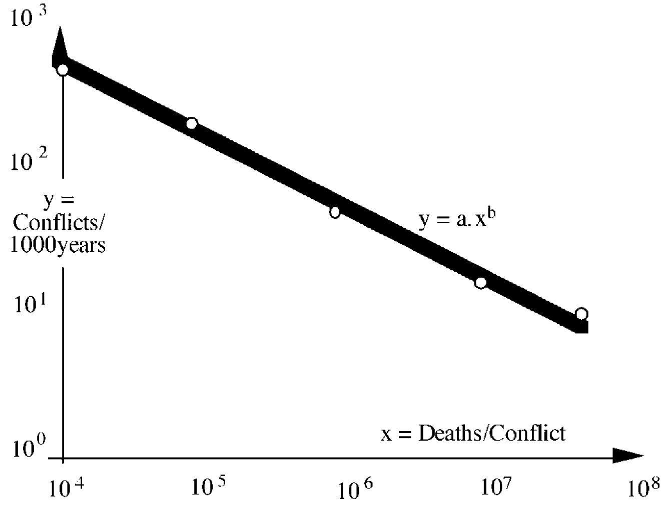
Graph 2.5 Reported crime statistics in an English county. The graph variability suggests two separate features: 1. Exponential increase in crime over 23 years; 2. High degree of variation about the regression line.



Graph 2.6 Reported Crime statistics as a fractal.

there is clearly an underlying trend upwards for whatever reason. Moreover, using the notion of self-similarity, and noting that the county in question was comprised of a number of divisions, it is reasonable to suppose that each of the divisions had similarly fractal crime statistics — and so it proved.

There is a relationship between weak chaos and fractals, in that both correspond to a power law, i.e., $y = ax^b$; for fractals, the index b is a non-integer. The development of fractal ideas is



Graph 2.7 Deaths in war. from Lewis F. Richardson, the British meteorologist. (Richardson, 1960).

not really new, although those developing them may have been largely unaware of the underlying consistencies. One such was Lewis Richardson, and English meteorologist, who plotted deaths in war from 1820 to the end of World War II. When Richardson figures are plotted on a log–log scale, Graph 2.7, the result is a straight line with a negative, fractal index.

The similarity between Graphs 2.6 and 2.7 is striking; but perhaps the more surprising observation comes from considering the advances in warfare and the science of killing that had taken place over the period from 1820 to 1946. In 1820, rifles were fairly primitive, machine guns and motor vehicles were nonexistent, and air power was virtually nonexistent in and over the battlefield. By 1946 two atomic bombs had been dropped. Yet, in spite of tremendous advances in the science of warfare, the number of deaths in war conformed over the period to a straight-line graph. Recent work suggested that Richardson's work could be extended at the lower end to the level of violence between individuals, and the fractal relationship still held.

There is much more to the burgeoning science of chaos, and it is clearly of major significance to understanding systems behavior and in designing system solutions. Whereas current practices tend to avoid chaotic regimes, it seems likely in the future that it will be possible to make great use of chaos in the design, development and creation of robust, adaptable and self-sustaining systems.

Period doubling

Another phenomenon associated with chaos is period doubling. This can be observed in the dynamic behavior of many physical objects. A dripping tap will drip regularly: this was, after all, the basis of some ancient clocks. Open the tap slightly, and the drops will come out, not singly, but in groups, with a delay between the groups. Open the tap some more, and the groups have more drips, and the delay between them gets longer still. Finally, the stream becomes chaotic. This phenomenon came to be known as period doubling — the period between the groups of drips first doubled, then quadrupled, then octupled, and so on.

Period doubling occurs widely in dynamical systems. It is observable in electronic oscillators, where increasing feedback causes the period to first double, then quadruple, and then to go rapidly into chaos. In the medical field, researchers have observed the same phenomenon in people with heart disease; in this case the phenomenon was called 'electrical alternands,' and presented as alternate stronger and weaker beats, such that the period between strong beats doubled: this occurred prior to the onset of fibrillation, offering the prospect of being able to anticipate heart attacks for some patients.

Information: Conserved, or Non-conserved?

Systems are pools of information concerning their functions, interactions, processes, architectures, purpose, objectives, etc.; they may also receive information, interpret it, use their interpretation, and exchange information with other systems. Information is unlike matter or energy, seemingly, in that information can be given away, yet the supplier still has it: it appears not to be conserved.

This is a simplification, of course, since information is negative entropy; receiving information reduces uncertainty in the receiver. Since there is a relationship between entropy and energy, a system receiving negative entropy is, in principle, potentially capable of doing more work. For practical purposes in simulation and modeling, however, it is often not unreasonable to consider information as a nonconserved component.

Information of interest to viable systems comes in many forms. Information about the environment may be sensed at a distance using eyes and ears, radar and sonar, passive and active sensing, and so on. In each case, desired information has to be extracted from a 'cacophony' of background information, and interpreted in some way. Generally, a system acts upon its own interpretation of information received, rather than on some 'ground truth.'

So, people often see what they expect to see. Doppler radars see only things that move. Air traffic management (ATM) area radars around London were puzzled by concentric circles of echoes moving towards the center of London each morning and outwards to the suburbs and beyond each evening. Initially dubbed 'angels,' these echoes were caused by large flocks of starlings coming into London to feed, and returning home to roost at night.

Information can be inferred, too. Supposedly, the adult human does not receive enough visual information via the eyes and the optic nerves to enable successful driving at night with only car headlights by which to see. That we can drive at night indicates that we are inferring information about the whole scene in front of us from visual cues. This system can break down: drivers in flat featureless areas were found to drive straight into ditches at night. Upon investigation, it transpired that the road system wound its way around the edges of fields, while the telegraph poles had been set in straight lines, sometimes alongside the road, but then going straight across fields where the road deviated. Drivers were using the telegraph poles as a cue to the road ahead, and were crashing into the ditches, but only on moonless nights. Accidents were rare on clear nights with a full moon . . . .

Similarly, some commanders in battle seem able to make successful decisions that should have required intelligence about the enemy, even though that intelligence was missing. Investigation suggested that these commanders were empathic, could infer what the enemy commander would do in the situation facing him, and exploit that inferred knowledge as intelligence.

Systems Science as Natural Science and Social Science

Systems science incorporates the natural sciences, which form the basis for the applied sciences: physics, chemistry, biology, astronomy, earth sciences, etc. It also incorporates the social sciences, including: psychology, anthropology, sociology, jurisprudence, economics, linguistics, and many more. Systems science invokes the scientific method, involving the proposition of hypotheses to explain phenomena, predictions based on the hypotheses, experimental studies to test the hypotheses leading either to the rejection of the hypotheses or the formation of theory, so binding specific hypotheses into logically coherent wholes. Where physical experimentation would be impractical or unaffordable, system science must needs resort to experimental studies, using dynamic computer simulations as experimental test beds.

Action research, in which researchers involve themselves in the physical and social environment, may be considered as scientific experimentation where the presence of the researcher can be shown not to affect the outcome of the experiment. On the other hand, some situations preclude action research; it would be a brave, or stupid, researcher who would explore the psychology of a prison riot by asking the participants to pause in mid-riot while he investigated their feelings and motivation.... Similarly, it has proved necessary to simulate the behavior of dangerous systems/operations where wide-ranging practical experimentation would be too risky and/or expensive. Such measures are acceptable only where the simulations are rigorous; where rigor is difficult to come by, experiment-by-simulation must take a broader view, address a wider potential spectrum of outcomes, and consider experimental results with caution.

Psychology is of particular importance in the development of models of systems behavior, since nearly all problem and solution systems concern social or sociotechnical systems, and necessitate the representation of human behavior, either individually or in teams/groups/societies. Psychology differs from anthropology, economics, political science and sociology in seeking to capture explanatory generalizations about the mental function and overt behavior of individuals, rather than relying on field studies and historical methods.

Behavior

Behavior refers to the actions or reactions of a whole, usually in relation to its environment, or to some stimulus, e.g., behavior as stimulus–response. Behavior can be conscious or unconscious, voluntary or involuntary. The more complex a system, generally the more complex will be its behavior, although some simple systems can exhibit remarkably complex behavior. Also, the more complex a system, the greater is its propensity to learn and to adapt its behavior. Intelligent behavior is marked by differing responses to the same repeated stimulus: while a simple system will respond in the same machine-like way every time, an intelligent system will change its response, perhaps to evade the stimulus, or to investigate its source.

So, if a woman strikes a man in the face, he may not respond. If she strikes out a second time, he may duck, flinch or catch her hand to stave off further attack. On the other hand, if a man strikes a man in the face, the striker may expect an immediate parry, if not a return blow. Should he strike a second time, he is pretty well guaranteed a fight, or else his victim will retreat if able. Of course, those with a strong moral and ethical code might choose to ‘turn the other cheek,’ which will present the striker with a dilemma... hence the role of psychology as a predictor of behavior. In each instance above, the behavior as response to stimulus might be deemed intelligent, since the response differed for the same repeated stimulus. The difference in response between a man and a woman illustrates in a small way the impact of culture, mores and situation on behavior.

For social systems and sociotechnical systems, there is perhaps a greater emphasis on group psychology, so that sensible predictions can be made about the behavior of teams, platoons, companies, etc. While not a precise science, it is surprising to the uninitiated to discover just how accurately a psychologist can predict behavior of an individual, provided the psychologists is aware of the individual's background, culture, and particularly their recent experiences up to the moment of prediction.

Interpretation and categorization

Complex organisms display the ability to categorize information: it appears to be a fundamental ability. A newborn calf can immediately distinguish mother, teat and food from non-food. Psychologists suggest that categorization is an essential feature of the brain, enabling it to reduce an otherwise bewildering set of sensory stimuli to significantly fewer categories. In some animals, the sensory organs take part in the process of categorization: the horizontal pupils of some grazing animals enables them to detect vertical stems of grass with greater accuracy; the eyes of some animals are tuned to the infrared to enable them to detect warm-blooded prey; and so on.

Tacit knowledge

To facilitate categorization higher organisms, and some mechanisms, too, create 'libraries of tacit knowledge.' These are everyday items of knowledge, developed since infancy, such as grass is green; sky is blue; things fall to the ground when dropped. Brains draw upon this tacit knowledge to facilitate categorization and recognize stimuli.

World models and world views

Higher organisms, and humans in particular, create so-called world models of the environment in which they live and operate. A world model is a stored image of how the particular world works, or appears to work. So, helicopters hover with the rotating blades above the fuselage; were you to observe a helicopter without blades, or one with the blades underneath the fuselage, it would confound your world model, and you would be alerted by a mental disjoint. A world model is a mental model space, within which tacit knowledge determines the basic rules of form, function, behavior, color, etc.

Weltanschauung, or world view, is an allied concept, describing as it does the philosophy or viewpoint from which a person sees and justifies situations and events. One *Weltanshauung* might consider it good, right and proper to drop atomic bombs on a country with which one is at war, in the interests of saving many lives by shortening the conflict. Another *Weltanshauung* might consider that killing is fundamentally and morally wrong under any circumstances, and 'just because they are doing it to us does not justify us doing it to them.' Neither *Weltanshauung* is either right or wrong, and neither is logical or illogical – they are what they are: philosophical viewpoints. The implications of adopting and expressing such viewpoints might prove important, however.

Interpretation

When a stimulus is received, it is, in effect, compared with memories of previously received stimuli recorded as tacit knowledge and world models; the particular stimulus is thus recognized and its meaning and implications drawn from memory. This process is subject to error where, for example, the stimulus is similar to previous ones, but actually from a different source. Alternatively, a new, previously un-sensed stimulus may be received, which does not accord with tacit knowledge and world models. The brain may actually ignore it, since it has no way of even registering it; alternatively, it may choose to ally the stimulus with others that it does recognize. In this case, it may interpret the novel stimulus as being like, or even the same as, something familiar. On the other hand, it may decide something is amiss and investigate further. Or, there is a third option . . . .

Belief system

Higher organisms, especially man, develop a so-called belief system. This is a set of beliefs reinforced by culture, theology, experience and training, as to how the world works, cultural values, stereotypes, political viewpoints, etc. If a stimulus is received, it may be interpreted with the effective aid of the belief system, to be whatever the belief system might lead the recipient to rationalize. So, a naval radar operator is viewing a radar screen in friendly waters when a radar track appears on screen coming from the open sea toward the ship. The operator is expecting an aircraft, which launched an hour earlier with a faulty identification system, to return any minute; his belief system assures him that the incoming track is the anticipated 'unidentified friendly.' He may be right: but, on the other hand . . . .

A belief system need have no basis in reality, so long as it consistently provides adequate explanations. The Mayans believed, apparently, that sacrificing the blood of young men would ensure that the sun rose each morning, would ensure the rains, would prevent flooding; every time they sacrificed young men, sure enough, the sun rose, the rains came, etc., so reinforcing their belief . . . and if the rain failed to come, perhaps the gods thought the sacrifice too small, so sacrifice more blood, until the rains arrive?

Figure 2.4 shows conceptually how an individual's and a society's belief system might be brought together and might mutually sustain each other. The figure shows interlinked reinforcing loops. The top loop shows that an individual's belief system gives a believer a straightforward world model, so that he or she can find satisfactory explanations and interpretations of everyday events and situations. This reduces the individual's psychological uncertainty, so reinforcing his faith in his belief system.

Lower loops show the relationships between belief and society. A shared belief system is at the heart of a culture. The model indicates how shared beliefs sustain the belief system, promote social cohesion, and enable the growth of class and power structures.

Conflict between two groups, including war, may be characterized as a 'battle between belief systems.' Icons emerge strongly in such conflicts: they may be revered objects such as stones, writings, buildings, flags or badges; whatever they may be, they may symbolize the central core of the belief system. When people become icons, the real person may become obscured behind the projected iconic image or persona.

Organizations develop their own, in-house culture and belief system, too, which leads them to act and behave in ways that might not seem entirely rational to an outsider. Marketing campaigns represent a company, not so much as it is, but more as it would like to be; perhaps in an attempt to

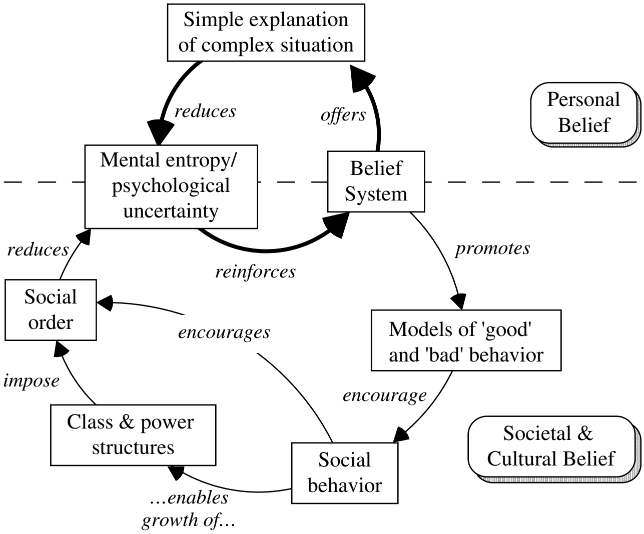


Figure 2.4 Sustaining belief systems.

influence the belief system of its own employees as much as those of customers. Call-answering services put customers on hold, repeating the mantra: ’we value your call;’ while clearly evidencing, by not answering, that they do not value the call. Such companies hope (forlornly?) to influence the belief system of the caller into judging an inferior service to be acceptable.

Instinct and archetype

The way in which the human brain develops is not well understood; the most remarkable thing about it, perhaps, is that for so many people on the planet, the brain is a relatively stable, highly capable organ. The basis for this stability is hard to find; experiments with sensory deprivation show that we depend on sensory inputs, without which we start to hallucinate and lose our frame of reference.

It is observed, for instance, that young children experience the most horrific nightmares, in which they seem to see monsters and apparitions, which bear no resemblance to anything they have ever experienced in their short and sheltered lives. Where can such images come from? Are they, somehow, inherited? Are they some imprinted memory of more primitive, prehistoric existence? Do they emerge naturally as the structures and functions within the brain develop?

Various theories of how the human brain functions have been put forward, some such as those of Freud and Jung based on ‘models of the mind.’ Other approaches seek to unravel the brain’s operation by examining its physical structure and observing which parts of the brain correspond to which activities. The well-known phrenological bust by L.N. Fowler was an early, discredited attempt to relate the bumps on the skull to human behavior. Since that time, the advent of sophisticated scanning machines has enabled researchers to observe how activities occur in the brain when the person being scanned is shown pictures, undertakes simple activities, etc; as a result, there is a much greater understanding of the complexities of the human brain, augmented in particular by studies of people who have had some impairment to the brain, such as the severing of the corpus callosum, the bundle of nerves joining the two halves of the brain.

Significant though such advances may be, they are insufficiently advanced to be of much use in comprehending the behavior of individuals, or groups of people. For this, we have to look to the work of Freud and Jung. (Jones and Wilson, 1987). Freud, the psychoanalyst, took a somewhat biomechanical view of the brain, identifying an id, ego and superego. Conflicts exist between id impulses, ego defenses and superego restrictions, with the ego mediating between 'primitive forces of the id' and the 'censoring, guilt-inducing power of the superego.'

Jung, on the other hand, created a richly populated, multilayered model for the mind, in which there were:

- conscious
- personal unconscious
- collective unconscious; the deep species-wide layer of the psyche underlying the personal unconscious
- archetypes; mythic images and motifs that go to makeup the collective unconscious
- complex; a group of interrelated and emotionally charged ideas or images
- individuation; the progressive emerging of the mature individual mind, coming to terms with thinking/feeling and sensing/intuition axes that determine the psychological types
- extrovert/introvert and anima/animus (the woman inside every man and the man inside every woman)
- active imagination; that which enables one to write or paint one's unconscious fantasies
- synchronicity; meaningful coincidence of two causally unrelated events
- self; the very center of one's being

Jung's model of analytical psychology is complex, even fanciful in some respects, but it was formed from years of research, and seems to offer explanations for some of the more bizarre behaviors which people display, particularly under times of emotion. Jung, too, considered the human mind as being part of some whole — the collective unconscious, which shaped and influenced humanity.

Another way of looking at his idea of collective unconscious, with its constituent mythic archetypes is to consider that, as humans, no matter what our individual differences and cultures, we all share some basic human instincts and patterns of behavior. Mothers will defend their children. Sons will rebel against their fathers. Teenage girls will be attracted to boyfriends that are unlike the girls' fathers. Men will engage in sex at the drop of a hat; women are less so inclined. Jung's mythic archetypes can be seen in a similar vein. The shepherd will protect his flock from wolves; as will the shepherd–king protect his subjects from marauders.

Figure 2.5 shows a diagrammatic representation of the developing psyche of the ancient Egyptians, as Jung might have seen it — both he and Freud were fascinated by ancient Egypt, with its overt psychological overtones. The figure shows the collective unconscious, which, in Jung's view, would underlie the personal unconscious and conscious minds of the people. Archetypes were in evident in abundance — the ancient Egyptians placed great emphasis on symbolism. The figure shows a few only:

- The king as shepherd of his people. The king carried a flail and a *heqa*, a shepherd's crook, as symbols of his authority. Today, archbishops carry crosiers, for much the same reason.
- The magus, or magician as high priest. Today we have people who can turn round ailing businesses, entrepreneurs, etc. Financial directors who can work on the books and turn an apparently ailing company into a seemingly-successful one overnight are modern magi.
- The pharaoh as the self and individual of the people, an icon of the nation.
- The divine king, leader and ruler ordained by divine right.

- The healer, the creator, the ideal....
- Zoomorphs; gods who were men and women with animal heads, such as Anubis, the jackal-headed god of funerary rights. In the legends of the time, he helped Isis bind together the sixteen parts into which her brother/husband Osiris had been cut by his brother Seth, so creating the first mummy. Isis formed a phallus out of Nile mud, and conceived the child Horus, so identifying with both the virgin birth and the perfect mother and child image, iconic archetypes that were handed down to the early Coptic Christian church amongst others.
- Duality, the propensity to see everything in terms of opposing pairs which must be reconciled. Today we have political left and right, for or against, black or white, man versus woman, good or bad, common or classy... duality is alive and well, as Jung would have expected.

According to Jung, these mythical archetypes form the basis for instinctive behavior. The myths may be just that — mythical — but these patterns of behavior, he suggests, are contained within us, at the level of the collective unconscious. In the normal course of events, we would remain unaware of these behavioral archetypes, but they can influence our behavior, and particularly they may behave the way in which someone feels he or she ought to behave.

So, when someone is put in charge of a group of people, he may feel that it his role to 'look after his new charges,' to guide them and protect them from others. On the other hand, he might decide that as the new boss he can do no wrong; in consequence, he lays down the law, enforces the rulebook, micro-manages, and brooks no criticism. In the first instance, we see the shepherd–king behavioral archetype; in the second, we see the king as divine ruler archetype. Similarly, the healer is someone who can seemingly make problems disappear, and so on.

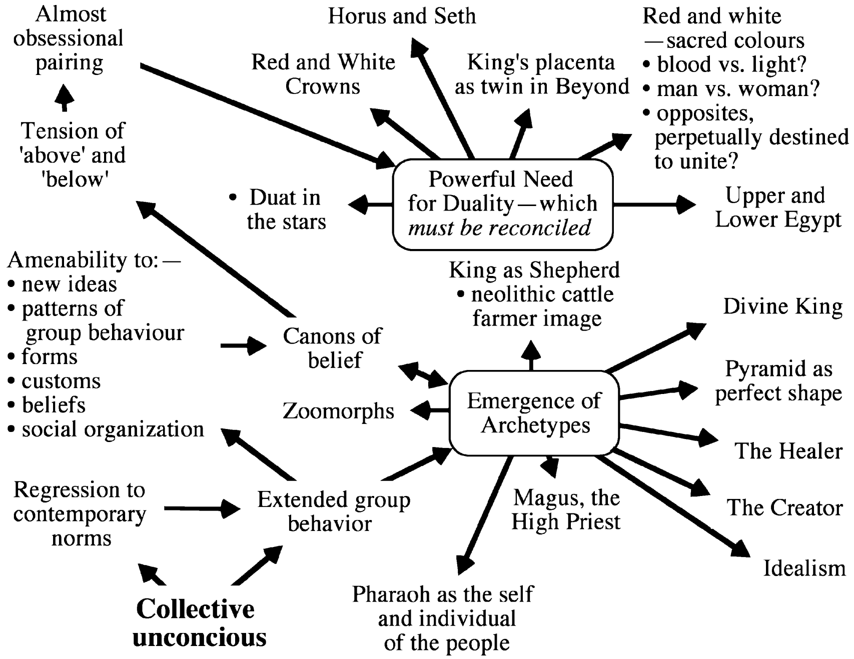


Figure 2.5 Jungian view of ancient Egyptian psyche.

Psychology forms a central thrust in the application of systems science, together with social anthropology.

Social and Cultural Anthropology

Anthropology is the study, particularly, of cultural and developmental aspects of humankind. In contrast to psychology, with its emphasis on theory, social and cultural anthropology are generally investigated though field studies, so that understanding may be gained about human behavior in context. Typical of the areas of interest might be social implications of technology; shamanism, new religious movements; political and economic changes; legal forms and institutions; cultural creativity; artifact-based theory; nationalism and the state; material culture; person and gender; relatedness and kinship; social development; hunters and gatherers; and many, many more.

Figure 2.6 illustrates how the anthropologist Desmond Morris proposes that humans developed their unique body hair pattern. The model suggests how man transitioned from tree-dwelling to hunter–gatherer, developed subcutaneous fat (uniquely among the great apes) to sustain him between meals, and shed much of his body hair to prevent overheating during the hunt; overheating would have been a threat with both subcutaneous fat and a covering of hair acting as insulators. The figure also illustrates the vital role of pair bonding between man and woman, such that the woman with child, who could not follow the hunt, was assured of food from the hunt. Compared with other mammals, the human female also evolved to make herself more frequently available to the male, who might return at any time from the hunt, leading to selective hair retention under the arms and

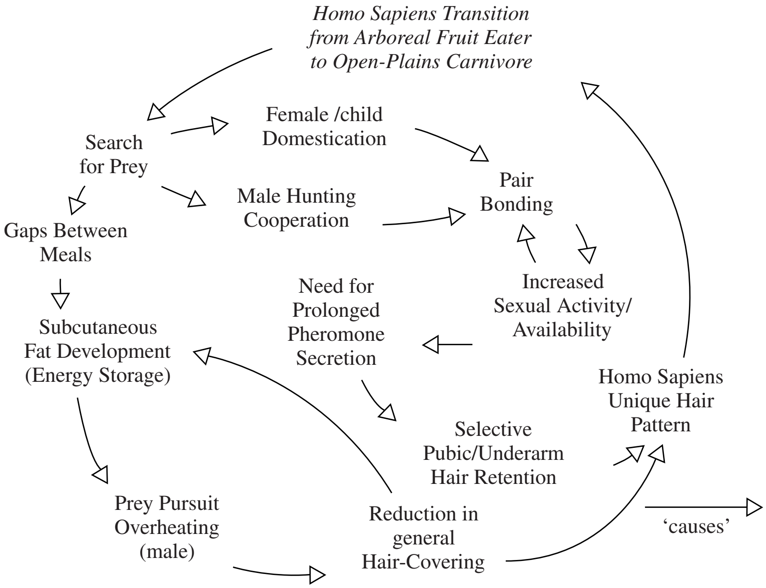


Figure 2.6 The Naked Ape. Causal loop model, showing how *homo sapiens* may have developed the pattern of body hair that is unique amongst mammals. (Hitchins, 1992)

around the genitals for the secretion of pheromones. All of which leads to the formation of the family as the instinctive social nucleus for humankind: families encouraged survival.

Man as the hunter–gatherer is evident in our everyday existences, if we care to look. The supermarket is laid out like so many hedgerows, and the most attractive pickings are just below eye-level, for both hedge and supermarket stall. The chairman of the company, who furiously seeks out new business, even though he is too old for such efforts and should have retired many years since, is acting out the role of the hunter pursuing the quarry.

Technology can also impact on this subliminal hunter–gatherer underlay. The effects of such technologies as television, the Internet and the mobile phone are undoubtedly great, but their full effect may be difficult to gauge in the short term.

The kinds of system of interest to both social scientists and systems engineers have major human content and context. Understanding and anticipating the behavior of people is often core to the achievement of successful outcomes; and, the behavior of people, individually and en masse, is evidently contextually, culturally, politically and economically influenced.

Social Capital

> Whereas physical capital refers to physical objects and human capital refers to the properties of individuals, social capital refers to connections among individuals — social networks and the norms of reciprocity and trustworthiness that arise from them. In that sense social capital is closely related to what some have called ‘civic virtue.’ The difference is that ‘social capital’ calls attention to the fact that civic virtue is most powerful when embedded in a sense network of reciprocal social relations. A society of many virtuous but isolated individuals is not necessarily rich in social capital. (Putnam, 2000)

Social capital is a relatively new expression of a concept that is well established — that the value of a social group is more than the sum of the individual parts. Social groups are cohesive, for instance, and that cohesiveness is related to the bonds that form, break and reform between individuals and groups within the society.

The notion of social capital is important in the context of systems science, since social capital moderates the desired effects of laws, changing economic circumstances, cultural upheavals, etc. At a trivial level, for instance, the rate at which a society may change, i.e., their resistance to change, is likely to be related to their social capital. Similarly, the ability of a society to recover from traumatic shock may relate to the degree of social capital. Policemen recognize the value of social capital, and find evidence of it, *inter alia*, in ‘neighboring’, i.e., the propensity of people to help each other out without external prompting, and in politeness on the roads such as letting people enter from side-roads into a stream of traffic.

Social capital is a whole system concept, and relates to the emergent properties, capabilities and behaviors of social wholes.

Social Genotype

We may be familiar with the concept of the organic genotype: the genetic makeup of an organism. We may think in terms of DNA, as being unique to an organism, with its molecular helix of coupled nucleotides. DNA, although not alive in any real sense, does seem to be eternal in that it is 'handed down' from organism to organism.

Societies may be thought of by analogy as having a social genotype. Instead of nucleotides and molecular bonds, there are social roles and interpersonal bonds. Like the organic genotype, the social genotype may be eternal; individuals may come and go, but the roles they adopt and act out remain largely unchanged, locked in by the relationship with other roles. So, a new manager coming into an organization will find himself interacting with subordinates, superiors and peers, all of whom will expect familiar behaviors from him. If he does not behave 'in role,' and conform to expected norms, he is likely to find himself unemployed — after a period of adjustment, of course, during which he will be expected to 'learn the ropes.'

In this manner, the behavior of a social group may persist from generation to generation, locked as it were into the role–relationship structure of the group or society. By further analogy, the genotype of the social group may interact with its environment to exhibit a social phenotype. Overt group behavior may change according to the environment in which the group finds itself.

To understand this, consider a group of families that have moved from, say, India to Indiana. In their new surroundings, they still form a cohesive group, maintaining their culture, their religion, their beliefs and their social practices. Some of these social practices may be alien to their host nation, such as arranged marriages for instance, and so may be concealed — or at least, not publicized. On the other hand, some of the members of the group may adopt western clothing, western customs and western practices when operating outside of the group in the wider community. On returning to the bosom of the family, they revert to the social and behavioral patterns of their social genotype.

The social genotype, then, contains social memory within its role–relationship structure. This is evident from the traditions, myths, legends and stories that are handed down within societies and cultures; but it also evident, more subtly, in the actual patterns of roles and relationships that, once formed and set, seem thereafter immutable.

It may be possible to bring together ideas of social capital with those of the social genotype. Moreover, for any society to persist, it has to exhibit homeostasis: there has to be a system in place for sustaining the society, for formulating social rules and for ensuring that such rules are observed. Similarly, there has to be a system for establishing and maintaining social assets, resources, foci for social interaction, etc. If these concepts are blended, a social genotype can be perceived in which there is a spectrum of archetypal roles and relationships that bind together to form an integral and essential part of an enduring social genotype with determined social capital.

For example, a society will endure only if it is able to manage antisocial elements from within and without. There will be a need for promulgation of the rules for acceptable and unacceptable social behavior: for the detection, location and apprehension of wrongdoers; for the imposition of sanctions to restrain, deter or reform offenders; and so forth. This appears to be true for any society or social group, including those forming companies, industries, enterprises, teams, brigades, squadrons, gangs, etc.

Managing Complexity

System theory affords the opportunity to manage complexity; that is, to effectively conceal perceived complexity so that our limited intellects can comprehend without being swamped by detail and variety. A system may be represented, not by its structure, function, form, etc., but by its emergent properties, capabilities and behaviors. If the system in question is dynamically stable, then so too will be its emergent properties, capabilities and behaviors, and these may be used to 'describe' the system without need to mention its structure, form and internal functions.

In the general case, and since our concern is exclusively with open systems, the properties, capabilities and behaviors in question will be those that emerge while the system is complete/whole, and dynamically interacting with other systems — this is the basis of the systems approach, in which we seek to understand things as dynamic parts of some dynamic whole, not in isolation. Of particular interest in managing complexity is the determination and manipulation of behavior, where behavior can mean both action and reaction to some stimulus.

Aggregation of emergent properties

It is possible and practicable to simulate the behavior of an open system. This may be done either by representing the object's interacting parts in detail, or by using some form of isomorphic behavior generator, such as a set of nonlinear difference equations, which exhibit the same behavior. In the second instance, the equations serve as a descriptor, or label, for the system and may be employed within simulation models in place of the system and its detailed internals.

If it is possible to represent the behavior of a system in this manner, then it should also be possible to represent the behavior of a second system; and, since such an open system may interact, it may also be possible to represent several systems simply by simulating their interconnected behaviors. This is reasonable within the notion of 'behavior,' since it is classically considered as a response to stimulus. When two or more systems are interconnected, the outflow from one is the inflow to another, and vice versa, so each stimulates the other(s), so preserving the context of 'behavior.'

Figure 2.7 shows the concept figuratively. It a shows a system/whole containing three parts, each represented by their (complementary) emergent properties, capabilities and behaviors, and all mutually interacting. They are also open to the 'outside world,' whence some of their interactions.

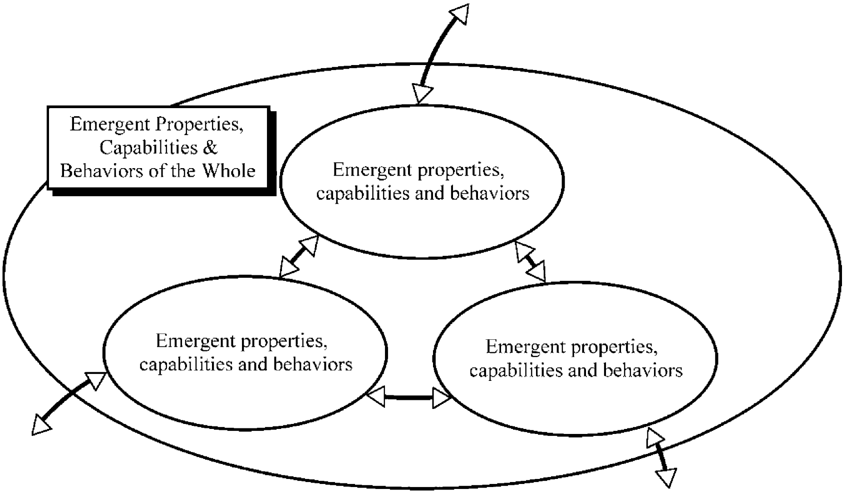


Figure 2.7 Synthesizing emergence. Emergence of the whole derives from the emergent properties of the parts and from their mutual interactions.

The emergent properties, capabilities and behaviors of the whole are derived exclusively from the emergent properties, capabilities and behaviors of the three contained, interacting parts — there is, essentially, no other source.

The figure, and the concept it represents, helps us to manage the complexity of the real world, which might otherwise overwhelm us. Suppose the three contained systems were a marketing department, a production department and a research and development (R&D) department, all working closely with each other in the conception, design, testing and manufacture of a new consumer widget, then it is to be supposed that the internal processes needed to make the whole function as needed might be legion. If we were to follow the activities of individuals, the story might become even more complex. But, if we can represent the departments as shown, we might find that we can use such a model as part of some wider investigation and experimental activity, without any further elaboration or detailing of the parts or the whole.

Anti-chaos

Instead of becoming progressively more disordered, as proposed by the Second Law, some systems exhibit ‘anti-chaos,’ that is, they develop order from disorder. This phenomenon has been observed in the natural world. The famous Belousov–Zhabotinsky experiment demonstrates that four substances (malonic acid, sodium bromate, sulfuric acid and ferroin), brought together in solution, result not in the normal chaotic mixing that might be expected, but instead form oscillating waves sweeping outwards across the surface with a set period. Instead of the disorder of chaos, this is anti-chaos: order out of disorder.

The Belousov–Zhabotinsky experiment may be a contrived example, but the individual organisms that group together to form slime moulds do so naturally: the phenomena described under the banner of anti-chaos are very real. The manner in which an enormous ant colony, or beehive can behave as a single, superorganism is also anti-chaotic. Human society en masse may exhibit anti-chaos, although we humans might be loath to accept such a notion, jarring as it would with our (illusory?) sense of independence and self-determination.

When a fertilized human egg, a zygote, starts to develop, it divides into cells; over a few weeks these cells differentiate into nerve cells, muscle cells, spleen cells, kidney cells, etc; there are some 250 different types of human cell. Each cell has the same DNA, of course, and the same number of genes — about 100 000 in the human genome. Differentiated cells have some of their genes active, some inactive: active cells make RNA and protein. And some genes can make other genes active or inactive, suggesting a potentially enormous complex of interactions.

Professor Stuart Kauffman of the Santa Fe Institute modeled the behavior of this complex, using an array of light bulbs as a simple analog of genes, with each light bulb being potentially on or off, as each gene might be active or inactive. The bulbs were interconnected, as the genes might be, by a web of connections forming a Boolean network, so each bulb could be switched on, or not, according to a set of rules. Rules might be ‘this bulb will light if two other bulbs to which it is connected are lit.’

The array of lights could be set into dynamic interaction by starting from some state in which some bulbs were alight and then progressing through states to see what bulbs lit/went out as a result of the interconnection rules. The objective was to see if there were any stable conditions in which particular bulbs, either individually or in groups, stayed alight from state to state.

With a fully connected set of bulbs, i.e., each bulb connected to every other bulb, there were very few stable states. Paradoxically, when the Boolean network was simplified such that each bulb was connected to only two others, stable states did occur. This was true even if both the connections, and the rules, were allocated at random.

This was, Kauffman observed, a stunning result. For 100 000 human genes treated simply as fully connected on–off switches, the potential combinations would be an astronomical, unthinkable number: 1 followed by 30 000 zeros. Provided with a simple interconnection pattern, with very few interactions, the number of stable combinations reduces to some 300 — which is comparable with the number of different cells in the human body.

Essentially, the simple connection of gene/element/light bulb/etc., to only two others, boxes the potential variety from 100 000 interacting entities into just 300, or so, stable options. This may help to explain the ubiquity of life on Earth, and suggest that life may be expected throughout the Universe. Does it explain, too, how an ant colony, in which each ant obeys only a very few rules, and is in contact with only a few other ants at any time, can operate as a superorganism with a limited set of behaviors? Does it suggest, perhaps, how the neurons in the brain can give rise to thought, awareness and behavior? And, does it suggest that humans living in societies with neighbors, and working in companies, organizations with colleagues in departments, etc., may be governed by the same underlying universal rules of organization?

Systems Life Cycles and Entropic Cycling

Open systems are interconnected in a never-ending, n-dimensional space; truly has it been observed that all things are connected. For those seeking to understand systems behavior, this may present a problem: it would be daunting indeed to have to understand the universe of conceptual system space in order to understand local phenomena.

However, another view of this n-dimensional space sees it exhibiting regions and layers, not unlike a spring mattress that can be held up and shaken; waves of movement flow to and from across the steel-spring mattress, but their mean behavior is bounded in regions of the mattress, as waves of motion move back and forth.

With such a complex backcloth, understanding and predicting open systems behavior would be daunting were it not for the many and varied examples to be observed, particularly in the natural world where all systems are open, interacting, dynamic, etc. We see natural systems come and go, to be replaced by others, often the same, sometimes different, in a continual shimmer of life, death, rebirth, growth and decay.

Searching for a theory to support this observed behavior in both the manmade and the natural world results in a number of propositional principles which will be presented individually first, before being bound into a hypothesis or theory.

Principle of system reactions

If a set of interacting systems is in equilibrium and either a new system is introduced to the set or one of the systems or interconnections undergoes change then, as far as they are able, the other systems will rearrange themselves so as to move to a new equilibrium.

This principle is axiomatic for physical system, and is a restatement of Le Chatelier's Principle, expounded in 1888 in connection with chemical equilibrium. It is also reminiscent of Newton's Third Law of action and reaction. The principle is also applicable to social, political, economic, biological, stellar, or any other wholes/systems.

The principle is noteworthy, too, for what it does not say. It has nothing to say about the *manner* of the rearrangement, its speed, direction, linearity or otherwise. Moreover, in the phrase ‘as far as they are able,’ it incorporates a let-out term. It may alternatively be stated as ‘ . . . will rearrange themselves as to oppose the change,’ which amounts to the same thing as moving to new equilibrium.

A trivial example of the principle might concern a person whose weight had been stable for many years, until he gave up playing squash and rugby, only to find that he put on another thirty pounds within six months before his weight stabilized at this new level. A nontrivial example might concern the level of employment in a factory subsequent to a downturn in business, resulting in reduced throughput and return on sales. These in turn will result in reduced purchase of raw materials, and the need for fewer workers. Once redundant workers have left, the factory may return to equilibrium, but at reduced throughput and manpower levels.

Principle of system cohesion

Within a stable system set, the net cohesive and dispersive influences are in balance.

Again for physical systems, this principle may seem axiomatic, a restatement of Newton’s Third Law. However, it is not so obvious in social systems. Consider the hymenoptera, and in particular the honeybees. Honeybees live in a hive with a single queen. The queen exudes a pheromone which is passed around all the bees in the hive, and which exerts a calming influence, such that all the bees get on with their allotted duties. As the hive grows, forager bees have to go further and further afield to find food, having scoured the immediate environs of the hive. At the same time, the hive numbers increase as new workers are hatched out.

A point is reached at which the amount of pheromone exuded by the queen has to be shared between so many bees that there is insufficient per bee to maintain her calming influence, and the time has come to swarm. A new queen takes off with a retinue to start up a new hive, and the process renews.

Not dissimilar processes can be seen in operation within human families and societies. Social bonds may hold the group together, while external influences tend to separate them. Equilibrium persists as long as these two are in balance . . . .

Principle of adaptation

For continued systems cohesion, the mean rate of systems adaptation must equal or exceed the mean rate of environmental adaptation.

This principle may seem rather obvious from the evolutionary biology perspective. It has been suggested that the dinosaurs died out some 64 million years ago, not owing to some meteor impact, but instead due to their inability to adapt quickly enough to falling levels of atmospheric oxygen in the atmosphere. After all, there were many creatures around before and after the dinosaur extinction that survived quite well, including sharks, turtles, crocodiles, beavers (!), and many others. Surely, a meteor strike would have wiped them out, too? No, an inability to adapt seems more likely . . . .

However, the principle applies to all interacting systems, not just prehistoric biological ones. Technological artifacts are a prime example, with manufacturers regularly updating their products, particularly brown goods and white goods, to keep pace with environmental change as well as fashion. For instance, impending shortages of potable water and fossil fuels are driving the evolution of improved reverse-osmosis desalination plants, and of lean-burn automobile engines, electric cars, hydrogen cars, and even cars that run on vegetable oils, rendering them CO_2 neutral — at least in the use of fuel, if not in their manufacture.

Principle of connected variety

Interacting systems stability increases with variety, and with the degree of connectivity of that variety within the environment.

This principle is less obvious. To get a feel for it, consider Figure 2.8, which represents some archetypal open subsystems within systems, with visible interconnected variety. The organic shapes may represent physical systems, social systems, ecological systems, economic systems, or whatever. As the outflow from any subsystem changes, its effects migrate throughout the system and some of them return to affect the initial system change.

The greater the variety of subsystems, the greater the prospect that the outflows from some of the set will match the inflow needs of others in the set — this is complementation. In the limit, there may be so much connected variety that it will prove impossible to invoke any change through the maze of cross- and feedback-connections. This would be a stodgy, overfull kind of stability, were it not for . . .

Principle of limited variety

Variety in interacting systems is limited by the available space and by the degree of differentiation.

The principle requires explanation of both ‘space’ and ‘degree of differentiation.’ Consider an organ pipe. Air in the pipe can vibrate in a variety of modes; the distance between the ends of the pipe,

Figure 2.8 Abstract opens systems (photograph and original painting by the author).

i.e, the available space, limits variety. The degree of differentiation is determined by the physics, which require each vibration mode to be an integer number of half wavelengths.

Variety appears to be limited in many spheres. There is a limited number of ethnic types on the planet: the terms caucasoid, mongoloid, negroid and australoid may be no longer in general use, but they illustrate the limits to variety in racial classification. Race is described today not in observable physical features, but rather in such genetic characteristics as blood groups and metabolic processes; again, blood groups are limited in variety.

Variety is limited in such things as varieties within a religion. Christianity may divide into Roman Catholic and protestant, and protestant may further divide into Methodist, Baptist, and so on, but the list of varieties is really quite short. Predators on the Serengeti Plain are limited in variety: there are lions, cheetahs, leopards. . . types of antelope, zebra, buffalo, etc., are similarly limited.

In general, even where there is seeming-profusion, there is a general limit to varieties within any category.

Principle of preferred patterns

The probability that interacting systems will adopt locally stable configurations increases both with the variety of systems and with their connectivity

As the weave of interactions between systems becomes more complex, it is increasingly likely that feedback mechanisms will arise, and that homeostatic balance will arise, perhaps acting through a series of interacting systems — see Figure 2.8, which illustrates the situation qualitatively.

In the figure, if the large object that looks like a chicken, on the left were squeezed rhythmically, and if all the various tubes were filled with fluids, then the tubes leaving the ‘chicken’ would pass pulses of fluid pressure to other entities in the figure. These would, in their turn, pass on the pressure pulses, and some of these would return as inflows to the ‘chicken.’ Looked at overall, we might reasonably expect waves of pulses going out, waves coming back in, and standing waves might be anticipated. Of course, there would be some absorption of the energy as the fluids passed through the pipes, inflated the various ‘systems,’ and so on, but it is reasonable to suggest that diminishing patterns of behavior would propagate outwards from the source. The greater the variety of systems, and the greater the web of interconnections, the more likely this would be to occur . . . .

Principle of cyclic progression (entropic cycling)

Interconnected systems driven by an external energy source will tend to a cyclic progression in which system variety is generated, dominance emerges and suppresses the variety, the dominant mode decays or collapses, and survivors emerge to regenerate variety.

This is entropic cycling, and it is observed in all complex systems. A classic example is to be seen in Yellowstone National Park (Romme and Despain, 1989). The subject of interest was the relatively rare occurrence of major fires in the forest. Fires were caused, generally, by lightning, which occurred every year, yet major fires were relatively rare, occurring about once every forty years in any given area of the Park. Why?

It transpired that the reason for the relative rarity of major fires was due to ecological succession. Each major fire created a space in which virtually nothing was growing. A few species were

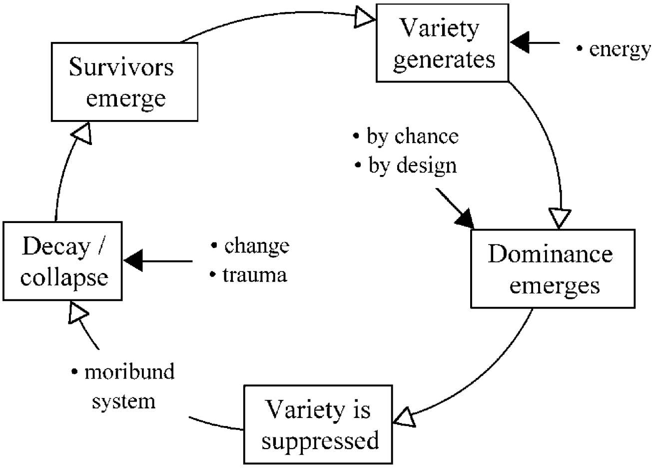


Figure 2.9 Cyclic progression — entropic cycling.

adapted, however, and these started to grow from corms. Birds and bats brought in seeds, and some of these took root where the conditions favored them.

The space encouraged species diversity, so a wide variety of soft-stemmed plants soon started to shoot up towards the sunlight, creating lush green undergrowth. Fast-growing, softwood trees started to grow, mature and then fall into the lush undergrowth, where they rotted down to provide nutrients for flora and fauna, and in particular for the slower growing hardwood trees that took many years to mature. As these hardwoods grew and matured, their canopies progressively shut out the sunlight and the ground level vegetation reduced. The hardwoods also drained the nutrients from the surrounding soil to fuel their growth, further diminishing the prospects for ground level vegetation. Finally, the hardwood trees lost branches, died, and fell on to the now tinder-dry forest floor where they presented an opportunity for the next lightning strike to start a major forest fire . . . .

The whole cycle, from fire to fire, took on average forty or more years. Before the forty-year period had passed, lightning strikes might set trees alight, but fires could not spread because of the damp undergrowth and the moisture retaining plants and softwoods.

And, the whole cycle presents an allegory for entropic cycling in civilizations, companies, enterprises, and complex systems in general — see Figure 2.9. Systems with variety can absorb/adapt to change, trauma and shock. Dominance tends to suppress variety. Once variety has been suppressed, the system becomes vulnerable — it lacks the ability to respond to changing circumstances, should they occur. A system which decays or collapses does not necessarily die, but may recover or re-form — not as the same system, but as something new, attuned to the contemporary context. And, what falls apart is the structure, the interaction between components — but not necessarily the components themselves.

System life cycles: the Unified Systems Hypothesis

The seven principles above have been presented independently; however, they can also be seen as complementary elements in a theory of systems, the Unified Systems Hypothesis, which offers a generic view of how systems synthesize, evolve, stabilize, decay and recycle in a never ending round of entropic cycling. An analogy is drawn between these processes and the human life cycle; a complex system is also said to exhibit a life cycle, in that it has a point of conception, periods of growth and change leading to maturity, followed by cessation of existence in its mature form.

Bringing the seven system principles together creates the causal loop model (CLM) of Figure 2.10. The figure offers insight into how systems evolve and change over time, and most usefully, what are the likely cause of downfall, and what might be done to prevent such downfall . . . .

To appreciate the model of Figure 2.10, start at energy in the top right-hand corner. Energy 'creates' variety, or rather it increases the space within which variety may manifest. We see this in all walks of everyday life: in the variety of housing in richer environs; in the variety of cars in richer cities; in the variety of jobs in cities as opposed to villages; in the variety of species in a tropical jungle compared with a tundra; and so on.

With variety generation, there is increased opportunity for varieties to interact and to react. Where some of that interaction is cooperative, symbiotic, and mutually sustaining, complementary sets of varieties may form. This may be seen as connected variety, which leads to stability owing both to the potential for homeostatic balance and constructive feedback. Complementary sets and connected variety are precursors of stability, or dynamic equilibrium as it might more properly be described in open system terms, i.e., the attainment of steady state. This is holism in principle and in practice, i.e., this is the formation of wholes. Note, there is nothing stated about the manner in which stability arises: it may be linear, chaotic, and even catastrophic . . . .

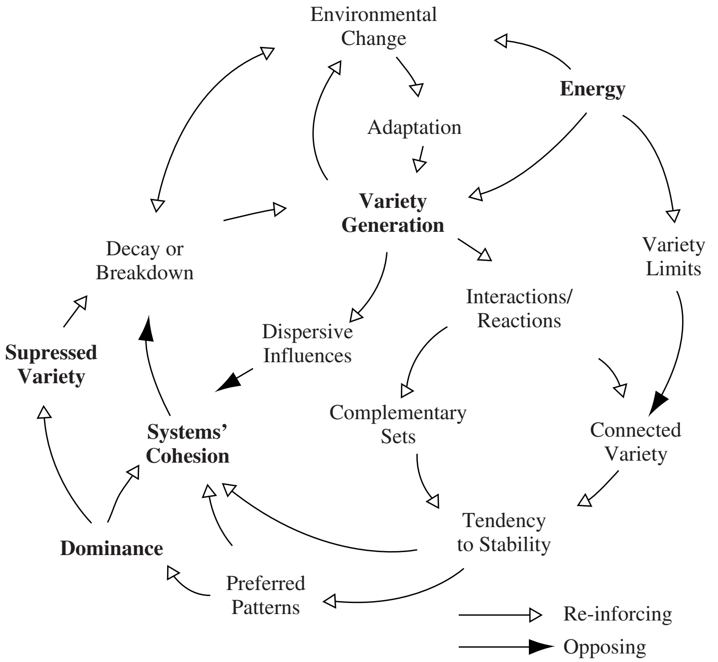


Figure 2.10 The Unified Systems Hypothesis and the system 'life cycle.' (Hitchins, 1992).

As an interacting web of systems forms, it adopts preferred patterns which, although exhibiting high energy, are generally in local energy wells; so, high energy, but not as high as they might otherwise be. And increase in energy would be required to move the system web from one preferred pattern to another; in other words, there is an energy barrier separating preferred patterns.

Preferred patterns encourage systems cohesion, the tendency of the various systems elements to cohere in some way, not necessarily in terms of physical space. This systems cohesion is challenged by dispersive influences, which may be varieties generated by energy and which did not connect to other varieties. In the human body, dispersive influences might be pathogens. In business, dispersive influences might be competition for skilled workers, increases in the base lending rate, and so on.

There is an observable tendency for systems with complementary varieties to encourage one of the varieties to become dominant, to be the leader, to overshadow, to set the rules and limits, etc. this may come about by chance, perhaps, but in the affairs of man it seems to occur as a by-product of male competition. Male-dominated societies require a strong leader. Curiously, female societies seem not to have the same need, although they, too, tend to establish a central coordinator or focus.

While there is no essential need for the dominant member to suppress variety, this seems to be the usual pattern. During times of hardship, in particular, a dominant leader may decide that ‘too much variety within the system is superfluous, even wasteful,’ and may eliminate some of it. Judging what is ‘too much’ variety is fraught with difficulty, so a blunt axe is generally employed. As with the forest in Yellowstone Park, a dominant element may simply absorb so much energy and nutrient that other varieties wither. In business, this is referred to by terms such as ‘returning to core business,’ as opposed to ‘establishing a wide portfolio against the vicissitudes of trade variability’ which occurs earlier in many large organization’s strategic policy.

With a reduction in variety, the system may still appear robust to an external viewer — as the forest of hardwood trees would appear robust. However, the system is vulnerable: when the environment changes, it will lack the variety with which to adapt and respond. In this event, the system will decay or collapse, and its constituents may rejoin the pool of varieties generated by energy, so rejoining the entropic cycle at the start point.

System longevity: system decay

The continual entropic cycle described above is not the only outcome that the Unified Systems Hypothesis proposes. The organismic analogy observes that complex systems, like organisms, often end in spectacular collapse. In the real world, complex systems often seem to collapse in a spectacular implosion, witness the fall of the USSR, and of many major corporations over the years. The model of Figure 2.10 illustrates a mechanism for this explosive/implosive tendency. There is a positive feedback loop in the figure: dispersive influences — systems cohesion — decay or breakdown — variety generation — dispersive influences. In the case of the USSR, once one country had broken away, it joined the throng of international dispersive influences, raising the stakes and encouraging others to break free — with the ensuing domino fall.

However, there are other feedback loops within the figure, which indicate that things do not have to be that way. Consider the loop: variety generation — interactions — tendency to stability — systems cohesion — decay — variety generation. . . . That is a negative feedback, or control loop. It indicates that a system may continue unabated, provided that it does not allow its variety to be suppressed or, if it is occasionally suppressed, to continually renew it.

These notions suggest a rather different basis for the conduct of systems engineering, which in the view of some practitioners is about creating new technological artifacts as solutions to complex problems. Using ideas from the USH as guides, it may be that complex, open systems may be sustained, enhanced, or even destroyed by using connected variety, or the lack of it, as tool or weapon in the armory of the system designer/architect.

The USH is a useful contribution to systems science, in that it is scale independent, system type independent, understandable, and lends itself to simulation and modeling, and in the solving of real-world problems.

Summary

The chapter has looked briefly at systems science: a fuller treatment would have absorbed the whole book and more: the body of systems science knowledge is extensive. Only the main threads that will be of use later, during the development of the systems methodology, have been sensibly addressed. In particular, these addressed the fusion of the natural with the physical sciences. Systems and systems engineering must, of necessity, address all kinds of systems, including natural ones, artificial ones and those comprised wholly or largely of humans — the social, socioeconomic and sociotechnical systems: though, on reflection, a social system is really a natural system: as an apiary or formicarium, so a human society?

The chapter has cursorily addressed the principal physical laws, notably the conservation laws, and those referred to as transport phenomena. Information, it is suggested, is best viewed in pragmatic terms as a nonconserved quantity although energy and entropy considerations still apply as information is passed between systems. Queuing and the analysis of queues are ubiquitous in understanding systems, their interactions, and their ability — or otherwise — to maintain dynamic equilibrium.

Regulation is seen as being significantly less about cybernetics, i.e., negative feedback, and more about the evolution of homeostasis by the balancing of opposing influences. That this is the case arises principally because all systems of interest are open systems, with continuous/continual inflows and outflows; this places emphasis on regulation of the whole by balancing inflows and outflows, as opposed to negative feedback. Cybernetics is an interest within systems science, but its role in underpinning systems stability appears to be secondary.

The need to understand human behavior has raised the profile of social psychology and social anthropology, particularly, within applied systems science. In this, the role of systems engineering, sometimes seen as an adjunct to engineering, is seen in distinct form, since some engineers seem less than interested in psychology, at least in connection with the conception, design and creation of systems. A useful differentiator between engineers and systems engineers, might be that, while the former provides artifacts for people to use or operate, the latter designs systems with people as focal points within the system. Are people inside the sociotechnical system-to-be-created performing functions, or are they instead outside of the artifact-system to be created, as users and operators of such artifacts? That is an important question that will be explored in later chapters.

Also presented in this chapter are systems science models, representing hypotheses rather than established, fully fledged theories. The first of these, the social genotype, draws an analogy between the biological genotype and a social genotype in which, in place of DNA, there are roles and relationships that form and set over a period, to become established. Once set, occupants of each role may come and go, but the role and its relationship with other roles goes on. A newcomer is expected to interact with others in the adopted role through the interaction matrix, and his or her behavior is expected to conform to the established norms; else, the newcomer will be rejected. A group's social belief system is harbored in this role relationship network, with tales, myths and legends being handed on from generation to generation. This appears true of cultures, companies, families, industries, political parties, etc., etc.

A second systems science model is touched upon, briefly — anti-chaos, the appearance of order from disorder. There does appear to by some underlying organizing principle at work in the Universe, presently only dimly perceived and little understood . . . .

The third systems science model is the so-called Unified Systems Hypothesis (USH), which highlights universal systems principles and draws them together into a holistic model of system entropic cycling, that we often refer to as life-cycling, by analogy with our own, organic mortality. The USH suggests the basis for systems cohesion, systems demise, and hence for systems engineering of a rather different variety than that usually pursued. . . on the other hand, it also expresses the basis for holism, the seemingly universal principle of whole formation.

Assignment

You are an international systems consultant, and have been called in to review a government's policy about government computing and processing systems, of which there are very many. Some are concerned with social care and benefits, some with national identify and insurance, some with defense, some with taxation and treasury, and so on; the range is vast. Concern has been expressed about the ultimate vulnerability of the government's computing resource. There are different attitudes being expressed.

One view observes that these various computing systems, although each individually large, are not fully integrated; there is, for instance, no single network connecting, say, defense, with treasury, or social benefits with taxation. Moreover, none is connected to the Internet, and so there has been no need to introduce any anti-viral measures. To the best of their knowledge, no such infections have been experienced . . . .

A second view considers the possibility and risk of some systemic weakness that might affect all the computing systems at once, and which might then bring down the government. The risk, they say, is simply too great to do nothing about it.

You listen to both views and undertake to review their facilities and report back in one week. Using the Unified Systems Hypothesis as your guide, or otherwise, and without actually having to visit any of their sites, identify potential weaknesses in the government's computing systems and strategies, and suggest ways in which they might reduce their risk, if any.