Differences in Additive Complexity between Biological Evolution and the Progress of Human Knowledge

June 30, 2003 · Emergence
Eliezer Geisler, Bruce Ritter


INTRODUCTION

As systems grow and evolve, they increase in complexity. Attributes such as size and added functionalities are the result of progression and adaptation to environmental dynamics. With structural and process complexities, there is also an increase in the volume and complexity of the knowledge generated by such systems and used by them to adapt, to grow, and to survive. Such additive complexities have received much attention from scholars, who have proposed frameworks that would explain how knowledge is generated and how it progresses.

Two main schools have emerged. One school, sometimes called “positivist,” argues for a universal mode by which human knowledge, particularly scientific knowledge, evolves and progresses. Karl Popper (1962) proposed a “critical rationalism,” by which conjectures about phenomena are challenged empirically with the object of refuting them. An opposing school includes Imre Lakatos (1999), who suggested that human knowledge, and science in particular, evolves by means of programs of inquiry rather than the particular challenging of individual hypotheses or single conjectures. In this school is also Paul Feyerabend (2000), who opposed a structured methodology to explore the progress of knowledge, arguing that knowledge evolves through cultural and historical events, which seldom follow a superimposed framework of rational selection. Another approach was advanced by Donald Campbell (1987), who suggested that human and scientific knowledge evolves in a manner similar to biological systems, in what is now called “evolutionary epistemology.”

In an extension of Popper’s critical rationalism, evolutionary epistemology argues that complexity increases as human knowledge approaches the domain of what constitutes science. To simplify, this school argues that as the complexity of knowledge increases, so must the criteria for selection and approval of what constitutes acceptable knowledge. In its highest form of progress, scientific knowledge evolves along the lines of the “survival of the fittest.” Hypotheses or conjectures compete for survival through a process of natural selection, with the criteria for rejection of theories being the equivalent of the factors in natural selection, which eliminate some biological species in favor of others.

This article summarizes the arguments of the two schools and focuses on a critical examination of evolutionary epistemology. We first suggest that the principles on which evolutionary epistemologists base their arguments are anchored in their failure to distinguish between three modalities of knowledge: the nature of knowledge and its mode of generation; the progress or development of knowledge from less to more complex; and the process and criteria used to accept or reject items of knowledge, hypotheses, or programs of science. We argue that an overall approach that takes into account all three modalities cannot be based on the existence or utilization of rational frameworks, nor solely on the idea that knowledge, and scientific knowledge in particular, progresses by means of the dynamics of programs, cultural influences, or unstructured yet related events. There is an inherent distinction, perhaps even a conflict, between the “nature of inquiry” and the “nature of the evolution and progress of knowledge” and the theories or models that describe and explain them.

We propose a different perspective. We believe that the main issue in these philosophies of science is the question: How is complexity architectured? We suggest a visual allegory of a notion of additiveness or complementarity. We offer an allegory by which knowledge evolves in a sedimentary manner, where layers of knowledge are added to existing frameworks. As enough layers are added, a new configuration emerges that accounts for scientific breakthroughs from conventional wisdom, in a form similar to the paradigmatic views of Thomas Kuhn (1996). The criteria for selection of each layer and its component can be reconciled with a Popperian critical analysis, and the accumulation of layers and their components attends to the arguments raised by Lakatos. This conceptual framework allows us to distinguish between the nature, the progress, and the criteria for selection of knowledge. We also argue that the joining of added complexity and differential architectures allows for progress in knowledge in general and also in scientific knowledge. We reject the arguments by evolutionary epistemologists that scientific knowledge evolves along the processes of natural selection, and that the more complex the structure of knowledge the more active these processes will become, so that the road from single-cell bacteria to complex biological systems is an upward march in evolutionary processes.
We argue that the progression of knowledge and its added complexity can only be understood and adequately described as a sedimentary build-up of items of knowledge, not as a succession of rejected and accepted theories or elements. We also consider the issue of "instructions" delivered from generation to generation and how these contribute to the additive nature of knowledge and its sedimentarity.

This article brings together theories and arguments across disciplines, up to the building of our framework for analysis and its allegorical structure. It accommodates the diverse philosophies while proposing a model that espouses a different perspective and a different model of knowledge creation and progression, and the role that complexity plays in it.

THE CONFLICT BETWEEN BIOLOGY AND SOCIETY AS AN EXPLANATION OF THE EVOLUTION OF KNOWLEDGE

In the formulation of a model of knowledge creation and progress, it is difficult not to compare such a phenomenon with biological evolution, as evolutionary epistemologists have compellingly done (Carnap, 1995a, b; Geisler, 2001; Plotkin, 1998). This is more pronounced where scientific knowledge is concerned. Campbell (1994, 1996) and Heyes and Hull (2001) recognized the conflict between the selfish attributes of biological evolution (Dawkins, 1977) and the more humanistic, moral, and cooperative aspects of social entities. Anchored in the paradigmatic constraints described by Kuhn (1996), Campbell believed that scientists are the instruments or vehicles by which knowledge is generated, distilled, and shared in the community.

One of Campbell’s notions that is central to evolutionary epistemology merits discussion. He proposed the concept of “downward causation,” which is the control element of hierarchies, where information and control flow in both directions. Lower-level entities are influenced by the selection system of higher-level entities in this hierarchy, and lower-level constraints and attributes are necessary for higher-level selection processes (from “genotype” to “phenotype” evolution). By extension, this notion would argue for cooperation and coordination along the hierarchy, between lower- and higher-level entities.

There is a variable that intervenes in this scheme, and that is complexity. If, as Campbell suggested, science progresses to become a method for knowledge creation that is better than other modes, because it defies social norms, then the level of complexity in the hierarchy of the “downward causation” model will influence such a tendency toward radicalism. The more complex the entities at the top of the hierarchy, the more their survival will depend on systemic balance, laden with cooperation among subunits. Hence, it can be argued that such cooperation and resultant compromises will make it more difficult for these entities to depart radically from norms that are, in part, dictated by lower-level entities in this same hierarchy (Hull, 1988; Leonard, 1998; Markova, 1996). Campbell’s attempt to reconcile his concept of “clique selfishness” fails to address adequately the relation between increased complexity and the distinct or even deviant behavior of scientific communities in their attempt to select and validate scientific knowledge (Brodie, 1995).

The conflict between biological and social models of evolution culminates in selection and validation of the highest form of knowledge: scientific knowledge. To achieve this process there is a need for a very complex array of entities, at the highest levels of the evolutionary hierarchy (we use the terminology and conceptual framework of evolutionary epistemologists). But under these conditions, the criteria for selective retention of items or “nuggets” of knowledge (hypotheses, theories) are subjugated more to the level of complexity (and its inherent consequences) than to the norms of evolutionary struggle (Bouvier, 2002; Geisler, 2001; Stewart, 2001).

In his later papers, Campbell (1994, 1996) recognized the wide range of methodological and conceptual consequences that emanated from his notions of the hierarchy and its levels of different entities of varying complexities, who compete and cooperate in the evolutionary setting (Gould, 1961; Heyes & Hull, 2001; Velmans, 1993; Wilson, 1998).

However, the differentiating power of complex entities (in defining their criteria for selective retention) over less complex entities is overwhelming in the hierarchy (Dent, 1999). The higher-level entities evolve by selection criteria that may shift the balance of natural selection of lower-level entities. Examples are extinction of biological species as a consequence of the human struggle for survival and the implementation of human science in this endeavor (Geisler, 2000, 2001; Quammen, 1996; Weiner, 1995). The concept of complexity in this illustration is the combination of the human entity and its scientific knowledge—creating a highly complex and synergistic system, in which the process and criteria of selective retention are reformulated. This leads to major reconfigurations along the evolutionary hierarchy, as lower-level entities now hasten to adapt to the redesigned architecture of their environment (Bunge, 2000; O’Connor, 1994). The tables may increasingly be turned, as this redesigned complex system exhibits traits of “selfishness” (found in genetic or lower-level entities on the hierarchy), while dispensing with the need to coordinate and cooperate that is inherent in the original design of the evolutionary hierarchy.

THE ARCHITECTURE OF COMPLEXITY AND KNOWLEDGE AND THE NOTION OF ADDITIVENESS: A MODEL OF PROGRESS
The distinction between biological evolution and the evolution of complex knowledge systems can be graphically described in Figure 1.

The figure suggests that the added complexity in knowledge systems generates changes in the architecture of the system, leading to value as a social phenomenon. By contrast, biological systems confronted with added complexity in their functionality add value as a natural phenomenon. The survival or extinction of a biological species is a natural occurrence, devoid of elements of culture, social intercourse, or social implications in terms of morality and ethics (unless such extinction is perpetrated by social or human entities). Knowledge systems become more complex through additions to the system that modify the system's architecture, thus creating value—not to the system itself but to the social context within which the knowledge is created and utilized (Bunge, 2001; Helfat, 1997). Therefore, a model of the progress of knowledge would be based on the following questions: How is complexity architected, and how does such architecture and changes in it contribute to the progress of knowledge in general and science in particular?

In biological evolution the complexity of biological entities is not a driving force in evolutionary transformation and dramatic changes in the make-up of these entities. Phenomena that are external to these entities cause upheavals in the balance of natural existence, in the form of “punctuated equilibria” (Gould, 2002). These phenomena of natural disasters extinguish entities regardless of their internal complexity, from microbes to dinosaurs.

In human knowledge, and scientific knowledge in particular, progress is inherent in the increasing complexity of the knowledge system that accumulates within human endeavor. This may be within a scientific discipline, or a knowledge system generated for business or social purposes. For example, the addition of knowledge about the structure of DNA and the mapping of the genetic code has increased not only the amount of knowledge on cellular structure and processes, but also the complexity of the cellular knowledge system that we now possess. The progress of scientific knowledge in cellular investigation has occurred because of additions to the existing knowledge base. Although devising the structure of DNA was in itself a breakthrough in analysis and reasoning, it nevertheless produced a substantial supplement to existing knowledge. Hence, the structure or architecture of the knowledge system of “What do we know about the biology of a living cell?” has drastically changed, to the extent that its complexity has increased and progress has been achieved.

**A MODEL OF THE PROGRESS OF KNOWLEDGE**

We define the following components of this model of the progress of human knowledge: nuggets, modalities of the phenomenon, and architecture. These are notions or terms that describe the building blocks of the model.

A nugget is the unit of measurement of knowledge. It is defined as intellectual content in knowledge (Rubenstein & Geisler, 2003). Nuggets may be compound statements in the form of propositions (if x ... then y) or statements that suggest correlations or influence of outcomes.
Modalities of the knowledge phenomenon are descriptions of the stages in the process of knowledge creation, progress, and transformation. There are three such modalities.

The nature and generation of knowledge

The first modality is the part of the process of the knowledge phenomenon that encompasses the creation of knowledge, including scientific knowledge (Carnap, 1995a, b). This part of the process can also be viewed as the “nature of inquiry,” in which knowledge is generated and assembled (Cook & Campbell, 1979; Kline, 1985; Leonard, 1998). At this point the knowledge, in the form of nuggets or propositions/hypotheses, is not yet screened or evaluated for its “truth” or value to the system into which it is assembled (such as a knowledge management system in a company or a scientific discipline).

The progress of knowledge

In this modality, the next step in the process is the nature of the progress of knowledge. The approaches that we reviewed earlier have focused on this step. They assumed that the generation and progress of knowledge are embedded in a single phenomenon. But there is also a third mode by which the progress of knowledge must be assessed, and that consists in the criteria used to accept or reject items of knowledge into the system in which it is being generated and developed.

Criteria for acceptance or rejection

These criteria represent a phenomenon that is distinct from the modalities of generation and progress. They obey a different set of risks, established by the system in which they operate. For each of the approaches discussed in this article there is a different set of criteria for the acceptance or rejection of knowledge, including scientific knowledge. Popper advocates empirical verification at the level of the individual hypothesis, whereas Lakatos argues for the synergy of the program and Carnap for the criteria that emerge from cultural and social influences.

We argue that none of these approaches can adequately explain all three modalities, thus explaining how knowledge progresses. In our model we argue that a more powerful notion that addresses all three modalities is the notion of additiveness, or cumulation. In this notion knowledge is added to an existing system by contributing to existing layers. Thus, items of knowledge can be individually screened with a Popperian critical rationalism, whereas their generation and additiveness satisfy the programmatic framework advocated by Lakatos (1994). We reject the arguments of evolutionary epistemologists that knowledge in general, and scientific knowledge in particular, evolves by natural selection, and that the more complex the structure of knowledge, the more active will be these processes.

The concept of architecture

The fourth component of the model is the concept of architecture. This refers to the organization of a volume of knowledge, operationalized by a mass of nuggets. The assembly of these nuggets within a certain structure is done by such broad criteria as the commonality of content, or its relation to a shared topic. For example, nuggets related to the organic cell will be assembled within a given structure. The way in which such a structure is organized is defined as the architecture of the knowledge thus accumulated. This definition can be extended to the structure of databases, containing a mass of related information and items of knowledge.

As nuggets are added to this architecture, there is an increase in the level of complexity of the structure. Added complexity occurs because of two key reasons. First, there is an increase in the number of possible arrangements by which knowledge can be organized; second, there is a diversity in types of knowledge being assembled within this structure. As new arrangements are added, there is the emergence of new “configurations,” defined as types of architectures or structural arrangements. For example, as knowledge is added to existing knowledge on the structure and processes of human cells, such knowledge becomes diversified as multiple disciplines are brought into the effort. Microbiology, flow models in physics, genetics, biochemistry, and similar areas of knowledge are added. The manner in which these different knowledge nuggets are now organized in a coherent form that allows a more comprehensive and accurate description of the phenomenon under study is the given architecture.

When, in our model, a certain mass of knowledge is added to the current system, a new configuration of the architecture emerges. This change may account for scientific breakthroughs, in a form similar to that suggested by Thomas Kuhn (1996). Knowledge does not emerge from a vacuum, but rather is added to an existing architecture. Each volume or layer of knowledge “stands on the shoulders of giants” that preceded it (Hawking, 2002). However revolutionary and pathbreaking such knowledge (nugget, theory, layer) may be, there is a relational connection that links the “new” knowledge to the existing architecture (Einstein & Infield, 1938; Kostoff & Geisler, 1999; Nonaka & Nishiguchi, 2001).
Adding layers to the existing architecture introduces added complexity, which may lead to a new configuration. The relationship between increased complexity and the progress of knowledge is explained by the emergence of a new architecture, with new or modified value of the knowledge framework thus formed to the system (scientific and social) in which it operates. The change is not evolutionary, nor is it solely animated by the research program or the culture within which it is generated. Rather, we argue that structural reconfiguration by cumulation of knowledge leads to the progress of knowledge—including scientific knowledge.

DYNAMICS WITHIN THE ARCHITECTURE

When additional knowledge is added to the architecture, there are similarities in the type of knowledge generated, the selection criteria used to include the added nuggets, and the nature of value that the added layer brings to the system. Although we would be tempted to offer the attractive framework of evolution and the “instructions” delivered in genotypes to more complex biological formations (Gould, 2002) as the elements in this change, we nevertheless view such a link in the principles of cumulation, not evolution.

Architectures change when there is an added “critical mass” of knowledge that is cumulated in a layer of an existing system. We define critical mass as the total volume of knowledge in the architecture (extant plus added) that reaches a point in which major rearrangement is triggered in the architecture. This phenomenon may generate a new direction in the area of investigation, a new “paradigm” (Kuhn, 1996) or new scientific concepts (Thagard, 1992). The key factor that drives such a change is the added complexity of the architecture—not evolution. Hence, additive complexity due to cumulation of knowledge would engender a departure from existing architecture to a different arrangement, leading to new research descriptions, breakthroughs, and the emergence of new concepts.

For example, recent advances in genetics, including the deciphering of the human genetic code, were possible because of the cumulation of knowledge about the human cell, its structure and the nature of its components. The discovery of the double-helix structure of DNA by Francis Crick and James Watson in 1953 was possible because a certain volume of knowledge had already been accumulated on DNA. Maurice Wilkins, a biophysicist, and Rosalind Franklin, a physical chemist, had previously taken X-ray diffraction pictures of DNA molecules and had shared their work with Crick and Watson.

An interesting study was sponsored in the 1960s by the United States Navy. Project “Hindsight”—as it was known—traced retrospectively the contribution of basic research to the development of 20 weapons systems. By using a critical events methodology, the study identified 9 percent of the events as research, while the rest were considered development. This study traced the knowledge inherent in the weapons systems as far back as a decade (Sherwin & Henson, 1967). A different result was obtained in studies conducted by the Illinois Institute of Technology (1968) and Battelle (1974). These studies examined nonmilitary innovations and their time horizon extended to 50-100 years in the past. In these studies, 50-70 percent of events were classified as “basic” or nonoriented research.

The farther in time we trace technological innovations, the more we encounter research as the building blocks of a knowledge base that has led to the innovation. This may be explained by the cumulation of knowledge from various disciplines that tends to be added to an architecture over longer periods of time.

In the case of microcellular research, the cumulation of knowledge can be viewed as an architecture that grows and changes as new knowledge is accumulated. Perhaps, as in the studies above, over 50 percent of the events in the past 50-100 years that have led to the current state of the art had been new knowledge. The cumulation of this new knowledge adds to the complexity of the knowledge base and, on reaching a certain volume and configuration, may trigger a breakthrough, as was the case with Crick and Watson.

The more complex and rigorous the system (e.g., scientific inquiry), the harder it is to form layers across knowledge systems that exhibit more differences than similarities. Such is the case of interdisciplinary science. This is not equal to evolution across species, because the distinguishing attributes are not anchored in genetic differences but in phenotypic or systemic differences, in which the three modalities described above are the influencing factors. There are differences in the mode of generation of knowledge, its mode of progression, and the criteria used for its selection. But unlike the strict genetic limitations of cross-species evolution and the diversity of species, knowledge nuggets can crossfertilize and knowledge itself exhibits attributes of convergence (Beebe, 2001; Blachowicz, 1998; Stein, 1989).

CUMULATION, LINEARITY, AND BREAKTHROUGHS

In the model of the progress of knowledge we propose that the cumulation of knowledge nuggets engenders changes in the configuration of the existing architecture, thus creating a structure favorable to breakthroughs and redirection. We propose that there is an increase in the complexity of the architecture, so that the combined effects of the new configuration are sufficient to generate redirection and new combinations of knowledge.

This phenomenon of cumulation is linear to the extent that knowledge is constantly added. However, as such knowledge accumulates, at certain points in the structure both the quantity and quality of the system may radically change. This is similar to
the notion of “punctuated equilibrium” (Gould, 2002), but different in that the synergy accrued in such accumulation and the emerging added value to the user of the knowledge will add to the complexity of the system, and hence to its propensity to radical departures and new concepts.

The phenomenon of the progress of knowledge in this model may be termed “continuous cumulation.” The more layers and nuggets already exist, the more will be added on a continuous basis, thus increasing the complexity of the system and its ability to reconfigure. This is not an evolutionary model and it does not rely on equilibrium as a steady state. Rather, knowledge systems are dynamic, in a continuous state of cumulation and addition of nuggets and layers.

For example, contemporary information scientists have suggested that the volume of information (including scientific knowledge) being generated every day exceeds the total amount generated over past centuries. This avalanche of cumulative knowledge adds complexity to the systems that contain it (databases and knowledge systems). The more voluminous and complex such systems, the higher the propensity for redirection and breakthroughs, hence the more innovations will be constantly generated, and many of these will be of a radical nature. Unlike biological evolution where such radical departures are rare and not dependent on the volume or complexity of biological species, the progress of knowledge is continuous until, inherent to the system itself, the configuration of the architecture changes and new concepts, ideas, and innovations will emerge.

CONCLUSIONS

The progress of knowledge and its added complexity can only be understood and adequately described as a sedimentary build-up of nuggets to layers of knowledge, not as a succession of rejected and accepted propositions or theories. The notion of additive or cumulative knowledge, added to layers of existing systems, accommodates the differences between the various approaches that we have reviewed in this article. The notion we advance here also allows for a more comprehensive view of knowledge systems, in that it offers some explanation for crossfertilization among diverse disciplines and areas of inquiry (Geisler, 1999).

Why is such a new approach important, and what difference would it make? In the design of knowledge systems, the framing of the system’s architecture and the establishment of selection criteria and the mode of progress are paramount in creating workable systems. If we accept the notion of additiveness and changes in architecture, the design of knowledge systems will then be based on exploring the workings of such changes in architecture, hence extracting the value of the system as a cumulation of the current framework and the marginal benefits that are accrued to it. Evolutionary concerns, survival issues, as well as programmatic and cultural considerations are relegated to a secondary role—or dispensed with altogether—in assessing the progress of the knowledge system (McKelvey, 1999; Nonaka & Takeuchi, 1995; Wagner et al., 1998).

Additional research is needed to examine the dynamics within knowledge systems where complexity increases have led to changes in their architecture. Other areas of interest are the relationship between the model advanced in this article and the design and structure of databases, and the ways in which knowledge from such databases progresses to allow for value to users. Finally, how can we quantify the critical mass of added knowledge that triggers changes in the architecture, and do these changes vary by the level of complexity of the extant system?

NOTE

An earlier version of this article was presented at the Managing the Complex IV Conference on Complex Systems and the Management of Organizations, December 7-10, 2002, Ft. Myers, Florida.

References


