

# MEASURING COMPLEXITY: THINGS THAT GO WRONG AND HOW TO GET IT RIGHT

Vincent Vesterby

## Abstract

Seven problems that occur in attempts to measure complexity are pointed out as they occur in four proposed measurement techniques. Each example method is an improvement over the previous examples. It turns out, however, that none are up to the challenge of complexity. Apparently, there is no currently available method that truly gets the measure of complexity. There are two reasons. First, the most natural approach, quantitative analysis, is rendered inadequate by the very nature of complexity. Second, the intrinsic magnitude of complexity is still holding at bay attempts to use both quantitative and qualitative methods combined. Further progress in complexity science and in systems science is required. Any method that simplifies will fail because it ignores what complexity is. Techniques of understanding that do not simplify, but rather provide ways for the mind to grasp and work with complexity are more effective in getting its measure.

## Introduction

For the analysis and management of complexity, simplification guarantees failure. It is understanding that is the proper tool for dealing with complexity.

Measuring techniques that simplify miss the intrinsic nature of complexity. Simplification fails because it is the opposite of complexity. It does not have what it takes to be a tool of analysis or management of complexity, and in practice, therefore, tends to avoid complexity, to shy away from direct dealings with it, or at best to provide nothing more than an inadequate approach.

Understanding does not simplify, but instead provides ways for the mind to grasp and work with complexity. Understanding accepts complexity—accepts it for what it is—observes it, and then uses the intrinsic qualities found therein as tools for further exploration, analysis, and the ongoing enhancement of understanding. An example of using understanding in this way was contributed to the 3<sup>rd</sup> International Workshop on Complexity and Philosophy at Stellenbosch.

Josef Zelger described an effective technique for deriving the most significant information from multiple interviews (2007: 187). He used fractal processing and organization such that while he simplified the language, he did not simplify the meaning. There is a fascinating parallel between the manner in which the components and levels of natural hierarchic organization are still present and playing their roles as the deep structure of the highest level, and the manner in which the significant content of the original interviews is refined and yet maintained up through the hierarchic organization of Zelger's method. The multiple occurrences of significant meaning at the initial stage of the technique, the lowest hierarchical level, are combined and still playing their role in the final product, the highest level. Instead of shying away from the complexity of the interviews, this method works with it, refines it to obtain the most significant meaning.

Simplification often occurs in attempts to achieve a quantitative measure of complexity. However, because of the role of organization in the nature of complexity, you cannot measure it adequately by way of quantification alone. Quantification is a simplification because it ignores the organizational aspects, the patterns of organization. Just as reduction without synthesis is not enough, quantitative analysis without qualitative analysis cannot actually measure complexity.

The distinction between the simplification that goes with quantitative measure alone and the understanding achieved by including qualitative analysis has to do with the difference between measuring something and taking its measure. Measuring gives a quantitative result, a magnitude, or an index number that can be used for comparing one situation with another. Taking the measure provides an assessment of the situation. To get the measure of complexity it is necessary to achieve an understanding of it. Because of the role of organization in the intrinsic nature of complexity, understanding requires that quantitative analysis be in the service of qualitative analysis.

This paper addresses issues in the status, legitimacy, and frameworks of knowledge regarding complex systems by analyzing why current methods of measuring complexity either fail or are inadequate, and by explaining why measurement must play an accessory role to understanding in the analysis and management of the serious complexity of systems from cells to ecosystems.

## **On the Nature of Complexity**

To measure complexity, it is necessary to work directly with the situation of concern.

First, complexity itself must be looked at—carefully—setting aside subjectivity, setting aside goals, intentions, assumptions, hopes, prejudices, and all the rest. Subjectivity distorts observation, distorts a person's relation with reality outside their mind. Considering the nature of the problems we face, we cannot afford the comfortable luxury of subjectivity. A realistic definition of complexity must be based on the nature of complexity itself, not on human issues of purpose, limitations of a disciplinary specialty, limitations of a methodology such as mathematics or computers, limitations of the mind that mislead a researcher to easy "solutions" such as simplification, or reduction not combined with synthesis. In the analysis of the intrinsic nature of reality, it must be expected that any situation will be anywhere from ten to thousands of times more complex than first anticipated. Achieving an understanding of complexity and the ability to manage it is, of necessity, a complex endeavor. In establishing an accurate, universal, basic descriptive definition of complexity, it is necessary to accept that it will involve complexity, that what it states about complexity will not imply any easy approaches. Instead, it will indicate what data and understanding should be acquired.

All situations, including all systems, are made up of components and relations between those components. Complexity is quantity and diversity of components and relations. Anything that increases these factors increases complexity. There are six basic quantities to the complexity of any situation—first, how many components there are, second, how many different kinds of components, and third, how many of each kind; fourth, how many relations there are, fifth, how many different kinds of relations, and sixth, how many of each kind. More detailed quantitative analyses of complexity are possible, such as how many relations a particular component has and how many different

kinds they are, but the six basic quantities are minimal for understanding the quantitative aspects of complexity. A method that neglects any of these six is incapable of providing an adequate quantitative analysis of complexity.

Determining the degree of complexity of a situation or system by way of its six basic quantities is just a beginning. There is more to the meaning of this basic definition than the obvious quantitative aspect. Diversity of components and relations means different kinds of components and relations. The definition includes what they are and what roles they play such that the definition is really about a pattern of interrelations, about a pattern of organization that has the quantitative factors as aspects of what it is. Complexity is quantity and diversity of components and relations, which together constitute a pattern of organization. Ultimately, it is organizational complexity that we must learn how to measure, how to live with, and how to manage.

## **Examples of What Goes Wrong**

Complexity is just plain hard to work with. The problem is one of magnitude, great numbers of components and relations, and from them, great complexity of organization. In research there are two common consequences. First, there is a tendency to shy away from complexity itself, avoiding direct dealings with it. And second, in those cases with a direct approach, there is a tendency for the chosen method to be too simple, and thereby not up to the challenge of complexity.

The problem with techniques for measuring complexity that rely on various forms of simplification is that they lose contact with the organizational aspect. They thereby remove the possibility of achieving understanding of the situations and systems of concern, and the problems that are occurring within them.

By examining a series of attempts to measure complexity, and seeing why each fails, there is exposed a trail from the unrealistic to the inadequate. The examples that follow show a failure to capture the organizational aspect of complexity despite the progressive improvement in approach that is evident in the series. There are seven steps in this progression that are evident in four example cases. These are steps of mistakes in the approach to measuring complexity that fall into the two broad categories of avoiding facing complexity, and facing it inadequately. While the first example is guilty of them all, the last example suffers from only one.

### ***Seven Mistakes in Approach***

#### **Imaginary Measure**

First there is the unrealistic approach. This avoids real complexity entirely by inventing an imaginary measure upon which to focus attention.

#### **Measuring Related Factor**

The second way shies away from complexity by measuring some factor that is related to but not actually intrinsic to the complexity of the situation. These factors are typically derived from the complex situation by way of some procedure each step of which takes the analysis further and further away from the nature of the complexity of interest.

#### **Measure Derived from Simple Stage**

A third approach avoids serious complexity by the choice of a situation at the simpler end of the development of complexity. In this case the results are not transferable to situations of greater complexity.

### **Measure Derived from Limited Field of Research**

A fourth problem occurs when a specialist attempts to define and measure complexity in terms of some particular branch of science or limited field of research, which inevitably results in a somewhat simple or otherwise limited view of complexity. What gets measured in these cases is not generally applicable to other complex situations.

### **Research Tool Dominates the Measurement**

A fifth way in which the organizational complexity of real systems is neglected occurs when a powerful and exceptionally successful research tool comes to dominate the thinking of the researcher. The nature of the tool and all that can be done with it tempts the user to be more involved with its use and less than realistic in its application to the intrinsic nature of the complexity of reality. Math and computers can have this effect. In these cases, what gets measured is often more an aspect of the tool than of the real world complex system that is the target of analysis.

### **Using Quantity Alone**

The sixth mistake in approach is the attempt to measure complexity by way of quantitative analysis alone. While a definitely realistic approach, it ignores qualitative analysis and is doomed to inadequacy.

### **Using too Few Quantities and Qualities**

And seventh, when both quantitative and qualitative analyses are employed, there is still the magnitude of diversity of relations to deal with. Too few quantities and too few qualities are used, which leaves this, the best approach, still inadequate.

### ***The Examples***

In the following examples, there are usually several problems in each case. Each example, however, is presented to emphasize one or two of the seven problems listed.

#### **1. Kolmogorov Complexity—Imaginary Measure, Measure Derived from Simple Stage, and Research Tool Dominates the Measurement**

Kolmogorov complexity is a technique that avoids measuring the target complexity by turning to a concept that does not refer to anything that exists. “The *Kolmogorov-Chaitin* complexity  $K(x)$  of an object  $x$  is the length, in bits, of the smallest program (in bits) that when run on a *Universal Turing Machine* outputs  $x$  and then halts” (Feldman and Crutchfield, 1998). But, as Penrose says (1989: 34), “One thing to bear in mind about a Turing ‘machine’ will be that it is a piece of ‘abstract mathematics’ and not a physical object.” It is an idea without a reality referent. If Kolmogorov-Chaitin complexity requires a Turing machine, then there is no such thing as Kolmogorov-Chaitin complexity.

#### **2. Logical Depth—Measuring Related Factor**

Logical depth is a technique that avoids measuring the target complexity by turning away from it and measuring something else. If Kolmogorov-Chaitin complexity were real, it would have been the length of a program. Logical depth is related in that it is supposed to be the length of time it takes to run that program. “Logical depth is the run time required by a universal Turing machine executing the minimal program to reproduce a given pattern” (Feldman and Crutchfield 1997: 6). The idea behind this form of complexity measure is the relation between the complexity of a situation and the length of time it takes to create that complexity—the greater the complexity, the longer the pathway from simple origins to that particular stage of complexity, and the longer the time it takes to cover that distance. Logical depth suffers the same fate as Kolmogorov-Chaitin complexity—the nonexistence of universal Turing machines.

The hope was to use something proportional to the complexity of a situation as an indicator of the magnitude of that complexity. If the Turing machine part is thrown away, then the basic idea can be applied to any real process that produces complexity. However, there are two problems that render the technique marginal at best.

First, while there is some obvious truth to the idea that it usually takes longer to create developed forms of complexity, there are actually so many different kinds of creative processes, each of which has its own variable relations between the running time and the nature of the emergent patterns of organization, that the proportional relationship is not consistent. The rate of biological evolution, for example, varies tremendously in concert with the nature of the situation in which it is occurring. With a stable environment and no access to new territories and new resources, evolution tends to progress relatively slowly. Many variations that occur are inappropriate to existing stable conditions and do not continue in the population as components of the gene pool. A changing environment or access to new resources provides opportunity for those variations to continue. Evolution progresses more quickly the more opportunity there is for variations to remain as parts of the gene pool. Thus, the degree of complexity of an organism is not reliably proportional to the time it took for that organism to evolve.

Compare the complexity of a Blue Whale with that of a one-celled organism living on the sediments at the bottom of the ocean. The difference in complexity between the two is beyond the capacity of the human mind to comprehend. But the ancestry of both organisms traces back to the same origin. The length of time of the evolutionary process that created the relatively simple one-celled creature is the same as that for the biggest, most complex animal with which it shares the ocean. They each have the same logical depth by this measure, and thereby should have the same magnitude of complexity.

The hoped for proportionality between running time and resultant complexity evaporates further if the technique is applied to obligate parasites. These creatures often evolve to a simpler form appropriate to their extremely specialized role. It takes extra evolutionary processing, extra running time, to create this decrease in the complexity of these organisms. There are other examples. With ecological succession, such as the recovery process of a devastated ecosystem, the climax community of the final, relatively stable stage can have less species diversity than some of the prior stages of that succession. As a last example, a programmer could design a program to progressively lessen the complexity of its output with additional running time. Perhaps logical depth (without the Turing machine) might be used in some relatively simple situations, but

where there is advanced development, the relations between the nature of the particular process of emergence and the nature and degree of the complexity of the emergent product are too complex to be sufficiently consistent for this technique to be of use.

The second problem with running time as a measure of the complexity of the emergent product is that it violates the prime imperative of analysis: Look to the subject of investigation itself. Running time is always two steps away from the intrinsic complexity of the subject of investigation. The real problem here is that the target complexity resides in the target situation, not in the program that created that situation, nor in the length of time it took to create that complexity. Each step away from what is the focus of study adds extraneous factors, which can play roles that distort the analysis. And finally, because logical depth measures something extrinsic to the complexity of interest, it misses entirely the crucial aspects of qualitative organizational complexity.

### **3. Calculating an Index Number—Measure Derived from Limited Field of Research and Using Quantity Alone**

The next technique for measuring complexity does not attempt to avoid dealing with it directly. It takes a realistic approach, counts the right things, and is appropriate for the intended goal, which is a simple estimate of commercial product complexity. Marc Meyer (1997: 97) presents a method that consists of (a) counting the parts of the complex situation, the different types of parts, and the interfaces (the relations) of each part, (b) multiplying these three sums together, and (c) calculating the cube root of the product of that multiplication to get a *complexity factor*. With access to these quantities such that they can be counted, or accurately estimated, the technique can be applied to any complex system, providing an index number for each system that is comparable with such numbers derived from other systems.

The problem is that this method is an example of a specialized measure designed for a limited goal. As such, it is inadequate for the analysis of more serious complexity because it is incomplete. There are the six quantities that are minimal for understanding the quantitative aspects of complexity—first, how many components there are, second, how many different kinds of components, and third, how many of each kind; fourth, how many relations there are, fifth, how many different kinds of relations, and sixth, how many of each kind. Meyer's complexity factor uses two of these six quantities directly, parts and kinds of parts, plus one extra, the number of relations of individual components. While this additional quantity is significantly helpful, it does not compensate. Four of the required quantities are left out—most significantly the number of relations and the number of different kinds of relations—leaving this method unable to identify, and thereby get the measure of, the organizational intricacy of the system.

These first three techniques for measuring complexity seek to produce index numbers that can be used to compare the complexity of one situation with that of another. This may work for relatively simple situations. However, it fails for systems with any significant diversity of relations because, as a strictly quantitative approach, it is a simplification that does not take into consideration the significance of organization in the nature of the complexity that results from diversity of relations. The six basic factors for understanding the quantitative aspect of complexity provide nothing more than a quantitative understanding. It does not matter how many additional, more detailed quantities are added to the six. A quantitative index can give only the amount of relation.

It cannot give the pattern of relation, and pattern of relation is of paramount importance to the nature of well-developed complexity. At the cellular level of organization, the first level of well developed complexity, Oltvai and Barabasi point out that, “Although molecular biology offers many spectacular successes, it is clear that the detailed inventory of genes, proteins, and metabolites is not sufficient to understand the cell's complexity” (2002).

A single index number is also inadequate because it does not distinguish different types of complexity. For example, at the organism level of complexity, a lion and a zebra may have relatively similar complexity index numbers, but that does not make explicit the difference between the two. Zebras, however, for the management of their life style, are quite concerned with the distinction. With developed complex systems, it always makes a difference what kind of systems they are.

#### **4. Crawley's Complexity Measures—Using too Few Quantities and Qualities**

The last example tackles complexity directly, focusing on the relational aspects. This case is of particular significance because it involves a transition from simple quantitative analysis to qualitative considerations. Matti J. Kinnunen presents several factors to measure that were suggested by Edward F. Crawley. “Crawley defines three complexity measures: the number of interconnections and their types, the sophistication of the interconnections, and sensitivity or robustness of the interconnections” (2006). The number of interconnections is a quantitative factor, while the variation in types is a qualitative issue. The sophistication of the interconnections is qualitative, while their sensitivity or robustness is primarily quantitative. Crawley's measures, like Meyer's, do not go far enough in that they do not include every factor that should be quantified. More significantly, and even though the method includes qualitative considerations, it fails because what it does cover in a qualitative manner does not lead to an understanding of the pattern of organization.

There are descriptions of complex systems, cells or ecosystems for example, that are much more inclusive than Crawley's set of measures. When honed down to their basic factors of quantity and quality, they could be used as the basis of a technique to take the measure of these systems. The problem, even here, is that such a technique would still be incomplete, and not yet up to the task of getting a measure of the complex systems that are of most concern. No technique has yet been devised for the measurement of complexity that can be applied to most complex situations such that the complexity of those situations can be compared one to another in a way that provides significant understanding.

When the best approach is still inadequate, it is, in large measure, because system science is not yet sufficiently developed to provide a complete list of which quantities and qualities must be counted and understood in order to take the measure of well-developed complexity. The magnitude of the task, the extent of the quantity and intricacy of the complexity, is still holding at bay the sciences of complexity and systems.

This state of affairs is commonly made evident by the language used in relation to highly complex systems. The systems from cells to ecosystems are the most complex known to exist. They are often referred to as “open systems” that are “far from equilibrium.” The problem is that both these descriptors do not distinguish these systems from those that are far less developed, nor from those that are different in kind. For

highly developed systems these descriptors are so general and primitive that they are out of place compared to those that are more appropriate, such as self-constructing, evolving, and adapting systems. Kauffman (1993: 389) provides an interesting example of the juxtaposition of the appropriate with the inappropriate, "...the evolution of *self-constructing* open, far-from-equilibrium systems..." It is like saying a living cell is composed of a multitude of interrelating molecules. So is a rock.

## How to Get It Right

If there is currently no method yet devised to significantly measure complex systems such as those met with in medicine, culture, economics, government, and human ecology, and if this is due to the state of development of science in general, and in particular the sciences of complexity and systems, in that the requisite information is not yet available, then what is to be done while we wait for those scientific advancements? The answer in short is to focus primarily on understanding these systems. It is easier to understand them than it is to measure them. And the reason for that is that there are general patterns of material organization of system origin, structure, and process that occur and play their roles in diverse situations and at multiple levels of the hierarchic organization of material reality, from elementary particles to galactic clusters. They are variously referred to as general systems principles, isomorphies, or as being analogous. The ability to recognize these patterns in their various forms, and to understand what influence they have on the nature of a system, provides broad and deep understanding—the understanding of the origins, structure, and processes of complexity.

If it is known what a system is and how it operates, that knowledge provides a route to predicting its behavior, managing it, and repairing it when necessary. The task of measurement is lessened, rendered more realistic, more practical, being required only in specific aspects of prediction, management, and repair.

The contribution to the Workshop on Complexity and Philosophy at Stellenbosch, from Dmitri M. Bondarenko discussed two of these patterns of organization that occur at the level of social organization. They are aspects of hierarchic order in human societies. In a heterarchic hierarchy, the position of an individual can change, while in a homoarchic hierarchy the social order remains the same in that an individual has little or no chance of changing social status. Bondarenko emphasized the inadequacy of a purely quantitative approach and the importance of adding qualitative analysis. "So, it does look like it is impossible to measure degrees of homoarchy and heterarchy in a society with mathematical exactness, for example, in per cent. A purely quantitative approach is also inapplicable . . ." "[T]he aim of this analysis in the vein of systems theory (e.g., Laszlo, 1996: 95–126) should be not to count the hierarchies but to understand the way they are related to each other" (2007: 37). Bondarenko further emphasized that these factors are general patterns of organization that occur and play roles in more than one kind of social situation. "[A]lso very importantly, I believe it is legitimate and even necessary to apply both notions – of heterarchy and homoarchy – within a broad framework of social relations and societal structure in general, not to power relations only" (2007: 39).

The contribution to the Workshop by Kurt Richardson made suggestions on how to bring a tool of analysis in line with the patterns of organization of the system under investigation, and thus deal with complexity as complexity. These suggestions counter



the tendency for the power of a tool to dominate the thinking of the researcher. He pointed out the possibility of multiple states for the nodes in networks, and arbitrary degree of transition function complexity. Then there is what he appropriately called a more sophisticated approach, which is to represent nodes as sub-networks (2007: 211).

### ***Diversity of Patterns of Relations***

There are a vast number of specific structural/process patterns of material organization that play specific types of roles in the various different situations in which they occur. A modern generalist uses the term *factor* to refer to anything that exists and that plays a role in the situation in which it occurs, and often refers to general patterns of organization as factors. A few examples of these factors that exist as specific patterns of organization are sequentiality, self-organization, emergence, hierarchy, open through-flow structure and process, modularity, feedback, growth, biological evolution, and ontogeny. Some others are change in self-identity, combinatorial enhancement, consequent-existence, determinate reality, development, initiation, and transformation point.

Virtually all of these factors develop, occurring in simple form in simple situations, and in increasingly complex forms as additional factors play roles in more complex situations. In simple form they play simple roles, and in more complex forms they play more complex roles. In general, the form they have in simple situations is the form of their intrinsic identity. When the pattern occurs in complex form at higher levels of organization, the foundational pattern is still there playing a deep structure role. Thus, what goes on at simpler levels is key to understanding higher levels. For example, it is not possible to understand human social systems, culture, economics, or history without understanding the psychology of being human.

While general systems deals with them in systems, and complexity deals with them in complex situations, a modern generalist finds and works with them wherever they occur, from their simple origins to their most developed forms and highest occurrences in the hierarchic organization of reality. By understanding what goes on at the simpler lower levels, a modern generalist gains improved understanding of what is going on at the more complex higher levels. For example the phrase, “far from equilibrium,” when used as a descriptor for complex adaptive systems, is both true in a minor sense, the usual meaning, and false in a significant sense when the development of the factor equilibrium is followed up through its interrelations with other factors. When complex adaptive systems, such as cells and organisms, are at steady state or homeostasis, those systems are actually at equilibrium in that the same factors that create and maintain the equilibrium in a chamber containing a gas are still present and playing the very same roles that result in steady state and homeostasis. The difference is that at these developed stages there are additional factors that are also playing roles resulting in a much more complex organization of the structure and process of these developed forms of equilibrium.

Homeostasis is not actually far from equilibrium. It is equilibrium, developed equilibrium, equilibrium and a whole lot more. To truly understand well-developed high level systems, it is necessary to understand the developments of the various factors that make those high level systems what they are. Developed systems are composed of subsystems, which are themselves made up of lesser systems. To understand the whole, it

is necessary to understand each of these hierarchic levels, what they are and how they interrelate one with another. Part of that understanding is how the various factors, like equilibrium and cause, that make systems what they are, change from level to level, from subsystem to subsystem, while still maintaining the basic nature of what they are.

Quantitative analysis is one tool of many that must be applied to derive qualitative analysis, to derive understanding. Qualitative analysis provides the understanding that in turn provides management capability. When analyzing complexity by way of understanding, it is most effective to think in the mode of organizational complexity, that is, by using the factors that together comprise this form of complexity. Some examples of the factors of organizational complexity are (1) development as understood by a modern generalist, (2) hyper-relational hierarchic organization, (3) networks, (4) modularity, (5) processes, and (6) systems that are composed of interrelating subsystems.

Applying this to real world problems, it is most effective to think in the mode of system malfunction. When a system is malfunctioning, the problem can often be traced to the malfunctioning of one of its subsystems. Fixing the subsystem brings the larger system back into its normal or intended manner of operating. The key to solving the overall problem here is to understand the interrelational organization of the system. It is necessary to know the basic subsystem components of larger systems and the manner in which they create and maintain the larger system. With these systems, it is not just quantity of components and relations, or amount of organization—but additionally pattern of organization. With significant complexity, it is understanding that provides the measure.

### ***Sophisticated Complexity***

The types of serious problems we face are occurring in highly developed systems, in situations of extreme complexity. There is an additional aspect of complexity that characterizes highly complex systems. The six basic quantities of complexity, plus all the more detailed quantities, interrelating all together, develop into sophisticated complexity.

As additional factors occur and play roles in a situation, the organization of that situation changes, it develops. Like nearly all factors of the origins, organization, and change of reality, organizational complexity develops, originating in simple form, and becoming progressively more complex with the roles of additional factors. The sequence of stages of development from single celled organisms up to ecosystems occurs at the most highly developed end of the development of organizational complexity. The sophisticated organizational complexity of these systems is unique due to the great diversity and intricacy of the ordered interactions of structure and process between the components.

These forms of organization are sophisticated compared to the complexity of prior stages. Sophisticated complexity is the most highly developed form of organizational complexity that is known. This is not the complexity derived from simple interactions of simple components. This is not the relatively simple complexity of crystals with their billions of components arranged in more or less precise order. Nor is it the simple complexity of the ordered relations that occur with fractals. Even the complexity generated with cellular automata is simple by comparison. This sophisticated complexity is beyond the initial stages of the complexity derived from the often complex interactions of complex components. It is beyond the impressive geologic complexity that occurs with

the chemistry of the hot stew of diverse components of a rising volcanic magma, as it eats its way up through the layers of various kinds of rock, before it reaches the surface and creates a volcano. Here the great diversity of atoms and molecules that become involved with a rising magma leads to a great diversity of relations, which in turn results in a great diversity of structure and process.

However, because of the heat and dynamics of the magma, the structure of the molecules and minerals that are created there, and the length and complexity of the chemical pathways that create them, are limited. Hence, magmas tend to be similar if they have similar sources and materials that they pass through. Such a magma that came up a billion years ago was much like one that is coming up today, and also like one that will occur a billion years from now. Even though the process of the rising magma adds new types of components to the system, thus increasing its complexity, that increase can go only so far as all the interactions between the components go as far as they can in the conditions of the magma. Despite its incredible complexity, a rising magma, which can be as large as a mountain, is actually simple relative to the complexity of a single living cell, which is too small for us to see.

Sophisticated systems are distinct from other situations and systems in that the development of progressive increase in complexity continues. They do this by way of subsystems that generate diversity, that generate new types of components that play roles as building blocks. Like the magma, the cell increases its complexity by a process of adding new types of components. The difference between the complexity that can be achieved by the magma's process of adding new components and what can be achieved by the cell's process is that the magma's process has only a limited diversity of additional components available to it, while the cell's process can generate a virtually limitless diversity of new of components. This results in new emergent pathways of development—new components, new relations, new patterns of material organization. Magmas are limited in their development because each of the various chemical pathways goes to its limit and stops, not creating any more new combinations of the available set of basic components. The same thing happens with virtually all the chemical pathways of sophisticated systems—except as those pathways get altered as a consequence of the special subsystems that generate new types of components.

With magmas, there occurs the developmental sequence: from diversity of components, to diversity of relations, to diversity of structure and process. With sophisticated systems, there is the same sequence. However, with the generation of new types of components the sequence goes on, not running to a natural end state, resulting then in greater diversity of modularity, both in structure and process. This, in turn, results in a greater number of hierarchies, greater diversity of hierarchic organization, and an increase in the number of hierarchic levels, both in structure and in process, a building of complexity upon complexity. All of these stages of development from increase in diversity of components to additional levels of hierarchic organization results in the great diversity and intricacy of the ordered interactions of structure and process between the components characteristic of sophisticated complexity.

Observation of this diversity and intricacy of ordered interrelation reveals an increase in the significance of individual components and the specific roles they play. With a crystal any component can play the roles of any other component. Removing a single atom or molecule does not alter the nature of the whole. Even removing the entire

outer layer on all sides of the crystal does not alter the nature of the overall organization. With a living cell, the loss of a single phospholipid of the cell membrane would have no significant effect, while the loss of the whole outer layer, which is a modular component of the system, would result in the disintegration of the cell. Increase of significance of individual components means less significance of quantification and more significance of qualitative understanding. Ultimately, it is highly developed organizational complexity, sophisticated complexity, that we must learn how to live with, and how to manage.

It is here with sophisticated complexity that a transition is required from quantitative analysis to qualitative analysis. It is here that the requisite tools for problem solving must be derived from understanding. The questions are no longer simply How much?, How many?, or How strong? The additional question now is, In what manner? This question is answered by the analysis of organization, both that of structure and that of process.

#### *Five examples of sophisticated systems*

The first example of a sophisticated system is a biological cell. There is within the internal system of molecular biology of the cell a mechanism, the DNA/RNA system, that produces proteins. The proteins and their roles are, in large part, the components of the structure and processes that give the cell its existence and that make the cell what it is. When that special mechanism creates, by way of mutations, new types of proteins that then play roles in the structure and processes of the cell, the cell is thereby changed. Because there is a vast number of possible types of proteins that can be created by the cell, and when the creation of new proteins contributes to the process of building upon what is already there, the process of creating new components results in a progressive increase of the diversity and intricacy of ordered interactions of structure and process between the components of the cell, that is, a progressive increase in complexity such that cells are examples of sophisticated complexity.

The second example of a sophisticated system is a population of cells living together. Cells reproduce, they divide, thereby creating new cells. The internal cellular mechanisms involved with the process of cell division can produce new cells that are slightly different from one another. There is no known limit to the diversity of cells that can be created in this way. With increasing diversity of cell types there can occur an increasing diversity of interactions between those cells, leading to diversity and intricacy of ordered interactions between the members of the population, such as competition, symbiosis, predator/prey relations, and mating with transfer of genetic material as occurs with bacteria.

The third example of a sophisticated system is a biological brain. Such a brain is an organ that has evolved the capacity to receive data, transform it into thoughts and knowledge, manipulate that knowledge, and create new concepts. The ability of a brain to work with what it has to create diverse new concepts is, again, vast. Adding those new concepts to the knowledge and conceptual basis already present in the mind leads to increasing diversity and intricacy of ordered interrelations of meaning and understanding.

The fourth example of a sophisticated system is a social system at the level of multicellular organisms. The basic components of a social system are the individual organisms, which reproduce new organisms. Through various processes, such as sexual reproduction, the genetic makeup of the offspring is different from that of the parent

organisms, and the diversity of the members of the social group is changed. With people, diversity of personal traits such as personality, strength, intelligence, and talent as in creativity, sports, or performance lends diversity to the manner in which they relate socially to one another. As the population grows, the increasing diversity of individuals and the increasing ways in which they interrelate adds diversity and intricacy to the ordered interrelations of the culture of a society.

The fifth example of a sophisticated system is an ecosystem. An ecosystem is a community of organisms together with the abiotic environment in which they live and with which they interact. Different types of ecosystems are differentiated by (a) the types of physical conditions, e.g. mountains or plains, terrestrial or aquatic, (b) the types of organisms that live there, and (c) the types of interactions that occur between the living components and the abiotic components. Change of factors of any of these three can change the nature of the ecosystem. One of the ways in which this happens is through the evolution of the organisms that make up the biotic aspect. Newly evolved species can have new characteristics and through them new forms of interrelations with both the biotic and the abiotic components of the ecosystem, thereby bringing about changes in the nature of the system. There are no known limits to the evolution of new species, and thus virtually no limit to the change effects they can have on the ecosystems in which they live. As in the previous examples, changes building upon prior structure and process can result in progressive increase of diversity and intricacy of ordered interrelations.

#### *The interrelations and development of these stages*

The five systems, cell, cell population, organ, social system, and ecosystem, are some of the levels of the natural hierarchy of biological organization. Each higher level is either entirely or to some lesser extent existentially dependent on the prior levels. In the sequence of examples of sophisticated systems, the cells of the first example occur in a group to form the second example, a population of interacting cells. In the third example a population of cells occur coherently bound in the form of an organ, a brain. A brain is one component of an organism, which is the component of the fourth example, a social system. And a social system constitutes an organized component of the fifth example, the ecosystem in which it exists.

There is a continuity of development from one level to another, from the lowest level to the highest level. All the factors present at all the levels, all the components and all the relations between them at all the levels, play their individual roles in concert to create this development of increasing hierarchy.

By way of the DNA/RNA subsystem, cells create a diversity of proteins. By way of cell division, a diverse population of cells is created. It is the process of creating diversity of proteins at the first stage that provides the diversity of cell types at the second stage. The process of creating diversity at the second stage, by way of a different mechanism, is dependent on the operation within each of its components of the process of the first stage. Because there are two hierarchic levels, and because the first stage of sophisticated system plays a role in the process of the second stage, that is, there are two stages of sophisticated system playing roles in the nature of the second stage, that higher level second stage is more complex than the first stage. The transition from one stage to the next is a situation development, but the difference in form and complexity of the factor sophisticated system is *factor development*. With factor development a factor

occurs in relatively simple form in a relatively simpler situation, and in more complex form in more complex situations where more factors are playing roles. Factor development occurs with emergence of each of the five stages represented by the five examples.

As the cells divide and create new cells at the second stage, the first stage, the creation of a diversity of proteins, is still there within each cell and still playing its role. The second stage, a population of cells, a group of interrelating cells, is still there, coherently so, and still playing their roles as they occur in the form of a brain. Individual animals that live in social groups, from fish to people, have brains that play significant roles in the processes of their societies. And social groups of animals play roles in the ecosystems in which they occur and with which they interact. At the highest level of sophisticated system, all the lower levels are still there and still playing their roles.

Sophisticated complexity is the consequence of a specific pattern of material organization, a specific pattern of system organization, wherein there is an ongoing internal mechanism whereby new types of components are created such that there occurs a progressive development of diversity and intricacy of ordered interrelation within the system. This pattern of system organization occurs in all of the stages of the factor development of sophisticated complexity as those stages occur in the overall situation development from the first stage, a living cell, through the intervening stages, to the fifth stage, an ecosystem. Living cells are a type of relatively low level component of ecosystems, and it is interesting to note that this pattern of organization, that turns both the cell and the ecosystem into sophisticated systems, occurs as an intrinsic quality of the low level cell, a component of the whole, and as an intrinsic quality of the ecosystem, that is as a quality of the whole.

Four of these stages of the development of sophisticated systems produce a diversity of unit components—molecules, cells, individual organisms, and species. The brain stage, while its existence is the result of the operation of the two lower level stages of sophisticated systems, its form of this factor is distinct from that of the other stages. Instead of unit components of one sort or another, the brain mechanism produces *connections* between already existing components, making it a significantly different form of sophisticated system.

With natural hierarchy, it is typical for factors of lower levels to still be there playing their roles within higher levels, and it is also common for prior stages of development to be continuing their roles in structure and process. It can also happen that a factor of a lower level can occur again in developed form at a higher level. Additionally, a factor can occur in a significantly different form and yet still be that factor, such as creating connections between units rather than simply creating units. To realistically understand the whole, it is necessary to understand the nature of the lower levels and the nature of how they are related. To understand the nature of sophisticated complexity as it occurs at the level of the ecosystem, it is necessary to understand this factor at all the lower levels and prior stages.

The modern generalist mode of analysis and understanding uses these factors, these patterns of organization, as tools for exploration, analysis, and further understanding. One of these factors is universal in that it is the universal pattern of organization within which all other patterns occur. That universal pattern is development. Development is sequential-difference, like the letters in a word, the words of a

conversation, or the motion of something through space. All patterns of organization have aspects of their origins, structure, and change that are based on sequential-difference. There are two basic modes of sequential-difference, two basic modes of development. One occurs with the sequential-difference from one part of space to another, or from one part of material structure to another. The other occurs with the sequential-difference from one part of an ongoing change to a following part of that change. All patterns have aspects of both in their manner of existence. Understanding these factors and using them as tools of analysis involves both the spatial/structural and the temporal/change aspects of their character.

Development as a tool is based on development as the intrinsic organization of reality. Because it is universal, it provides a universal viewpoint in which all other factors of the existence and nature of reality can be placed in their appropriate relations to one another. The use of development in this manner is one of the defining features of the modern generalist mode. As an intellectual tool, development provides a universal framework for understanding everything, including sophisticated complexity and the problems we have with sophisticated systems.

## References

- Bondarenko, Dmitri M. (2007). "What is there in a word?: Heterarchy, homoarchy and difference in understanding 'complexity' in the social sciences and complexity studies," in K. A. Richardson and Paul Cilliers (eds.), *Explorations in Complexity Thinking: Pre-Proceedings of the 3<sup>rd</sup> International Workshop on Complexity and Philosophy*, ISBN 0979168813.
- Feldman, D. P. and Crutchfield, J. (1997). "Measures of statistical complexity: Why?," *Physics Letters A*, ISSN: 0375-9601, 238: 244-252.
- Feldman, D. P. and Crutchfield, J. (1998). "A survey of "complexity measures," SFI 1998 Complex Systems Summer School, 11 June.
- Kauffman, Stuart A. (1993). *The Origins of Order: Self-Organization and Selection in Evolution*, New York: Oxford Univ. Press, ISBN 0195079515
- Kinnunen, M. J. (2006). *Complexity Measures for System Architecture Models*, Master's thesis submitted to the System Design and Management Program, MIT.  
<http://www.helsinki.fi/~mjkinnun/Text/MitThesis.pdf>
- Meyer, Marc H. and Lehnerd, Alvin P. (1997). *The Power of Product Platforms: Building Value and Cost Leadership*, New York, NY: The Free Press, ISBN 0684825805
- Oltvai, Zoltan N. and Barabasi, Albert-Laszlo. (2002). "Life's complexity pyramid," *Science*, ISSN 0036-8075, 298:5594:763-764.
- Penrose, R. (1989). *The Emperor's New Mind: Concerning Computers, Minds, and the Laws of Physics*, New York: Oxford University Press, ISBN 0198519737.
- Richardson, Kurt A. (2007). "The role of information 'barriers' in complex dynamical systems behavior," in K. A. Richardson and Paul Cilliers (eds.), *Explorations in Complexity Thinking: Pre-Proceedings of the 3<sup>rd</sup> International Workshop on Complexity and Philosophy*, ISBN 0979168813.
- Zelger, Josef. (2007). "Two ways of reducing linguistic complexity," in K. A. Richardson and Paul Cilliers (eds.), *Explorations in Complexity Thinking: Pre-Proceedings of*

*the 3<sup>rd</sup> International Workshop on Complexity and Philosophy*, ISBN  
0979168813.