Biomimetics in Design-Oriented Information Systems Research

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Abstract. Modern information systems (ISs) are becoming increasingly complex. Simultaneously, organizational changes are occurring more often and more rapidly. Therefore, emergent behavior and organic adaptivity are key advantages of ISs. In this paper, a design science research (DSR) question for design-oriented information systems research (DISR) is proposed: Can the application of biomimetic principles to IS design result in the creation of value by innovation? Accordingly, the properties of biological IS are analyzed, and these insights are crystallized into a theoretical framework to address the three major aspects of biomimetic ISs: user experience, information processing, and management cybernetics. On this basis, the research question is elaborated together with a starting point for a research methodology in biomimetic information systems.

Keywords: Information Systems, Design Science Research, Biomimetics

1 Introduction

Information systems (ISs) are socio-technical systems that involve users, information and communication technology (ICT), and organizational processes [1]. Current ISs in large organizations are becoming increasingly complex. Therefore, innovative design approaches that yield more adaptive and robust ISs will facilitate the management of that complexity. Biology provides existing examples of highly complex systems that run smoothly without the need for human intervention. Technological ISs that exhibit biologically inspired features (e.g., emergent, organic and autonomous behavior) have the potential to greatly facilitate complexity management. *Biomimetic ISs* are defined as complex socio-technical message systems whose designs are based on the principles of biological information processing. Organizations can be regarded as complex evolving systems in co-evolution with other systems [2]. Accordingly, organizations are co-evolving with information technology (IT). Therefore, the ability of technical ISs to adapt to that co-evolution, a feature embodied by *emergent application software* [3], could become a key advantage for the organizations that use these systems. For these reasons, we pose the following as our main research question: How can biomimetics enhance IS design?

2 Related Work

Information systems research (ISR) is often based on behavioral science research (BSR), in which empirical observations of existing ISs in real-world organizations lead to theories that can be applied for IS design and management. Thus, BSR is a scientific paradigm in the sense of Kuhn [4]. Such paradigms are collections of beliefs shared by scientists, namely, sets of agreements regarding how scientific knowledge is to be understood.

March and Smith [5] and Hevner et al. [6] proposed a research methodology that is complementary to ISR, called *design science research* (DSR). The motivation for introducing design questions into ISR is progress. Theories do not create innovation; only design leads to technological advances. Therefore, there is a need for a rigorous scientific methodology for treating IS design as research. There is a complementary research cycle (a synthetic methodology, in the sense of Pfeifer and Scheier [7] p. 21) in which BSR, which is based on empirical science, provides truth, and DSR, which is based on engineering science, provides utility.

A similar but more radical approach proposed by Österle et al. [1] is called *design-oriented information systems research* (DISR). The cited memorandum goes so far as to state that ISR ought to be design-oriented, that is, DSR is considered to be the primary goal of ISR. The reason for this assertion is the (normative) assumption that ISR is intended to be beneficial to society. Discovering true propositions using BSR alone does not create value; therefore, designing innovative solutions using DSR methodologies is regarded as the primary orientation of ISR. Projected onto biomimetic DISR, this means designing and studying biology-inspired artifacts (frameworks, prototypes, methods) that provide solutions and thus create value for IS users and/or managers.

To implement DISR artifacts, we turn to Reis [8], who asks, "Who better than Nature can design complex structures and control the intricate phenomena (processing routes) that lead to the final shape and structure (from the macro to the nano level) of living creatures?" The term *biomimetics*, meaning to imitate (*mimesis*) life (*bios*), was introduced by Otto Schmitt [9]. Bar-Cohen [10] defines biomimetics as "the study and imitation of nature's methods, designs, and processes." It can be described as the abstraction of good design from nature [11]. Biomimetics has been successfully applied in many design disciplines (e.g., sensor engineering [12], business management [13], and robotics [7]).

Biologically inspired ISs apply biomimetics for information processing, user interaction, and social collaboration. For example, IBM's vision of autonomic computing [14], [15] encompasses an organic, self-organizing approach to IT systems management inspired by the autonomic nervous system. IBM recently launched a cognitive computing initiative [16] with the purpose of developing a unified computational theory inspired by insights from neuroscience.

The EU project titled Nature-inspired Smart Information Systems (NiSIS) created an umbrella term, *biomimetic intelligence* [17], which is defined as “the ability of an information system to mimic nature-inspired adaptive and intelligent behavior to better pursue its goals, to improve the robustness, efficiency and usefulness of its functionalities and enhance its interfacing capabilities to the external world.”

Dressler and Carreras [18] have studied the application of biological principles in ISs (e.g., wireless networks, service lifecycles, and peer-to-peer networks), which can be regarded as an approach to biomimetic IS engineering. Others have applied biomimetic principles to various socio-technical problems (user interaction and organizational processes). For instance, William and Huggett [19] explored a biomimetic information retrieval system that utilizes associative network structures analogous to that of human episodic memory for data organization in information management systems. Kampfner [20] suggested a biologically inspired approach to information management that utilizes implicit control, such that power is delegated to the smallest possible subsystem to reduce the organizational costs of information processing and decision-making.

An important aspect of life is its *emergence*. In this context, the *emergent properties* of living systems (and of complex systems in general) are attributes that arise out of more fundamental subsystems yet cannot be completely reduced to these subsystems [21]. *Emergentism* is the view that in complex systems, the whole is more than the sum of its parts. In the words of Anderson [22], “Psychology is not applied biology, nor is biology applied chemistry.” Life can be seen as an emergent property of the interaction of the Earth’s matter with the Sun’s energy. There are two aspects of emergence that are important to engineering:

- *Design for Emergence.* This concept [23] refers to the creation of artifacts that exhibit emergent properties; the design itself is intended to allow patterns to arise that cannot be reduced to the initial design but rather come into existence only through the interaction of such an artifact with its environment. An example of design for emergence in ISs is Wikipedia. The design of Wikipedia itself determines only the structure and function of the Mediawiki software. The content, that is, the actual encyclopedia with its collection of the world’s knowledge, is an emergent property of the interaction of that software with its millions of users.
- *Emergent Design.* This concept [24] refers to an engineering approach that uses evolutionary, iterative processes for artifact implementation. Initially, the design is not fixed. The design of an artifact develops only over several iterations during the process of implementation. Emergent design has been proposed for application in learning environments [25], architecture [26], and even IS management [27], [28].

Although the emergent design of ISs and design for emergence in ISs are indeed biomimetic approaches, these concepts can be generalized further for the application of general principles of biological ISs to DISR

3 Biomimetic Information Systems

According to Österle et al. [1], an IS encompasses three layers: users, ICT, and organization. Biology-inspired IS research thus means the application of biological principles not to computational methods per se but rather to *socio-technical ISs.* This is a more general approach that extends questions of computing to aspects of social science (e.g., user experience and real-world organizations). Therefore, we wish to analyze the properties of biological ISs with the intent of developing a theory of biomimetic IS design. Our proposal is to apply biomimetic principles to all three layers: (1) user interaction, (2) information processing, and (3) organizational processes.

A system is an interaction of entities that form an integrated, complex whole. In contrast to energy systems, the components of an IS interact via *information interchange*. Meanwhile, a computational system is a system that emulates a Turing machine. Not all computational systems interchange information, and not all ISs compute. The central aspect of information is a message that is transported from a sender to a receiver. In biology, ISs co-evolve with energy systems. A broad range of media are available for the transmission of information messages, such as electrical charges, hormones, DNA, pheromones, airwaves, and electromagnetic waves. Examples of biological ISs include nervous systems, immune systems, human societies, and ant colonies. Discussing the properties of biological ISs enables the application of these principles for the design of innovative socio-technical ISs.

- *Emergence.* "The mere term "organism" expresses the fundamental role that interactions, self-organization and emergent behavior play in all biological systems (…) Biological systems on many different scales exhibit emergent behaviour" [29]. In fact, the concepts of information and semantics themselves have emerged in biological evolution [30].
- *Learning.* "Processing and use of information in biological systems can be said to have evolved out of the need for survival in the face of an uncertain environment. Accordingly, biological information processing can be said to support function to the extent to which these systems are able to adapt" [20].
- *Evolution.* "Nature builds from accidents that happen to work and creates new mechanisms on top of old ones" [31].
- *Fitness.* "Biological organisms use information about the environment to stimulate or drive responses that boost the likelihood of survival and successful reproduction" [31].
- *Networks.* "In biology, networks depict how molecules (metabolites, proteins), cells (bacteria, neurons), or organisms (ants) interact to jointly solve problems and coordinate responses" [32].
- *Autonomy.* "Autonomous systems are those that perform the necessary operations to maintain their own identity. This notion of autonomy provides a powerful way to conceptualize what is special about living systems" [33].
- *Tolerance.* "Robustness is one of the characteristics of biological systems that is most admired and most desired for engineered systems" [31]. Biological ISs are tolerant to unexpected events occurring in their environments.

Biomimetic ISs are artificial socio-technical ISs that are designed with biology as a source of their operational principles. Thus, these seven principles can be applied in IS design. Table 1 summarizes these principles and compares each of them with a corresponding aspect of conventional IS design. Based on Table 1 and the three layers of IS as defined by Österle et al. [1], three aspects of biomimetic IS design can be identified.

Table 1. Comparison of the principles of biomimetic versus conventional IS design

Biomimetic IS	**Conventional IS**
Emergence	Planning
Learning	Programming
Evolution	Determination
Fitness	Function
Networks	Hierarchy
Autonomy	Control
Tolerance	Rigidity

- *(A) Biomimetic User Experience.* If a system is allowed to learn through interaction, then the user experience of that system can become one of interacting with a tolerant, learning, adaptive system. Social and knowledge structures are based on networking. Instead of requiring every aspect to be controlled through user interaction, the system is able to operate in the background and perform many tasks autonomously. The system is tolerant to inconsistent user inputs.
- *(B) Biomimetic Information Processing.* The content and even the functionality of a system can be allowed to emerge through interaction and artificial intelligence reasoning. Instead of every action of such an IS being deliberately programmed, many behaviors are incorporated through machine learning, thus making biomimetic ISs more adaptive to organizational changes. Biomimetic ISs can operate on network structures, both for knowledge representation and for user interaction. Finally, the application of tolerance principles (e.g., approximate reasoning) makes biomimetic ISs much more robust.
- *(C) Biomimetic Information Management.* To avoid over-planning, emergent properties can be deliberately included in an IS such that both the design and the behavior of the IS may emerge through interaction, thereby significantly reducing manual configuration costs. Instead of all aspects being determined prior to implementation, such systems are allowed to evolve iteratively. Instead of IS design being treated as a function of the goals of an organization, ISs are optimized for their fitness, with user experience and acceptance serving as the fitness function.

4 Research Methodology

Computing is both an engineering task and a science [34]. Both methodologies complement each other. Through the implementation of artifacts using existing technology, new insights, principles, and theories can be formulated, which, in turn, lead to new and improved artifacts. In the field of computing, DSR closes the loop of engineering design and scientific analysis by allowing for the study of artifacts as part of the process of their creation. Nonetheless, “computer science is a field of empirical inquiry” [35]. Through the design of computing machinery and algorithms, the computational universe is observed, and theories are formulated empirically.

By projecting these principles to the realm of ISR, the scientific analysis of IS design can also be regarded as an empirical inquiry, thus adding to computer science the social dimensions of user experience and organizational processes. According to Österle et al. [1], the aim of DISR is normative, serving the purpose of being *beneficial to society*. “Design-oriented IS research aims to develop and provide instructions for action (i.e., normative, practically applicable means-ends conclusions) that allow the design and operation of IS and innovative concepts within IS (instances).” For this reason, to find new methods of formulating potentially beneficial IS concepts and to add a new dimension to the solution space, we propose the following research question*: How can the application of biomimetic principles to information systems design lead to the enhancement of value creation through innovation?*

This question is also a knowledge question, not only a design question. We want to know whether, and if so, how, the application of biomimetic principles to IS research can create value for users. Yet, in accordance with the principle of “knowing through making” [36], we can only answer this question if we can design and evaluate biomimetic ISs. Accordingly, the intended research anticipates successive iterations of the following partially overlapping research activities:

- *Conception:* Creation of designs, including foundations, for biomimetic ISs. This encompasses the identification of biological principles to address IS challenges and the transformation of these principles into designs with regard to specific solutions.
- *Prototyping*: Implementation of these biomimetic ISs as software systems, if possible, in real-world settings and in organizations with productive users.
- *Evaluation*: Analysis of the properties of biomimetic ISs in (inter-)action.
- *Conclusion*: Formulation of theories based on the underlying principles. To that end, we allow for not only analytic but also synthetic approaches to theorizing.
- *Publication*: Dissemination of the developed concepts, prototypes, evaluations, and conclusions to the scientific community.

This general method is merely a starting point for addressing the central, challenging task of transforming the descriptive account presented in this paper into actionable prescriptions for the design process. Further theorizing towards this end will be informed by findings from future case studies and informed argumentation.

5 Conclusions and Outlook

This paper introduced a research question concerning the application of biomimetic principles in DISR. A short literature survey was conducted, operational principles of biological ISs were theorized, and a conceptual framework for biomimetic IS design was derived. Based on these premises, the research question to be investigated was stated, together with a starting point for a possible methodology to answer it. This paper merely offers a research design, and our research is a work in progress; therefore, not many conclusions can be drawn at this point. One conclusion that can be shared is that although much research has been undertaken in the field of biologically inspired computing, there has been much less activity in the area of biomimetic ISR. Bio-inspired methodologies have been applied to IS engineering; yet, to our knowledge, there has not been any in-depth design science research into the question of how biomimetic designs can create value for socio-technical ISs. Therefore, in the future, the proposed research may fill this gap.

The authors are investigating emergent behavior and networked knowledge structures for enterprise search, combining existing top-down methods with biomimetic bottom-up approaches to knowledge interaction [37]. This research effort is but one aspect of the broader context depicted in this paper. Furthermore, several DISR projects will be undertaken to investigate our research question by designing biomimetic ISs to evaluate the effects of the application of biomimetic principles to IS design.

References

1. Österle, H., Becker, J., Frank, U., Hess, T., Karagiannis, D., Krcmar, H., Loos, P., Mertens, P., Oberweis, A., Sinz, E.J.: Memorandum on design-oriented information systems research. Eur. J. Inf. Syst. 20, 7–10 (2010).
2. Mitleton-Kelly, E.: Ten Principles of Complexity & Enabling Infrastructures. Complex Systems and Evolutionary Perspectives of Organisations: The Application of Complexity Theory to Organisations. pp. 23–50. Elsevier (2003).
3. Loucopoulos, P.: Requirements Engineering for Emergent Application Software. In: Cordeiro, J., Maciaszek, L.A., and Filipe, J. (eds.) Enterprise Information Systems. pp. 18–28. Springer Berlin Heidelberg (2013).
4. Kuhn, T.S.: The Structure of Scientific Revolutions. University of Chicago Press, Chicago, IL (1962).
5. March, S.T., Smith, G.F.: Design and natural science research on information technology. Decis. Support Syst. 15, 251–266 (1995).
6. Hevner, A., March, S.T., Park, J., Ram, S.: Design Science in Information Systems Research. MIS Q. 28, 75–105 (2004).
7. Pfeifer, R., Scheier, C.: Understanding Intelligence. MIT Press (2001).
8. Reis, R.L.: Biomimetics. Curr. Opin. Solid State Mater. Sci. 7, 263–264 (2003).
9. Bhushan, B.: Biomimetics: lessons from nature–an overview. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 367, 1445–1486 (2009).
10. Bar-Cohen, Y.: Introduction to Biomimetics. Biomimetics. pp. 1–40. CRC Press (2005).
11. Low, K.H.: Preface: Why biomimetics? Mech. Mach. Theory. 44, 511–512 (2009).

12. Johnson, E. a. C., Bonser, R.H.C., Jeronimidis, G.: Recent advances in biomimetic sensing technologies. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 367, 1559–1569 (2009).
13. Richardson, P.: Fitness for the future: applying biomimetics to business strategy, http://opus.bath.ac.uk/23269/, (2010).
14. Horn, P.: Autonomic Computing: IBM's Perspective on the State of Information Technology. IBM Press (2001).
15. Kephart, J.O., Chess, D.M.: The vision of autonomic computing. Computer. 36, 41–50 (2003).
16. Modha, D.S., Ananthanarayanan, R., Esser, S.K., Ndirango, A., Sherbondy, A.J., Singh, R.: Cognitive Computing. Commun ACM. 54, 62–71 (2011).
17. European Commission: Nature-inspired Smart Information Systems. The European Community, Framework Programme "Information Society Technologies" (2008).
18. Dressler, F., Carreras, I. eds: Advances in Biologically Inspired Information Systems. Springer Berlin Heidelberg, Berlin, Heidelberg (2007).
19. William, M., Huggett, P.: Biomimetic Information Retrieval with Spreading-Activation Networks. (2007).
20. Kampfner, R.R.: Biological information processing: the use of information for the support of function. Biosystems. 22, 223–230 (1989).
21. O'Connor, T., Wong, H.Y.: Emergent Properties. In: Zalta, E.N. (ed.) The Stanford Encyclopedia of Philosophy (2012).
22. Anderson, P.W.: More is Different: Broken Symmetry and the Nature of the Hierarchical Structure of Science. In: Bedau, M.A. and Humphreys, P. (eds.) Emergence. pp. 221–230. The MIT Press (2008).
23. Vogiazou, Y.: Design for Emergence: Collaborative Social Play with Online and Location-Based Media, Volume 153 Frontiers in Artificial Intelligence and Applications. IOS Press, Amsterdam ; Washington, DC (2007).
24. Kitamura, S., Kakuda, Y., Tamaki, H.: An approach to the emergent design theory and applications. Artif. Life Robot. 3, 86–89 (1999).
25. Cavallo, D.: Emergent Design and learning environments: Building on indigenous knowledge. IBM Syst. J. 39, 768–781 (2000).
26. O'Reilly, U.-M., Ross, I., Testa, P.: Emergent Design: Artificial Life for Architecture Design. In Artificial Life 7 Proceedings (2000).
27. Johnson, L., Stergiou, M.: Emergent design and development of information systems: The theoretical justification. In: Torres, M., Sanchez, B., and Wills, E. (eds.) Systemics, cybernetics and informatics; World multiconference on systemics, cybernetics and informatics. pp. 457–463. Int Inst Informatics & Systemics, Florida, USA (1999).
28. Waguespack, L.J., Schiano, W.T.: Thriving Systems Theory: An Emergent Information Systems Design Theory. 2013 46th Hawaii International Conference on System Sciences (HICSS). pp. 3757–3766 (2013).
29. Green, D.G.: Emergent behavior in biological systems. In: D.G. Green and T.J. Bossomaier (Editors), Complex Systems: From Biology to Computation. IOS. pp. 24–35. IOS Press (1993).
30. Wright, D.: The emergence of information organization in biology. Proc. Am. Soc. Inf. Sci. Technol. 46, 1–4 (2009).
31. Wooley, J.C., Lin, H.S.: A Computational and Engineering View of Biology. Catalyzing Inquiry at the Interface of Computing and Biology. National Academies Press (US), Washington (DC) (2005).
32. Navlakha, S., Bar-Joseph, Z.: Distributed Information Processing in Biological and Computational Systems. Commun ACM. 58, 94–102 (2014).

33. Bechtel, W.: Biological mechanisms: Organized to maintain autonomy. Syst. Biol. Philos. Found. 269 (2007).
34. Hoare, T.: The Logic of Engineering Design. In: Guy, K. (ed.) Philosophy of Engineering. pp. 14–20. The Royal Academy of Engineering, London (2010).
35. Newell, A., Simon, H.A.: Computer Science As Empirical Inquiry: Symbols and Search. Commun ACM. 19, 113–126 (1976).
36. Mäkelä, M.: Knowing Through Making: The Role of the Artefact in Practice-led Research. Knowl. Technol. Policy. 20, 157–163 (2007).
37. Kaufmann, M., Wilke, G., Portmann, E., Hinkelmann, K.: Combining Bottom-Up and Top-Down Generation of Interactive Knowledge Maps for Enterprise Search. In: Buchmann, R., Kifor, C.V., and Yu, J. (eds.) Knowledge Science, Engineering and Management. pp. 186–197. Springer International Publishing (2014).