ON THE INFORMATION PROCESSING ASPECT OF THE EVOLUTIONARY PROCESS

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ABSTRACT

A premise of this paper is that the dynamics of any system, by which we mean here the collection of processes that perform its functions and thus achieve its purpose, needs information for the execution, control, and coordination of such processes. The information processing aspect of a dynamics is precisely what provides the information that it needs in order to proceed (Kampfner, 1998). The dynamics of the Earth ecosystem, for example, includes the collection of processes that encompasses the origin and evolution of life and the development of human society. In this paper I refer to the part of this all-encompassing process that includes the behavior and evolution of biological systems and human organizations as the evolutionary process. The main focus of the paper is the information processing aspect of this evolutionary process. More specifically, I focus on the evolution of the information processing capabilities of biological organisms and systems, including human individuals and organizations. Especially important is the emergence through this evolutionary process of increasingly complex structures that have made possible more complex behaviors and, consequently, more complex ways of processing information. Superimposed on this evolution is the creation and development of artificial means of information processing and the integration of their use into the information processing aspect of human individuals and organizations. The idea is to contribute to the understanding of the potential that the development and use of artificial information processing devices and systems offers for the effective support of the functions of modern organizations and their adaptability. However, the tremendous potential of computer-based information systems and information technology cannot be fully realized if they do not appropriately extend the information processing capabilities that exist at all levels of the dynamics of the organizations that they support. A sufficient understanding of the information processing aspect of this evolutionary process is in my opinion necessary for the appropriate, synergistic extension, with computer and information technology, of the information processing capabilities that already exist in modern organizations.
Keywords: information processing aspect, evolutionary process, artificial information processing, human intelligence.

INTRODUCTION

The view of information processing as an aspect of the dynamics of systems (Kampfner, 1998) acknowledges the fact that all dynamic systems need to process information in order to execute, control, and coordinate the processes that constitute their dynamics. The information processing aspect of any process can be seen as the one that allows it to obtain, store, transform, and communicate the information that it needs in order to proceed in an appropriate manner. As an aspect of the dynamics of systems information processing necessarily occurs at all levels and in all the processes that contribute to the achievement of a system's purpose. It clearly follows from this view that the nature and characteristics of each process is what determines the kind of information that it needs in order to proceed and how it uses and produces (i.e. processes) this information. Three main categories of natural processes can be considered form the standpoint of the evolution of the information processing capabilities of systems. The first category includes all the processes of natural, non-living systems, whether they occur at the subatomic and macromolecular levels, at the level of human experience, or at cosmological levels. These processes handle the information they need in order to proceed in a form that is completely determined by the laws of physics. The information that they use and produce is implicit in the values of the physical variables and conditions that determine their state. They use and produce (e.g. process) the information they need by transforming the values of the physical variables and the conditions in which they occur as they proceed. The processes of the first category underlie the dynamics of natural, non-living systems at all levels; they have been around for billions of years; their evolution, which is part of the evolution of matter in the universe precedes what we call here the evolutionary process. A second category consists of the biological processes that handle the information that they need in a manner that is implicit in their biochemical, macromolecular, and biological nature. Like the purely physical processes of the first category the biological processes of the second category and their information processing aspect are consistent with the laws of physics. The processes of the second category, however, are not completely determined by these laws. The biological structures that they have developed through evolution allow for a behaviour that is more varied and adaptable than that of purely physical systems. A third category consists of processes whose information processing aspect is capable of handling explicitly represented information, that is, information that is not implicit in their physical, biochemical, and biological nature. They do so with the participation of agents (such as people and artificial information processing devices) that have the ability to ascribe specific meanings to the objects, patterns, or configurations that constitute the explicit representations of information. By processing the information that the explicit representations convey, these agents may influence the processes in which they participate, and those with which they interact on the basis of that meaning.

The use of explicit representations of information enables in important ways the increase of the information processing capabilities of the processes that use them. One of the most important properties of explicit representations of information is that they make possible for the dynamics in which they participate to use information processing capabilities that are above and beyond those that are implicit in the physical, biochemical, and biological nature of the participating processes. The ability to process some kinds of explicitly represented information may exist in some form in biological organisms other than humans. However, the explicit representations of information that require the use of the information processing capabilities of human intelligence or those of the artificial information processing devices that we develop and use are by far the most important ones, especially from the standpoint of their use in modern organizations.

On the Information Processing Aspect

The goal of this paper is to contribute to the understanding of the role that the creation, development, and use of artificial information processing devices and systems has played in the evolution of the information processing capabilities of natural systems. Particularly important to this role is in my opinion the direction that their continued development and use must take in order to increase the information processing capabilities underlying human activity in an effective a manner. Considerable attention is given here to modern organizations because their well-defined structure and dynamics facilitates the study of the effect that modern information technology has on their ability to function and on their adaptability. An important claim of this paper is that the tremendous potential of computer-based information systems and information technology cannot be fully realized if they do not appropriately extend the information processing capabilities that exist at all levels of the dynamics of the organizations that they support. Another important, related point made here is that the appropriate continuation of what we call here the evolutionary process requires that the extension of the information processing capabilities that are already available to the dynamics underlying human activity be achieved with the necessary compatibility and synergy.

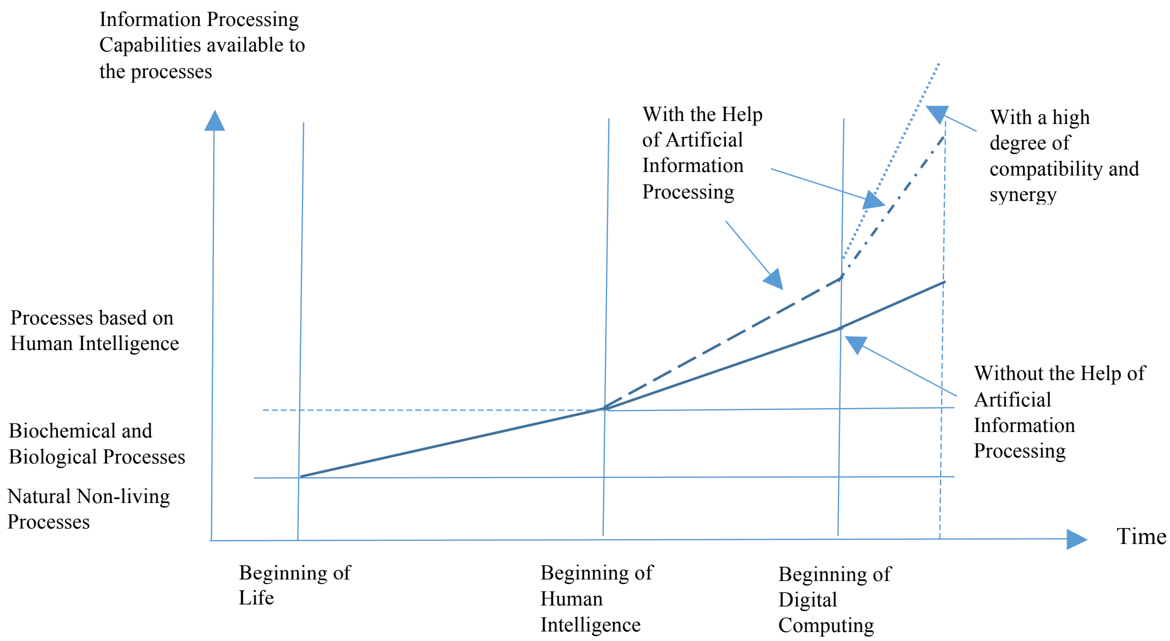

Figure 1 Increase of the information processing capabilities available to various types of processes from the beginning of the evolutionary process to the present. It shows the effect of artificial means of information processing on these capabilities. It also depicts the potential effect of using artificial means of information processing with a high degree of compatibility and synergy. No scale is intended to be shown.

This paper is organized as follows. Section 2 characterizes the information processing aspect of natural, non-living processes, the kinds of information that they handle and the ways in which they use and transform the information. The information that makes these processes possible is implicit in the values of the physical variables that describe their state at any given time. These processes, their interactions, and the information that they use and produce as they proceed are completely determined by the laws of physics. The evolution of the information processing aspect of these processes can be seen as characterized by the emergence of increasingly complex molecular structures that make correspondingly complex processes possible.

Section 3 discusses the evolution of the information processing aspect of the dynamics of biochemical and biological processes as it seems to have occurred from the beginning of life to just before the advent of human intelligence. The fact that the structure of a system influences its dynamics continues to be especially important in this part of our discussion. It helps us to see that the emergence of more complex structures as part of the evolution of biological organisms has made possible the achievement of more complex behaviours. The information processing aspect of these more complex behaviours clearly underlies the more complex and powerful ways to obtain, transform, and communicate the information that such behaviours need in order to proceed.

Section 4 is about the significance of the emergence of human intelligence for the subsequent evolution and development of the information processing capabilities of human individuals, organizations, and society in general. The increasingly rapid pace at which the information processing aspect of the dynamics of all the systems in which human intelligence participates has grown is strongly associated with our ability to create, develop, and use explicit representations of information. The use of such representations is therefore central to our discussion. It probably started with the ability of biological organisms to respond in specific ways to specific patterns of environmental features. The information that the explicit representations of information convey is not implicit in the physical, biochemical, or biological nature of the dynamics in which they are used. In fact, the dynamics that uses explicit representations of information needs the participation of some agent with the ability to ascribe some meaning to the specific objects, patterns, or configurations that represent the information. Moreover, in order for the explicitly represented information to be of some value, the agents that give meaning to it must also be able to respond to this information on the basis of the meaning ascribed to it.

Human intelligence has also been capable of extending its own information processing capabilities with artificial means of information processing. The ability of human intelligence to create and use artificial means of information processing can in fact be thought of as an extension of its ability to create and use explicit representations of information. Section 4 also discusses some of the artificial information processing devices and systems that have been created and their contribution to the evolution and further development of the information processing capabilities of natural and artificial systems.

The use of artificial means of information processing has had a significant impact on the evolution and development of the information processing capabilities of human individuals, human organizations, and society in general. In this respect the impact of digital computing is particularly important. The tremendous advances in computer and information technology that it has brought about have dramatically increased the information processing capabilities of many routine, structured aspects of the dynamics of individuals, organizations, and social systems. While this trend continues, it has been extended to include other less structured, more creative aspects of this dynamics. In Section 5 I discuss some basic requirements for the integration of computer-based processes into the dynamics of organizations and the kind of information processing capabilities with which they contribute to this dynamics. Digital computing contributes to the dynamics of organizations with the power of algorithmic computation in the form of computer-based processes that can be executed in an autonomous manner. The potential that digital computing offers for the support of the dynamics of organizations is obviously tremendous. Any part of the information processing aspect of the dynamics of organizations that can be expressed in algorithmic form can be taken up by digital computing provided that the necessary interfaces can be constructed. Some important parts of the information processing aspect of the dynamics of organizations in which human intelligence excels, however, cannot be taken up as yet by digital computing.

Section 6 looks at the use of modern computer and information technology as a continuation of the enhancement of the information processing capabilities of human individuals, organizations, and human society that started with the evolutionary process. It looks at the development of computer-based information systems in organizations from the standpoint of this broader perspective. The basic idea is that the compatibility of information processing with the dynamics it supports, that has become apparent in nature through the evolutionary process, must be an overarching goal of information system development in organizations and, more generally, of the creation and use of artificial means of information processing. The compatibility of information processing with the dynamics it supports, intended here as the effectiveness with which it supports the other aspects of the dynamics, however, is very difficult to achieve with artificial means of information processing. Moreover, this difficulty increases with the complexity of the information processing capabilities that are artificially provided. Since this compatibility involves in principle all the levels of the information processing aspect of the dynamics of a system, it represents both a great challenge and a tremendous opportunity. The challenge comes from the need to understand the information processing aspect of the dynamics to be supported with information; the opportunity comes with the effectiveness of the support of function and adaptability that this compatibility and the synergy that it entails bring about.

Section 7 is a brief overview of the abstraction-synthesis methodology of information systems development, or ASM (Kampfner, 1987, 1997). This methodology focuses on the information processing aspect of the dynamics of organizations and the way in which it must be extended with computer-based processes. The ASM applies a function support design principle (Kampfner, 1987, 1997) that seeks the compatibility of the computer-based processes that the information system provides with the dynamics that they support and with the adaptability of the organization. The search for the synergistic combination of digital computing and the dynamics of human organizations and systems is an overarching goal of the information systems development effort in the ASM.

THE INFORMATION PROCESSING ASPECT OF NATURAL NON-LIVING SYSTEMS

The information processing aspect of the processes that constitute the dynamics of purely physical systems is what makes sure that such processes have all the information that they need in order to proceed. In a general sense, we can explain this idea by saying that a physical object, or process, sends information to another object or process by affecting its state. In other words, a process 'knows' about the state of another object by the way in which such object affects its state. Notice that many objects or processes may be exchanging information with each other at the same time and that any two objects may be sending and receiving information. We should keep in mind that any particular natural, non-living process interacts with other processes in a manner that is determined by its own physical characteristics. In particular, the form in which it uses and produces the information that it receives from other processes in order to proceed determines its information processing aspect. In this respect, a natural, non-living system processes information that is implicitly represented by the states that it undergoes throughout the execution of the processes that participate in its dynamics. The information processing aspect of its processes can thus be thought of as the transformations of the implicit representations of information that occur as these processes are executed. These transformations are determined by the physical characteristics of the processes and by those of the information that they receive from other processes. At the same time, the information that the processes of a natural, non-living system send to other processes is embodied in the way in which they interact with them. The effect that the information that they send has on the receiving processes is determined by the physical characteristics of the processes that receive the information. The information processing aspect of the dynamics of these systems is thus intrinsic to the processes that participate in the dynamics and indistinguishable from the other aspects of these processes. The information that they handle is implicit in the values of the physical variables that describe their changing state at any given time. The natural, non-living processes use and transform the information by changing the values of the variables that define their state as they proceed, in a manner that is intrinsic to their physical characteristics.

The information processing aspect of the dynamics of natural, non-living systems is thus completely determined by the laws of physics. It naturally provides the information that the participating processes need for their execution, control, and coordination. The dynamics of these systems does not need any additional means of information processing and communication in order to proceed. An example of this kind of behavior is the influence that the moon exerts on the tides of earthly seas. In this case the magnitude of the tides is influenced by the gravitational force that the moon exerts on the parts of the earth where the tides take place. It is also influenced by other factors and conditions affecting the physical processes that produce them. As the forces and conditions that affect these processes change, so does the information that they implicitly represent.

The evolution of natural, non-living processes can be associated with the emergence of increasingly complex molecular structures that allow for processes with a correspondingly complex information processing aspect. As we know, the evolution of non-living processes and their information processing capabilities has been slower than biological evolution by several orders of magnitude. The part of the long evolution of non-living processes that is most important to us here is clearly the one that more closely precedes the beginning of life. For it is in this part where the emergence of the molecular structures, processes, and conditions that we associate with life become more apparent. Particularly relevant to the understanding of the information processing aspect of the prebiotic processes and the primordial living processes that they preceded are the physical, chemical, and thermodynamic properties underlying the self-organization of matter and the origin of life. One of these properties is the existence of "catalytic loops"-stages in which the product of a chemical reaction is involved in its own synthesis. According to Prigogine and Stengers (1984) this is a necessary condition for instability in a chain of chemical reactions occurring in a system that is in a far-from-equilibrium situation. Under certain conditions specific to a set of chemical reactions the stability of the stationary state that occurs in close-to-equilibrium situations may be jeopardized by a catalytic loop. In these cases, a system of chemical reactions that leaves a particular stationary state after a critical threshold has been reached may also reach a "limit cycle." This amounts to achieving a qualitatively different behaviour and therefore to self-organization. This type of self-organization exemplifies the emergence of molecular structures that allow for more complex chemical processes. The increased complexity of these chemical processes necessarily entails that they have a correspondingly more complex information processing aspect.

THE EVOLUTION OF INFORMATION PROCESSING IN LIVING ORGANISMS BEFORE HUMAN INTELLIGENCE

In this section I discuss the evolution of the information processing aspect of the dynamics of biochemical and biological processes as it seems to have occurred after the beginning of life but before the advent of human intelligence. The fact that the structure of a system influences its dynamics is particularly important to this part of our discussion because the evolution of the information processing capabilities of living organisms is strongly associated with the emergence of increasingly complex biological structures that have made correspondingly complex behaviors possible. The information processing aspect of the processes underlying these more complex behaviors must in each case provide the necessary information. Of the structures that originally emerged, the most significant ones are perhaps molecular structures such as nucleotides, amino acids, and some polymers of these bases such as nucleic acids and proteins. This was followed by the emergence of more complex structures such as cells and their organelles, multicellular organisms with their tissues and organs, etc. The emergence of each of these structures allowed for behaviors that provided some competitive advantage. Together with these new behaviors came of course the information processing capabilities that allowed them to obtain, transform, and communicate information as required by their underlying processes.

Many of the processes that perform the functions of biological systems, especially those at lower levels of biological organization, use and produce implicit representations of information. The information that the implicit representations convey is naturally transformed by the biochemical processes that use them as they proceed. The fact that these physical, chemical, and biological processes can proceed appropriately without any form of explicit representation of information shows in my opinion that they naturally have the information processing capabilities that they need. Since they handle the information in a manner that is determined by their own physical and biochemical characteristics the information processing capabilities of these processes are naturally compatible with them and with the dynamics in which they participate. Moreover, the fact that these processes have passed the test of natural selection guarantees that their information processing capabilities support effectively the functions of biological systems and their adaptability.

Cell-to-cell communication illustrates the kind of information processing capabilities that the processes of second category mentioned earlier typically possess. Cell-to-cell communication, is a type of process that the cell-membrane, an important biological structure, makes possible. An example of cell-to-cell communication is the action of hormones that influence gene transcription. It includes the penetration of signalling molecules through the plasma membrane into the cytoplasm or nucleus of a cell where they bind to receptors and form hormone-receptor complexes that regulate the transcription of DNA (Gartner, Hiatt, and Strum, 2003). The information representations that are handled by the information processing aspect of the processes underlying this type of cell-to-cell communication are obviously an implicit, integral part of the structures and conditions that occur in these processes. The way in which these representations of information are transformed and used are obviously determined by the physical and biological nature of the processes in which they occur. The information processing aspect of the dynamics is in this sense indistinguishable from the other aspects. In this case, however, the information processing aspect of processes such as the penetration of signalling molecules through the plasma membrane into the cytoplasm and the subsequent regulation of DNA transcription is easier to visualize.

THE EMERGENCE OF HUMAN INTELLIGENCE AND ITS INTEGRATION INTO THE DYNAMICS OF HUMAN INDIVIDUALS AND HUMAN ORGANIZATIONS

Human intelligence is perhaps the most significant result of what we refer to here as the evolutionary process, the process that encompasses the evolution of the information processing capabilities of biological organisms and populations from those of the primordial living organisms to those of human individuals and the human organizations of the present time. This section is about the significance of the emergence of human intelligence for the subsequent evolution and development of the information processing capabilities of human individuals, organizations, and society in general. My purpose in this section is not to explain how human intelligence came to be or how it actually works which at the present time is very difficult to ascertain in any precise manner. Rather, the idea is to refer to what I believe are especially important contributions of human intelligence to the enhancement of the information processing aspect of the dynamics of human individuals and human organizations. One of these contributions is its ability to create, develop, and use explicit representations of information. The creation and use of explicit representations of information has made it possible to incorporate into the dynamics of systems information processing capabilities that go beyond those that the physical, molecular, and biological nature of their processes can implicitly provide. In doing so, it has also contributed to the enhancement of the information processing capabilities of human intelligence and those of the dynamics of the systems in which it participates. Moreover, I would argue that the use of increasingly complex explicit representations of information, either directly or through the use of artificial information processing devices, has been crucial to the increasingly rapid pace at which the enhancement of these information processing capabilities has occurred.

It is obviously difficult to determine the point in the evolutionary process at which the dynamics of biological organisms became capable of using explicitly represented information. The use of explicit representations of information probably started when biological organisms became capable of responding to specific patterns of environmental features. Obviously, the use of explicit representations of information needs some kind of intelligence in order to ascribe some meaning to the specific objects, patterns, or configurations that represent the information, and to decide the actions to be taken on the basis of the ascribed meaning. The amazing complexity of the behavior of living organisms makes in many cases very difficult to ascertain whether the behaviors that they undertake result only from the physical, biochemical, and biological properties of their dynamics or if they include the use of some kind of cognitive abilities. It is also very difficult to determine the point during the evolutionary process at which the dynamics of biological organisms became capable of processing explicitly represented information. We can be certain, however, that human intelligence is capable of using and producing a variety of explicit representations of information and that has incorporated their use into the dynamics of systems in which it participates, including of course human organizations.

The explicit representation of information involves the use of objects, symbols, or patterns with an agreed upon meaning. The evolution and development of the information processing capabilities of human individuals and human organizations can be associated in many ways with the use of explicit representations of information. Such use has made possible the development of natural languages, both spoken and written, and many other forms of communication involving visual, graphical, acoustic, and other kinds of information-conveying symbols. The use of explicit representations of information facilitates the thinking process of individuals and groups by providing, among other things, a means to record, organize, and communicate partial and final results of such a process.

The creation and use of explicit representations of information entails the existence of the information processing capabilities needed to process the information that they convey. Clearly, these information processing capabilities are above and beyond those that are implicit in the physical, biochemical, and biological nature of the participating processes. They have been provided primarily by human individuals and by the artificial means of information processing that we create. From the beginning, the ability of human intelligence to associate specific objects and patterns with the situations in which they occur has, in my opinion, been essential to the development and use of explicit representations of information. One of such objects and patterns, whether naturally occurring or artificially produced, becomes an explicit representation of information when two or more people ascribe to it a sufficiently similar meaning. Once the meaning of a particular representations of information is agreed upon by a group of people it can be used by them as means of conveying or communicating information.

On the Information Processing Aspect

An ability of human intelligence that seems to be essential to the creation and use explicit representations of information is that of developing, understanding, and using abstract concepts (see, for example, Carey, 2009). Some understanding of the concepts of information, information processing, and computation is clearly necessary for the creation and use of explicit representations of information. Counting with small sticks or other objects, for example, requires the ability to associate the number of counting elements, sticks in this case, with an equivalent number of instances of the objects counted. This counting method exemplifies the use of simple forms of explicit representation of information, a simple notion of information as a numeric quantity, and a primitive notion of arithmetic. It also shows that some idea of information and information processing is needed in order to consciously build explicit representations of information for the purposes of information storage and communication.

The increase in complexity of the explicit representations of information used that characterizes the evolution and subsequent development of the information processing capabilities of human individuals and human organizations has in my opinion been accompanied by a corresponding increase in the computational capabilities of the information processing devices and systems needed in order to process such explicit representations of information. The first artificial information processing devices provided essentially a means of storing and organizing the explicitly represented information. The information so represented was at that time processed largely with the information processing capabilities of the people using them.

The ability of human intelligence to extend its own information processing capabilities and those of the organizations and systems in which it operates with artificial means of information processing has had in my opinion a significant impact on the evolution of the information processing capabilities of human individuals, human organizations, and society in general. The ability to create and use artificial means of information processing can in fact be thought of as an extension of the ability of human intelligence to create and use explicit representations of information. An artificial information processing device is a process or mechanism that models a particular class of transformations on a particular type of information representations. It performs a computation by transforming the set of representations of information that it receives as an input into another set that represents the desired result. The latter can be produced or displayed as an output. The results that an artificial information processing device produces, however, are valid only if the changes that it causes in the information representations that it transforms correspond to the changes that actually occur in the objects being represented. In the counting method described above, for example, adding a number of sticks to a given count corresponds to a similar increase in the number of instances of the objects counted.

Many kinds of explicit representations of information to be processed with the help of artificial devices have been subsequently developed. These devices include the printing press, the telegraph, sorting and tabulating machines that use punched cards, the gramophone, radio transmitters and receivers, electromechanical calculators, various kinds of timers and meters, etc. The integration of the use of artificial means of information processing into a growing number of human activities has gradually increased the frequency of their use. Their scope of application has been broadened as many new activities have been created on the basis of the information processing capabilities that they provide.

Human intelligence clearly started as the main source of the information processing capabilities needed to process the artificial representations of information. The number and computational power of the artificial information processing devices used, however, increased as more powerful methods of transforming explicit representations of information in specific, well-defined ways were developed. This in turn increased the magnitude and computational power of the information processing capabilities provided by artificial information processing devices to the dynamics of organizations. Among these artificial information processing devices, however, the digital computer is particularly important, as explained in the next section.

EXTENDING THE INFORMATION PROCESSING CAPABILITIES OF ORGANIZATIONS WITH DIGITAL COMPUTING

This section discusses the contribution of digital computing to the enhancement of the information processing capabilities of the dynamics of human individuals, organizations, and human society as well as the potential that it offers for their future enhancement. Like any other artificial form of information processing digital computing involves the use of explicit representations of information. In fact, what makes digital computing so special is the representation of computational knowledge in the form of computer programs. A computer program describes an algorithm, that is, an effective procedure that performs a particular computation. When a computer program is represented in a suitable binary format it can be executed by a digital computer. When this happens the digital computer in fact applies the algorithm that the computer program describes to the data that the computer program receives as an input. The output of the computer program, on the other hand, contains the results that the application of the algorithm produces. Notice that the executable version of the computer program, the inputs that it receives, and the outputs that it produces are all explicit representations of information. They are all binary representations because this is the form of information representation that digital computers use.

The characterization of digital computing as a means of transforming representations of information that I am using here is convenient because from this perspective it is easier to relate the computer-based processes that information systems provide to the other processes that participate in the information processing aspect of the dynamic of an organization. Whether implicitly or explicitly, all of these processes transform representations of information. Let us have a brief look at the contributions of digital computing to the information processing aspect of the dynamics of modern organizations.

Let us consider first the computing power that digital computing brings to modern organizations. As a means of processing explicit representations of information, digital computing brings the power of algorithmic computation to the dynamics in which it operates. According to the Turing-Church thesis (see, for example, Minsky, 1967;

Hopcroft and Ullman, 1979; Hofstadter, 1980) any algorithm can be computed by some Turing Machine. Since an algorithm can be represented as a computer program, the result just mentioned endows digital computers with the computing power of a Turing machine, provided that both the storage space and the computing time needed for the execution of the algorithm in question are available. This means that a digital computer can in principle compute any computable function.

The fact that through its execution a computer program applies the computational knowledge that its representation describes is particularly significant. It means that such computational knowledge can take up any part of the information processing aspect of the dynamics of organizations that can be appropriately performed by computer-based processes, that is, any part of the information processing aspect of the dynamics that involves computations for which an algorithm exists. In order to participate in the dynamics, however, the computer-based processes that the computer programs generate need to interact with processes of the organization and its environment that handle a variety of representations of information. Since the computer-based processes manipulate only binary representations of information, they need to have the appropriate interfaces in order to interact with these other processes. Two types of interfaces are required. One of these types of interfaces converts the information that the computer-based processes receive from other processes into a binary form. The other type converts the binary information that the computer-based processes produce into a form that is appropriate for the processes that receive the information.

In some cases, the processes that interact with the computer-based processes process the information in an implicit manner. This happens for example in processes that are fully or partially automated. Here, some of the interfaces of the computer-based processes convert into a binary form the information that they receive from the physical processes with the help of sensors, meters, data acquisition equipment, and the like. Notice that in this case the interfaces make available to the computer-based processes explicit representations of information that otherwise would be processed only in an implicit manner. Other interfaces convert the binary information that the computer-based processes produce into a form that is suitable to the physical processes that receive it and deliver it to them.

The use of digital computing as part of the dynamics of human organizations is controlled by the people that determine the time at which the execution of a particular computer program is to be initiated. Once initiated, however, the execution of a computer program proceeds in an autonomous manner, that is, under the control of the digital computer, until its execution terminates. This means that the computational knowledge that a computer program represents can be made part of the dynamics of an organization whenever the computation that it performs is appropriate, the inputs to the computation can be made available to it, and the results that it produces can be made available in an appropriate manner to the processes that need them.

Digital computing is an incredibly powerful source of information processing capabilities. It does not only incorporate the power of algorithmic computation into the information processing aspect of the dynamics in which it participates; it brings with it the benefits of the tremendous speed and capacity of modern computer and information technology to a growing variety of processes. To capitalize on this tremendous potential, however, the computer-based processes must be designed to be compatible with the dynamics that they support, and with the adaptability of the organization. As explained below, their design must also take advantage of the available synergies.

SYNERGY WITH NATURE AS A GOAL OF ARTIFICIAL INFORMATION PROCESSING

Natural systems process information in a manner that is naturally compatible with the other aspects of their dynamics. This compatibility, which entails a mutual reinforcement of the system's components that produces a considerable degree of synergy, is in my opinion at the root of the effectiveness with which the information processing aspect of the dynamics of natural systems supports their functions. The information processing aspect of the dynamics of the systems that we create, however, is in part artificial. For this reason, as explained earlier, its compatibility with the dynamics it supports depends on the accuracy with which it models the processes of the organization. In this section I look at the development of computer-based information systems in organizations from the standpoint of its contribution to the enhancement to the information processing capabilities that already exist in organizations and, more generally, those of human society. From this perspective, the achievement of the necessary compatibility and synergy can be seen as a means of taking the information system development process in a direction that enhances the information processing capabilities that already exist in the dynamics that they intend to support. The information processing capabilities to be enhanced are fundamentally rooted in the dynamics of natural systems, in what has been referred to before as the biological information processing infrastructure of organizations (Kampfner, 2000). The most important ones are of course those provided by human intelligence, but all the information processing capabilities that exist in organizations must be taken into account in the search for the necessary compatibility and synergy. It must be noted that by enhancing the information processing capabilities of organizations in an appropriate manner the information processing capabilities of natural systems, including human society, are necessarily enhanced as well.

As a product of human design, artificial information processing systems, including computer-based information systems, are not naturally compatible with the dynamics that they are intended to support. In fact, the achievement of the necessary compatibility represents an enormous challenge for the designers of information systems. Moreover, the challenge becomes greater as the information processing capabilities that they provide become more complex. A fundamental reason for this is that the artificial means of information processing are essentially made to describe and manipulate representation of objects, relationships, and processes as their users perceive and understand them. Originally these models provided information processing capabilities whose use could be easily controlled by the people using them. The evolution of information processing, however, made increasingly complex the information processing capabilities that these models provided. At some point during the evolution of human intelligence, however, the emergence of more advanced notions of information and information processing made digital computing and algorithmic computation possible. What is critically important about this event is in my opinion that digital computers execute computer programs in an autonomous manner. The algorithmic descriptions that computer programs represent are executed from beginning to end without human intervention. This makes the computational power of algorithmic computation potentially available to the dynamics of an enormous amount of systems. A great many of the processes performed in organizations, for example, may be supported by computer-based processes, frequently in a simultaneous, or concurrent manner.

But the way in which the power of digital computing grows reinforces the idea that its compatibility with the dynamics it supports is in general more difficult to achieve. Computer programs are in fact computational models of specific processes and activities of the systems they support (Kampfner, 1985). Executing a computer program amounts to simulating, or actually performing, the processes that it models. The compatibility of the processes that the execution of a computer program generates clearly depends of on the accuracy with which they model the processes of the organization. A computer program, when executed, may actually realize the processes it models as it is the case in real-time situations, or it may simulate the effect of these processes as it happens when the simulated processes are not occurring at the time the computer program is executed. In any case, when the execution of the computer program is part of the dynamics of the organization, that is, when the results it produces are going to be used by other processes that participate in this dynamics, they must be accurate and must be delivered in the right form and at the right time. This is precisely what I mean by the compatibility of the computer-based processes with the dynamics they support.

The compatibility of digital computing with the dynamics it supports depends also on the ability of the computer-based processes to interact properly with the other processes that participate in the dynamics. This in turn requires the appropriate interfaces between the interacting processes. As mentioned earlier, these interfaces convert the binary representations that the computer-based processes produce into the forms required by the processes that receive the information. They also convert into a binary form the information that comes from other processes. In addition, the interfaces of computer-based processes provide buffers and other mechanisms that allow for the interaction with processes that use or produce information at different rates and at different places than the computer-based processes do.

The interfaces of computer-based processes make possible to extend the information processing capabilities of human individuals and organizations with digital computing. The interfaces that convert non-digital information into a digital form, for example, allow digital computing to process information that otherwise would be processed by other, non-digital means. The interfaces that convert the digital representations that the computer-based processes produce into other non-digital forms, on the other hand, allow the computer-based processes to deliver to other processes the results of their computations.

In order to be effective, digital computing must also be compatible with the adaptability of the systems it supports. Adaptability is the ability of a system to cope with the uncertainty of its environment (Conrad, 1983). Since organizations typically face and uncertain environment, the designers of information systems must seriously consider the effect that any feature of their design might have on the adaptability of the organization. An important factor to be considered in this respect is the potentially negative effect that the programmability of digital computing has on the adaptability of the systems it supports. Michael Conrad's tradeoff principle of information processing (Conrad, 1983) asserts that any information processing system trades programmability for adaptability. According to this principle, digital computing falls on the programmability side of this tradeoff while biological information processing, which includes the direct, unaided use of human intelligence, falls on the adaptability side. A consequence of this tradeoff is that, because of the increase in programmability that its use entails, computer-based information processing has a potentially negative effect on the adaptability of organizations. One of the reasons why the programmability of computer-based processes are not adaptable is that they are not modifiable by a process of variation and selection as biological systems are. Instead, they need to be modified when the processes they support change, as it frequently happens in organizations because of the uncertainty of the environment they face. Modifying a computer program is obviously costly. The cost of modifying the computer programs is in fact an important part of the cost that the programmability of digital computing imposes on the adaptability of organizations. The negative effect that the programmability of digital computing has on the adaptability of organizations is obviously greater when the computer programs model processes that change frequently, or when the necessary changes affect sets of highly interdependent processes (see, for example, Kampfner, 2008).

The potentially negative effect that the programmability of information processing has on the adaptability of an organization can be avoided or at least reduced. Conrad's tradeoff principle provides a basis on which this can be done. A basic idea in this respect is to assign digital computing to the support of processes that are less likely to be affected by changes in the environment and to processes that are easier to change if the need arises.

It is worth noticing that the compatibility of computer-based processes with the adaptability of organizations may also be related to their compatibility with certain aspects of their dynamics (Kampfner, 2002, 2006). A case in point is that in addition to the effect that the programmability of digital computing has on the adaptability of organizations it imposes special demands on the quality and accuracy that the computational models that the computer programs represent must have in order to be compatible with the dynamics they support. The fact that these computational models need to anticipate the behaviour that they model clearly shows that their compatibility with the dynamics of organizations becomes more difficult to achieve as the processes that they model become more complex and when the dynamics they support changes frequently (see, Kampfner, 2011). The difference, however, is that in the case of adaptability the compatibility is needed in order to cope with the uncertainty of the environment; the compatibility with the dynamics of the organization, on the other hand, is needed in order to achieve effective function support.

The compatibility of digital computing with the dynamics it supports is necessary for it to extend its information processing capabilities in an appropriate manner. The synergy that the compatibility of information processing with the other aspects of the dynamics brings about has been obtained in natural systems through the evolutionary process. Part of this synergy comes, in my opinion, from the fact that the information processing aspect of purely natural, biological dynamics uses the same physical, chemical, and biological processes and mechanisms that other aspects of the dynamics use. The information processing capabilities naturally provided by human intelligence (i.e. provided without the help of artificial means of information processing) for the use of explicit representations of information seem also to have been used in a compatible, synergistic manner. When the use of explicit representations of information involves the use of artificial means of information processing, however, obtaining the necessary compatibility and synergy is the responsibility of their human designers. An important claim of this paper is that obtaining this compatibility and synergy should be part of a broader effort that aims using the enormous capabilities that digital computing and other artificial means of information processing potentially provide not only for the effective support of the functions of organizations but also for the enhancement of the information processing capabilities that nature provides.

COMPUTATIONAL SYNERGY AS A GOAL OF INFORMATION SYSTEMS DEVELOPMENT: THE ABSTRACTION-SYNTHESIS METHODOLOGY

Our brief overview of the evolution of information processing in natural and artificial systems suggests that the synergistic combination of natural and artificial computing is essential to the development of computer-based information systems and to their successful integration into the dynamics of modern organizations. Part of this synergy is inherent to the compatibility of the computer-based processes with the dynamics they support. Sometimes, however, the synergy obtained through the development process may go beyond what the necessary compatibility entails. In any case, the synergy of artificial information processing with the dynamics in which it operates must be a goal of information systems development or any effort that integrates the use of artificial means of information processing into the activities of modern society. We must keep in mind, however, that the information processing aspect of an organization exists at all levels of its dynamics, from the subatomic, molecular and macromolecular levels, through the levels of human behavior, up to the level of the system as a whole, and beyond. Therefore, in order to achieve the necessary compatibility and adaptability, and to capitalize on the available synergies as much as possible, all the relevant levels of the dynamics must be considered.

In this section I briefly discuss the abstraction-synthesis methodology of information systems development, or ASM (Kampfner, 1987, 1998). The ASM aims at extending the information processing aspect of the dynamics of organizations with computer-based processes in a manner that effectively supports their functions and their adaptability. The ASM follows the function support design principle mentioned earlier (Kampfner, 1987, 1997) in order to achieve these goals. The function support design principle calls for the design of computer-based processes that are compatible with the dynamics they support and with the adaptability of the organization. The *abstraction* part of the methodology consists of two phases, the first one, the information needs analysis phase, involves the study of the information processing aspect of the processes that perform the functions that the information system will support. The focus of this analysis is the information that the processes that perform these functions need in order for them to achieve their goals.

On the Information Processing Aspect

Understanding this aspect involves determining the forms in which the information is represented and transformed throughout the current processes on the one hand, and by the new or modified processes on the other. Both the implicit and the explicit representations of information must be considered in this analysis.

The second phase of the abstraction part of the methodology is the analysis of the requirements of the information system. It focuses on the way in which the information processing capabilities of the organization need to be modified in order to achieve its new or modified goals. It determines the requirements of the interfaces that provide the new computer-based processes with information and those that convey the information that they produce. In addition, the requirements analysis phase determines and specifies the transformations of information that the new computer-based processes must perform in order to support effectively the new or modified functions of the organization.

The *synthesis* part of the ASM starts with the third phase, the design of the information system. Obtaining the necessary compatibility of the computer-based processes with the dynamics of the organization and with its adaptability is a basic, critical design goal. The ASM follows a synthetic approach to design in which alternative designs are obtained by putting together specific versions of the required components. This approach is possible because in the ASM the requirements of the information system are specified, whenever this is possible, in terms of what needs to be accomplished by the information system instead of particular ways of achieving it. This eliminates the design and implementation biases and constraints that the *a priori* consideration of particular platforms, architectures, or products imposes on the possible designs and, consequently, makes the consideration of a greater number of designs possible.

Each of the designs obtained through the synthesis process must of course be evaluated as to its ability to meet the requirements of the information system and to contribute to the adaptability of the organization. The main guide to the achievement of acceptable designs in the ASM is the function support design principle (Kampfner, 1987, 1997) mentioned earlier. This principle calls for the design of computer-based processes that are compatible with the dynamics they support and with the adaptability of the organization. It applies to all the phases of the development process. The design phase, however, is especially important to the success of its application. The reason is that it is in this phase where the acceptable designs, that is, designs that meet the requirements of the information system in a manner consistent with the function support design principle are actually produced. The flexibility that the unbiased nature of the requirements specification allows in the ASM makes it possible to enhance the synergy that the synthesis process can achieve. It also makes it easier to find more than one acceptable design. When this is the case, one that also meets specific design objectives such as low cost, portability, reliability, scalability, or a greater contribution to adaptability, among others, can be selected for implementation.

The fourth phase of the ASM, which is the second phase of the synthesis part, is the implementation and the installation of the information system. The purpose of this phase is to integrate the computer-based processes that the new information system provides into the dynamics of the organization while making sure that it supports the functions of the organization in an effective manner. This phase includes the implementation of the design by coding and testing the new software, testing the new hardware, and installing the information system. Many approaches to the implementation and installation of a computer-based information system can be used (see, for example, Hoffer, George, and Valacich, 2002). The installation of the information system, for example, can be done directly in which case the old system is turned off while the new system is turned on. It can also be done in parallel, in which case the old and the new systems work at the same time until the new system is considered working properly. Another approach to the installation of the new system consists of phasing out functional parts of the old system and substituting them with corresponding parts of the new system. What is missing in current approaches to the implementation and installation of the information system is the idea of applying what has been learned throughout the development process about the information processing aspect of the dynamics of the organization. Using this new knowledge would improve the effectiveness of the support provided to the functions of the organization. Moreover, the compatibility of the computer-based processes with the dynamics that they support, their contribution to the adaptability of the organization, and the synergy with which they enhance the information processing capabilities of the dynamics are of great significance on their own right. For the benefits of extending the information processing aspect of organizations with artificial means of information processing are just a small part of what can be obtained at higher levels of human and social behavior. The enormous benefits that potentially can be achieved, however, are obviously lost when they artificial means of information processing are not developed and used in an appropriate manner.

REFERENCES

Brynjolfsson, E., and McAfee, A. (2014). *The Second Machine Age*, W. W. Norton & Company, Inc., New York.

Carey, S. (2009). *The Origin of Concepts*, Oxford University Press.

Conrad, M. (1983). *Adaptability*, Plenum Press, New York.

Conrad, M. (1985). On design principles for a molecular computer, *Communications of the ACM*, 28: 464-480.

Gartner, L. P., Hiatt, J. L., and Strum, J. M. (2003). *Cell Biology and Histology*, Lippincott, Williams and Wilkins, Baltimore, MD.

Hoffer, J. A., George, J. F., Valacich, J. S. (2002). *Modern Systems Analysis and Design*, Prentice Hall, Upper Saddle River, NJ.

Hofstadter, D. (1980). *Godel, Escher, Bach: An eternal Golden Braid*, Vintage Books, New York.

Hopcroft, J. E. and Ullman, J. D. (1979). *Introduction to Automata Theory, Languages and Computation*, Addison-Wesley Publishing Company, London.

Kampfner, R., (1985) "Formal Specification of Information Systems Requirements," *Information Processing and Management*, 21(5): 401-414.

Kampfner, R. (1987). A hierarchical model of organizational control for the analysis of information systems requirements, *Inf. Syst*. 3(3): 243-254.

Kampfner, R. (1997). "Function Support as an Information Systems Development Paradigm," *World Futures*, 50: 689-702.

Kampfner, R. (1998). Dynamics and Information Processing in Adaptive Systems, *BioSystems*, 46: 153-162.

Kampfner, R. (2002). Digital and biological computing in organizations, *BioSystems*, 64: 179-188.

Kampfner, R. (2006). Adaptability and the integration of computer-based information processing into the dynamics of organizations, *BioSystems*, 85: 30-36.

Kampfner, R. (2008). "A basic principle for the architecture of computer-based information processing." *SIG on Information Systems Design and Information Technology, 52nd Annual Meeting of the International Society for the Systems Sciences*, University of Wisconsin, Madison, Wisconsin, July 13th to July 18th.

Kampfner, R. (2011). "Handling the Variability of Information Processing in Complex Systems: An Information Systems Design Perspective," *SIG on Information Systems Design and Information technology, 55th Annual Meeting of the International Society for the Systems Sciences*, University of Hull Business School, UK. July 17-22.

Minsky, M. L. (1967). *Computation: Finite and Infinite Machines*. Prentice-Hall, Englewood Cliffs, NJ.

Prigogine, I. and Stengers, I. (1984). *Order Out of Chaos*. Bantam Books, New York.