

# **Ross Ashby's general theory of adaptive systems**

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## Abstract

In the 1950s and 1960s Ross Ashby created a general theory of adaptive systems. His work is well-known among cyberneticians and systems scientists, but not in other fields. This is somewhat surprising, because his theories are more general versions of the theories in many fields. The philosophy of science claims that more general theories are preferred because a small number of propositions can explain many phenomena. Why, then, are Ashby's theories not widely known and praised? Do scientists really strive for more general, parsimonious theories? This paper reviews the content of Ashby's theories, discusses what they reveal about how scientists work, and suggests what their role might be in the academic community in the future.

**Keywords:** Cybernetics; Complexity; Adaptation; Self-Organization; Requisite Variety

## 1. Two kinds of contributions to science

There are two ways in which more general theories can be constructed. The first type of more general theory results when a new dimension is added to an existing theory (Krajewski 1977). The new theory is more general because it can explain a larger number of phenomena. For example, in physics relativity theory added the consideration that the relative velocity of two objects would affect mass, length, and time. The gas laws added the diameter of molecules, which previously had been treated as point masses. In cybernetics Heinz von Foerster's work added "amount of attention paid to the observer" to the traditional philosophy of science (Umpleby 2005).

The second type of more general theory is a more abstractly worded theory. The theories of Ross Ashby are examples. However, these theories still require the knowledge in more specialized fields in order to operationalize them and put them to use. For example, Ashby spoke about the need for requisite variety in a regulator. Operationalizing this theory in computer science requires specifying the speed or memory capacity of a computer. In game theory variety is expressed in possible moves. An example of requisite variety in management is the need to match production capacity to customer demand. I shall now review Ashby's method and theories.

## 2. Ashby's method

Ashby used state determined systems to describe the processes of interest to him – regulation, adaptation, self-organization, etc. He used state determined systems not because he thought

the world was deterministic. (Some of my students have jumped to this conclusion.) Rather, he wanted to communicate clearly about topics that had previously been dealt with vaguely. Also, he wanted to deal with nominal, ordinal, and interval variables as well as cardinal variables, since control and communication often do not lend themselves to the cardinal variables that are possible in fields such as physics and economics. Furthermore, he wanted to create a general theory that would encompass systems defined on both animate and inanimate objects. As Ashby put it,

Cybernetics treats not things but ways of behaving. It does not ask “what is this thing?” but “what does it do?”... It is thus essentially functional and behaviouristic. Cybernetics deals with all forms of behavior in so far as they are regular, or determinate, or reproducible. The materiality is irrelevant... The truths of cybernetics are not conditional on their being derived from some other branch of science. Cybernetics has its own foundations (Ashby 1956, 1).

Ashby was particularly talented at creating examples to illustrate his theoretical points. For example, he illustrates learning as movement toward equilibrium by describing how a kitten finds a comfortable position near a fire or learns to catch mice (Ashby 1960). As one example of a sequence of events, he put a flow chart on the door to his office with steps including “knock,” “enter,” etc. (Conant 1981, 363) His example of “The Dynamics of Personality” described a recurring sequence of events in the lives of a husband and wife (Conant 1981, 365). His example, “A Brief History of Amasia,” illustrated legal, cultural, and strategic rules in a multi-nation system somewhat like Europe at the start of World War I. The events that unfolded were determined by the rules within the system (Conant 1981, 367-9).

As I read Ashby’s books I imagined my own examples in fields of interest to me. However, some of my students have wanted examples in their fields of interest to be already in the text. Hesitancy to exercise imagination may be an obstacle to appreciating the relevance and importance of Ashby’s work.

Ashby was concerned not with simple phenomena or with unorganized complexity (e.g., molecules of gas in a container) but rather with organized complexity, including brains, organisms, and societies. His approach to studying organized complexity was unusual. Rather than building a more complex structure by assembling components, Ashby chose to look for constraints or interaction rules which reduce the maximum possible variety to the variety actually observed. Laws, whether scientific or parliamentary, are examples of constraints, which reduce variety from what can be imagined to what is observed.

### **3. Level of theorizing**

Ashby’s level of theorizing was unusual. His interdisciplinary theories are more general or abstract than the theories in most disciplines. Consequently, it can be said that his theories lie at a level of abstraction between the theories in disciplines such as biology, psychology, and economics and more general fields such as philosophy or mathematics.

However, theories at a more general level are neither sufficient nor necessary. A more generally worded theory is not sufficient because “domain-specific knowledge,” which is

obtained from discipline-based theories, is still needed in order to apply the theory in practice.

Also, a more generally worded theory is often perceived as not being necessary. That is, if a scientist is interested only in one field, a theory worded in more general terms may be seen as contributing nothing essential to his or her field. In discipline-based universities only a few people are genuinely interested in more than one field. So, few people feel a need for more general theories. Furthermore, a factor limiting the growth of cybernetics in the United States is that Americans look for meaning through examples or applications. Europeans are more likely to search for meaning in more general conceptualizations (Umpleby 2005). Ashby's theories are very helpful to scientists who are interested in knowing how the theories in two or more fields are similar. In this way his theories aid the transfer of ideas from one field to another. This is why his theories have been of great interest to systems scientists and cyberneticians.

Ashby's theories, because they are very general, are very good theories in that they are parsimonious. They explain a large number of phenomena using few statements. Although Ashby's theories have been criticized for being so general they are tautological (Berlinski 1976), an alternative view is that his theories are axiomatic or definitional. It is remarkable that Ashby was able to formulate theories that work for so many domains. Discipline-based theories do not. One can take the formal structure and operationalize it in many fields. Ashby's general theories then become a tool for developing more specific, operationalizable theories in specific disciplines.

#### **4. Ashby's epistemology**

One interesting feature of Ashby's work is that it is compatible with second order cybernetics (the idea that the observer should be included within the domain of science) even though Ashby never directly addressed the issue of the observer or second order cybernetics. Indeed, Heinz von Foerster created the phrase "second order cybernetics" in 1974 after Ashby's death in 1972. To understand Ashby's epistemology, it is important to be familiar with the terms he used and his definitions. What is observed, he called the "machine." For Ashby, "the system" is an internal conception of "the machine." A "system" is a set of variables selected by an observer. Ashby does not directly discuss the role of the observer in science or the observer as a participant in a social system. But because he defines a system as a set of variables selected by an observer, his work is quite compatible with second order cybernetics.

#### **5. Regulation**

As a person concerned with the successful functioning of brains, Ashby was concerned with the general phenomenon of regulation. Ashby divides all possible outcomes into the goal subset and the non-goal subset. The task of a regulator is to act in the presence of disturbances so that all outcomes lie within the goal subset. In accord with the general nature of his theories, systems that we recognize as regulators can be potentially defined on organisms, organizations, nations, or any other objects of interest.

There are various types of regulators. An error-controlled regulator can be very simple, for example a thermostat. A cause-controlled regulator requires a model of how the machine

will react to a disturbance. One consequence of Ashby's view of regulation is the Conant and Ashby theorem, "every good regulator of a system must be a model of that system." (Conant and Ashby 1970). Von Foerster once said that Ashby told him this was the idea he was looking for when he began his explorations in cybernetics.

## **6. Learning**

For Ashby learning involved the adoption of a pattern of behavior that is compatible with survival. He distinguished learning from genetic change. Genes determine behavior directly, and genetically controlled behavior changes slowly. Learning, on the other hand, is an indirect method of regulation. In organisms that are capable of learning, genes do not determine behavior directly. They merely create a versatile brain that is able to acquire a pattern of behavior within the lifetime of the organism. As examples, Ashby noted that the genes of a wasp tell it how to catch its prey, but a kitten learns how to catch mice by pursuing them. Hence, in more advanced organisms the genes delegate part of their control over the organism to the environment. Ashby's Automatic Self-Strategizer is both a blind automaton going to a steady state, at which it sticks, and a player that "learns" from its environment until it always wins (Conant 1981, 373-6).

## **7. Adaptation**

As a psychiatrist and director of a psychiatric hospital, Ashby was primarily interested in the problem of adaptation. In his theory of adaptation two feedback loops are required for a machine to be considered adaptive (Ashby 1960). The first feedback loop operates frequently and makes small corrections. The second feedback loop operates infrequently and changes the structure of the system, when the "essential variables" go outside the bounds required for survival. As an example, Ashby proposed an autopilot. The usual autopilot simply maintains the stability of an aircraft. But what if a mechanic miswires the autopilot? This could cause the plane to crash. An "ultrastable" autopilot, on the other hand, would detect that essential variables had gone outside their limits and would begin to rewire itself until stability returned, or the plane crashed, depending on which occurred first.

The first feedback loop enables an organism or organization to learn a pattern of behavior that is appropriate for a particular environment. The second feedback loop enables the organism to perceive that the environment has changed and that learning a new pattern of behavior is required. Ashby's double loop theory of adaptation influenced Chris Argyris (1982) who wrote about "double loop learning" and Gregory Bateson (1972) who coined the term "deutero learning."

The effectiveness of the double loop conceptualization is illustrated by the great success of quality improvement methods within the field of management. Probably no set of management ideas in recent years has had a greater impact on the relative success of firms and the relative competitiveness of nations. This success is indicated by the international acceptance of the ISO 9000 standard as a minimum international model of management and the creation of quality improvement awards in Japan, the U.S., Europe, and Russia to identify the best companies to emulate. The basic idea of quality improvement is that an organization can be thought of as a collection of processes. The people who work IN each process should also work ON the process, in order to improve it. That is, their day-to-day work involves

working IN the process (the first, frequent feedback loop). And about once a week they meet as a quality improvement team to consider suggestions and to design experiments on how to improve the process itself. This is the second, less frequent feedback loop that leads to structural changes in the process. Hence, process improvement methods, which have been so influential in business, are an illustration of Ashby's theory of adaptation.

## **8. Intelligence**

Ashby defined "intelligence" as appropriate selection. He asked the question, "can a mechanical chess player outplay its designer? He answered the question by saying that a machine could outplay its designer, if it were able to learn from its environment (Conant 1981). Furthermore, intelligence can be amplified through a hierarchical arrangement of regulators. The lower level regulators perform specific regulatory tasks many times. The higher level regulators decide what rules the lower level regulators should use. A bureaucracy is an example. Gregory Bateson said that cybernetics is a replacement for small boys, since in earlier days small boys were given the tasks of putting another log on the fire, turning over an hour glass, etc. Such simple regulatory tasks are now usually performed by machines, which are designed using ideas from cybernetics.

## **9. The law of requisite variety**

The law of requisite variety is sometimes called Ashby's law. It is probably his most widely known contribution to science. One can explain the law either as a relationship between information and selection or as a relationship between a regulator and the system being regulated. In terms of a relationship between information and selection, the law of requisite variety says that the amount of selection that can be performed is limited by the amount of information available. Once one has exhausted the information available, no further rational grounds for selection exist. For example, universities routinely require applicants to submit not only their grades in earlier schooling but also their scores on standardized tests. Recommendations are also required. If such information is not provided, no rational grounds for selection exist.

In terms of the relationship between a regulator and the system being regulated, the law of requisite variety says that the variety in a regulator must be equal to or greater than the variety in the system being regulated. For example, when buying a computer, one first estimates the size of the task – the data storage space and speed required – and then buys a computer with at least that capacity. A smaller computer would not be adequate. As a second example, when a manager supervises employees, it is necessary that the manager pays attention to only some of the behavior of the employees. Otherwise the manager will not be able to control the variety the employees can generate. "Management by exception" refers to the practice that a manager trains subordinates how to handle various tasks. When they encounter a task they have not been trained for, they ask the manager. The result is that each employee interacts with the manager only occasionally; and the manager is able to supervise several subordinates.

The law of requisite variety has some important implications. When confronted with a complex situation, there are only two choices – increase the variety in the regulator, usually

by hiring staff, or reduce the variety in the system being regulated. The second strategy is possible because the observer defines “the system.”

In an earlier article (Umpleby 1990) I described four strategies of regulation: 1) one-to-one regulation of variety, for example, football or war; 2) one-to-one regulation of disturbances, for example crime control in a city (2/ 1000); 3) changing the rules of a game, for example government regulation of industry (1/ 640,000); 4) changing the game, for example the global models produced by the Club of Rome in the 1970s (12/ 4 billion). The global models focused on population, resources, and environment rather than the ideological competition of the Cold War (Meadows, et al., 1974). As the subject of attention moves from the concrete to the conceptual the impact of decisions increases. By choosing a more conceptual strategy, rather than a more direct and immediate strategy, it becomes possible to regulate a very large system, such as the global economy. In the example above the difference in regulatory capability between any two steps is a factor of about one thousand. However, the same strategies can be used in managing a household or managing an organization. The law of requisite variety says that variety must be controlled, if successful regulation is to be achieved, but variety need not be controlled directly. If one is clever in creating conceptualizations and organizational structures, the amount of variety that can be controlled can be very large.

## **10. Self-organizing systems**

In the 1950s the concept of self-organization was of interest due to a debate over whether one should program machines that would behave in an intelligent manner or design machines that would learn from their environments, hence, they would organize themselves. In 1956 at a conference at Dartmouth University people in the field of artificial intelligence chose the first strategy. Cyberneticians chose to continue studying neurophysiology in order to better understand learning and human cognition.

Three conferences on self-organization were held around 1960. At the time a self-organizing system was thought to interact with and be organized by its environment. However, Ashby formulated a different conception of self-organization: “every isolated, determinate, dynamic system obeying unchanging laws will develop organisms that are adapted to their environments.” (Ashby 1962) He explained the idea as follows: Imagine a system. It has unstable states and stable, equilibrium states. Over time it will go toward the stable, equilibrium states. As it does so, it selects, thereby organizing itself. Such a system is open to energy (it is dynamic) but closed to information (the interaction rules among the elements of the system do not change). At about the same time Heinz von Foerster, with his example of the magnetic cubes in a box, explained how such a system could generate more complex entities (von Foerster 1962).

Interest in self-organizing systems reemerged in the 1980s and 1990s as a result of interest in cellular automata, fractals, and chaos theory. Although there clearly were new techniques available for computer simulation, it is surprising that so little reference was made to the basic theoretical work done in the 1960s (Asaro 2007). Ashby’s definition of self-organization is different from the earlier definition. The earlier definition of self-organization is what one finds in the literature on complexity where it is possible to speak of self-organizing, adaptive systems (Waldrop 1992). In Ashby’s definitions an adaptive system is

open to information, but a self-organizing system is closed to information (the interaction rules do not change during the period of observation).

The principle of self-organization is an example of Ashby's talent for formulating general principles. His principle of self-organization is a more general version of Adam Smith's theory that industrial firms will compete to bring to market products desired by customers, Charles Darwin's theory of natural selection among organisms and species, Karl Popper's theory of scientific progress by means of conjectures and refutations, and B.F. Skinner's theory that behavior modification can be achieved through rewards and punishments. In each case variation is subjected to selection in a competitive environment.

Furthermore, the principle of self-organization leads to a general design rule – to manipulate any object, expose it to an environment, such that the interaction rules between the object and its environment change the object in the desired direction. This type of regulation relies not on changing the object directly but rather on changing the environment of the object. For example, to make steel from iron, put the iron in a blast furnace; to educate a child, send it to school; to regulate behavior of individuals, administer rewards and punishments; to control corporate behavior, pass laws and create regulatory agencies.

## **11. The future of Ashby's legacy**

Ross Ashby left a legacy of elegant theories of regulation, learning, adaptation, and self-organization. He created a new level of theorizing about systems that process information and perform selections. These theories have influenced many fields – computer science, robotics, management, psychology, biology, sociology, political science, and the philosophy of science. As a transdisciplinary field cybernetics serves as a catalyst for further developments in many fields. That is the role that cybernetics and general systems theory have played until now. However, when we think about the impact that these theories may have in the future, at least two possibilities come to mind.

Just as physics provides a theory of matter and energy which is used in the various fields of engineering, cybernetics may one day be seen as providing a theory of form and pattern for the various fields of the social sciences, library science, computer science and design disciplines such as architecture and public policy.

Also, more general theories hold great promise for Institutes of Advanced Study, which are becoming common on university campuses as ways of fostering interdisciplinary communication. Indeed, John Warfield has suggested that such institutes should offer their own degrees and that systems science and cybernetics should be the core curriculum. He proposes that the modern university should be thought of as consisting of three colleges. The Heritage College would consist of those fields that teach what we have learned in the past – the sciences, the humanities, and the arts. The Professional College would consist of the applied fields – engineering, law, medicine, business, and agriculture. The Horizons College would be concerned with the future and with design. It would integrate the knowledge of the other two colleges and bring people together to work on problems that do not yield to disciplinary analyses and solutions (Warfield 1996).

Despite the fact that more general theories are more valuable because they explain more phenomena with fewer statements, Ashby's theories have not received as much attention as



they deserve. The reason no doubt lies in the traditions in universities that enforce narrow specialization. However, as knowledge grows and an integrated understanding is needed to cope with the problems of a global society, probably increased attention will be paid to more general theories. When that day comes, Ashby's work will receive renewed attention and acclaim.

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