From Information Systems to Complex Adaptive Information Systems

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Abstract. In this paper we try to argue for the need of a reconceptualization of information systems. We highlight a number of problems encountered in current information system and argue that faced with these problems it is either impossible or unnatural and difficult to tackle the problems with current artificial intelligence techniques. The first problems are the problems of vague terms and personalization and the well-known Knowledge Acquisition Problem. We introduce two other problems which we name the Unknowability Problem and the Explication Problem which cannot be solve in current information systems, even in principle. We show how there is a meaningful mapping between information systems and what has been termed complex adaptive systems, and propose to take the analogy seriously by letting it guide our construction of whole information system that show a coherency lacking in current information systems.

Introduction

The World-Wide Web has been characterized as a complex adaptive system soon after it took off in the early 1990s. This is to say that it is "intrinsically dynamic, far from a global optimum, and continually adapting to new circumstances," [14] which conforms to Holland's idea of complex adaptive systems (Cas) [7]. That this is so is certainly self-evident, given the policies that govern both the Internet and Web. However, one needs to be careful with this analogy.

A system is a Cas if it is composed of a large number of simple (and similar) entities, called agents to avoid any preconceptions as to their concrete nature [7], who interact locally according to a small set of simple rules and who change their interactions according to circumstances. A standard example invoked to illustrate this idea is an ant colony using stigmergy—indirect communication via the environment—building an anthill. The ants are the agents of the Cas, the anthill an emergent product of the system. By comparing the Web to the anthill we notice why the characterization of the Web as a Cas is incorrect. The Web is being created by humans who setup web pages and put links in them to make their pages traversable as hypertext. Rather than "created" we ought to say the Web is an outgrowth, or emergent product, of human activity—it corresponds to the anthill. The agents of the Cas are we humans.

This paper is concerned with complex adaptive information systems (Cais), i.e. complex systems in which the agents *are* the information. Munnecke [14] also used the term Cais, but it was later independently reintroduced by Kovács and Ueno [10]. While the former gives a valuable checklist on how to "plan systems with the same propensity [as Cas] to spawn emergent properties" (a task which converges with what we had in mind) we proposed [10][11][12] concrete ideas on how to realize them (a point on which Munnecke remains silent).

We start by defining information systems and highlighting some problems associated with them. We then introduce complex adaptive information systems and argue that they could help solve those problems. We are forced to reconsider the very nature of information systems, since the implicit understanding we have of them has an (often unnoticed) influence on the way we tackle problems within the current approach towards information systems.

Some Background

The background of our proposal was an investigation into the problems encountered when searching for information on the web especially with mobile devices. Given the technical limitations of the mobile

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environment, the question that we investigated was how could information system be made more intelligence with regard to understanding the meaning of vague terms and the personalization of the content provided.

Our investigation of a system to support *vague and personalized search* (in the form of a Gourmet Advisor [11][12]) called several questions to mind. How do we represent vague terms? How do we determine there meaning? How to we link information in the information system to them as to make vague information retrieval possible? Similar questions abound regarding personalization. How do we determine the user's situation? How do we utilize what we remember from past interactions with certain users? How do we customize information tailored to single users? These are essentially all questions of knowledge acquisition, representation, management and procession.

After analyzing vague terms and personalization we came to the conclusion that both problems are instances of a broader problem, that of context. The ability to retrieve information based on context dependents on the ability to be able (i) to describe contexts, (ii) to acquire the knowledge about contexts, (iii) to link contents to context and retrieve it accordingly, and (iv) to constantly adapt to changes. Though there are ways to solve all these problems to a certain extent in isolation, we argued that current artificial intelligence techniques (possibly applied in current types of information systems) are unable to handle these requirements *together*. We argue further that this inability is due to the current conception of information systems (and resulting problems) and proposed a new model for information systems [10], which is inspired by complex adaptive systems. The proposed model includes mechanisms to grow (as opposed to build an information system), to constantly adapt, and to link context to contents. The boldest—and possibly most controversial—step we do in our model is to assert that we needn't represent semantics or meaning of words in order to handle vague meaning, but that *the system will self-organize structures that will implicitly carry that meaning.*

Information Systems and Associated Problems

This section is meant to define what we understand under information system (IS) and point out some problems of such systems.

A IS, simply stated, is a computer system that contains information, or contents, that is put there by information providers such that users seeking this information can consult the IS. The IS provides means for storing, managing and retrieving this information. A search engine on the web such a Google is thus an information system, as are Ekipara [www.ekipara.com], Citeseer [citeseer.com], or your library's OPAC. You use the Goggle primarily to find web sites, Ekipara to find shopping venues in an area (via the web or your mobile phone), Citeseer to find scientific papers and OPAC to find out about books available in your library.

Many users of IS have difficulties to express their information needs. Being able to state precisely, with exactly the right terms, what one is looking for is the biggest obstacle in any search process. Users often know what they are looking for only once they see it and only after they have seen it contrasted with what else is available. IS however force us to state our search need precisely or they make us search for it in predefined category systems. Users also need to use logical connectives which they seldom fully understand and aren't able to user iterative search properly to refine their search criteria. IS also cannot handle vague personalized search, in the sense introduces above.

Large-scale online information systems usually have a large number of information providers, a system that manages huge amounts of contents, and sometimes millions of users. This poses a number of problems to those systems. Where does the information provided come from, how is it acquired, how is it represented and stored, and by what means is it made retrievable? How is a query matched with the contents in he system? The architecture of the whole information system, *including the distribution of roles*, affects how these problems are solved. (Note that in a personal IS, the role of information provider and user could be combined in one person.)

It is important to realize that the actual contents of an information system is maybe the easiest to acquire as there are usually people interested in making the contents available, such as store-owners who want to sell products. The problem, when acquisition is not that simple, is one of knowledge acquisition. How this is solved depends on the format content/information/knowledge needs to be represented in. *There is however a bigger problem; that of acquiring knowledge and information that is not explicitly part of the contents that is to be managed by the information system.* It is this implicit knowledge that we will be concerned with mostly. For example, if we want to retrieve restaurants (the content) based on the taste of their food, the question arises of how to acquire and represent this information, because even if taste descriptions are contained in the contents, their meaning won't be.

So when attempting to find a solution to the acquisition problem, we need to know the following:

- What knowledge needs to be acquired in what form?
- Who *does what*, i.e. who does acquire the knowledge?
- Who is actually *able* to acquire the knowledge? (If a logical formalism is to be used, normal users won't be able to do this and an expert is needed.)
- Who can *know* what? (Take vague terms, because an expert cannot know the meaning of words and cannot anticipate how that meaning will change, he cannot acquire this knowledge.)
- How easily can non-experts contribute knowledge? It should be easy for anybody to contribute explicitly or implicitly no matter what his ability/quality/knowledge.

The fact that we very often cannot answer the first question will turn out to be a strong argument against knowledge representation.

Knowledge acquisition problem (KAP). The *knowledge acquisition problem* refers to the bottleneck encountered in knowledge based AI systems because it is extremely difficult to supply the system with all the knowledge that it needs to function. Sometimes, collaborative acquisition methods by non-expert users are possible [4], but only if it is possible to explicitly state the knowledge one means to acquire. In the case of vague terms, this seems to be impossible. In the case of personalization the acquisition problem shows up when we try to formalize the notion of context.

Unknowability Problem (UP). The biggest drawback of standard approaches is what we term the *unknowability problem*. When building an information system we cannot know in advance either the exact categories or terms that will be used, neither can we know how they are used, nor can we know in advance their meaning. When trying to personalize the content search process, there are so many possible contexts, that it is impossible to know or anticipate what to do in all these contexts.

UP relates to the fact, that there are certain things we cannot know, even in principle. The designer cannot know, and if he could, he couldn't explicate (see EP below). Though Kauffman speaks in a complete different context, his words express the problem nicely:

"[T]he biosphere appears to be doing something we cannot describe beforehand—not because of quantum indeterminacy or chaotic dynamic behavior *but because we don't have the concepts ahead of time* [emphasis added]. [W]e seem to confront a limitation on knowledge that we had not recognized before. The evolving biosphere is doing something we had not recognized before; *we do not have the categories*. The same, I think, applies to technological evolution: No one foresaw the Internet a century ago." ([8], p. 138)

This fact is immediately relevant for ontology as well. If we try to formalize what exists we are constraint by the concepts we have now. This is true for knowledge representation and machine learning, as we need to set up ontologies, or category systems, for the computer for these techniques to work, but if we don't have the categories, we cannot do this set up.

So, we cannot know, what are the most likely used/helpful categories, words, terms to describe stuff, whether they are the same for all kinds of food, regions, groups of people. For some, money might be most important category, for some atmosphere, for some the food. *Giving the same interface to all of them makes the information system difficult to navigate, as we impose a category system on the user!*

Explication Problem (EP). If it wasn't for KAP and UP, then the explication problem becomes a definite hurdle. The explication problem refers to the impossibility to explicate the meaning of vague knowledge in a logical formalism using that formalisms semantics. Don't be fooled by the fact that fuzzy logic proposes to do exactly that, the reason that this is impossible is that there is now way of knowing what the best way is to explicate that meaning, we won't know in advance what categories to use or what form of statements to use to explicate the meaning. As we proceed in formalizing vague knowledge we will always encounter problematic cases, exceptions and unstatable facts. We would have to constantly change the ontology underlying the formalization process. All this is reminiscent of the qualification and frame problems of planning in AI (see [9] and references given therein) but more general.

If one approached these problems as engineering problems then, based on above discussion, one would be inclined to try and find standard AI techniques and work out a combination that, put together cleverly, would solve the problems. What is more, one would be inclined to consider the problem in terms of knowledge representation and knowledge processing, to build systems that are intelligent and can support the search process of the user. However, this not only leads ad hoc solutions, which are prone not to be general but also unprincipled. A solution lacking backing principles is not satisfying because it is hard to justify and doesn't lead to insights into why exactly it solves the problems. There are some obvious ways of solving these problems, but these aren't applicable, for they all run into one of the problems discussed for information systems above.

What Kind of System Do We Need Then?

The conception of IS one holds influences and constrains the solutions that are possible and the ways we think about these problems. Large-scale information systems face a number of difficulties, the ability to handle context in the light of above stated three problems (KAP, UP, EP), is but one of those difficulties. We can keep trying to solve these problems using old categories and our old concept of IS; or we can step back, and rethink IS. Using the old categories we run into the danger of trying add-hoc solutions using tools that have originally been devised for different problems. We advocate the latter approach, that is to change our conception of IS, hoping to see the problems and possible solutions in a new light.

It is important to realize, that in order to arrive at a shared understanding, an iterative process is necessary in all but the simplest cases, the interactive process cannot be banned from the search or information retrieval process. It can only be simplified, streamlined and made more pleasant.

What we need is a system that embodies notions such as context, interaction, adaptation and isn't too much concerned with semantics or knowledge (which as we have seen is impossible to aquire in a system that doesn't exhibit extensive self-organization.) We must get away from the old categories and reframe the problem in new terms. So, in spite of the stated research aim (vague personalized search), it is felt that it is important to step back and consider the whole system first in order to understand where exactly AI techniques come into play.

The new question thus becomes, how do you model a whole information system such that this shared understanding about the context and its role in determining the meaning of vague terms and the relations between context, vague terms, users and contents emerges. In summary, a solution needs to be implicitly collaborative, statistical, needs to embrace self-organization and emergence and exhibit perpetual novelty, that is a strive for never-ending newness. Only by exhibiting these properties can the problems KAP, UP, EP be overcome by information systems.

A good candidate of systems are complex adaptive systems which exhibit very desirable properties in there natural manifestations. However, in order to arrive at a meaningful mapping between them and information systems we need to come up with some entities *in the* system, playing the role of agents.

But What Are The Agents?

We said that Munnecke's analogy is incomplete because it didn't name the agents of the system and that, therefore, strictly speaking, the Web itself is not a Cas. There is nevertheless a vague feeling that the ideas on the Web really are themselves like agents, even if they cannot be agents *of* the Web *as system*. Munnecke [14] realizes this by stating that the Web "is an organic process: successful ideas are replicated; unsuccessful ones die away."

In order to realize this we view all knowledge in the system as pieces of information, called memes (Dawkins' terms). These memes live in an environment, called the substrate, which determines the rules by which the memes interaction, and by which the memes form larger structures. These self-evolving structures are modeled by links between memes representing association. Memes thus form meme networks in the substrate. Interaction between users and the system are mediated by active site for which we use the term workspace. Interfaces use the workspace to communicate with the substrate. Rules for creating links and changing link strengths in the workspace (adaptation rules) as well as rules determining what parts of the meme network in the substrate plays a role in the current context of the workspace (lifting rules) determine how the system develops during interaction with users. Interfaces place memes such as keywords from the user into the workspace where they are activated to signify their importance in the current context. This activation is then spread to other memes via links governed by activation-spreading rules. This models interaction between memes and leads to perpetual adaptation.

Memes, we have said are pieces of information and play the role of agents in a Cais. We use the term for those pieces of information as it has desirable connotations. When people imitate each other, something is passed on, transmitted, and replicates itself. This something was given the name meme, introduced by Dawkins in *The Selfish Gene* (cf. [3]) In analogy, when users and IS interact, pieces of information are transmitted in both directions. Memes, as replicators (the original reason why Dawkins coined the term to sound like gene [ibid.]), must adapt in order to survive. This stresses the fact that pieces of information must try to evolve in the substrate such that they make themselves retrievable to users in contexts where they are most likely to be able to replicate themselves to the user's brain. In the Cais memes live in a substrate, on the side of the user there is another substrate, which is equally being "parasitized" [5] by memes, the human brain. So, turning things around, *a Cais must provide a place that memes can parasitize as well.*

The Oxford English Dictionary defines meme as "An element of a culture that may be considered to be passed on by non-genetic means, esp. imitation." In an information system such as the Gourmet Advisor, memes can be vague terms describing the taste of food as "refreshing", names of food, or any other concept relevant for the domain. But also pieces of information that we consider to be the contents of the IS, such as documents, images, URLs are memes in a Cais. Memes survive, if they are constantly reactivated in workspaces (see below), the more and the more often a meme is activated in a workspace the "fitter" it becomes. In order to secure survival, it adapts to changing circumstance by changing its links to other memes (see below).

Complex Adaptive Information Systems

The gist of our argument goes like this: (i) complex adaptive systems (Cas) are a successful and pervasive kind of system in nature, (ii) information systems (IS) are common on the net but face a number of difficult problems, (iii) Cas have desirable properties that, if we could infuse them into information systems, might solve the problems of IS, (iv) there is a mapping from Cas to IS, and (v) a model/architecture/framework for IS can be devised based on the mapping, leading to what we have called, complex adaptive information systems (Cais) [10]. In this chapter we review the problems faced by IS, introduce Cas and show how an analogy between Cas and IS leads to a mapping suggesting a new kind of information system.

The desiderata behind our proposal of Cais are that there should be *one general framework that is not a flick work of techniques put random together, but such that all aspects can be justified based on first principles.* The set of principles on which the framework is build should be small and simple. These principles must not be tailored to the application at hand (in our case the Gourmet Advisor), but should be general enough for Cais to be applicable in as wide a range of information systems as possible.

Our proposal of complex adaptive information system (Cais) has been inspired by complex adaptive systems (Cas). We have no space to recapture the properties of Cas, but see Waldrop's popular science introduction for a readable overview of the field [17]. The abstract properties shared by all Cas is that they are composed of a large number of so-called agents, such that there are not too many and not too few [2] of these agents. The term agent was originally introduced by Holland to prevent any preconceptions we might have of concrete entities [7]. Agents interact with other agents, but only locally. This local interaction between agents is constraint by the laws of the environment in which the agents live (eg, gravity on earth, or the speed of sound). The interesting thing about Cas is, that in spite of possibly extremely simple interaction realized by the agents on a local level, the *system as a whole* exhibits self-organization and the emergence of seemingly goal-directed behavior. The behavior of the system as a whole is not orchestrated by an entity that could exert global control to direct the system; it is completely unguided in this way.

Simulation of Complex Adaptive Systems in the Computer. When implementing or simulating a Cas on a von-Neumann-architecture, one needs to create the environment where the open-ended interactions among components of the complex system and the interaction between the components and the environment can take place. When there are two or more systems that are to coevolve, the structural linkage between the systems must also be taken care of. All interactions must be locally confined, not centrally controlled, and global behavior must not be programmed. One needs to give up high programmability of von-Neumann systems for the dynamics of component interaction [6][2]. This means, one needs to program the environment, simple components, the ways they can interact, and the physics of the whole system. This environment is variously called relationship package [13] or enabling substrate [15].

We simply use the word *substrate* to denote the simulation of the environment that determines the physics of the space in which a complex adaptive system exists and evolves. The dictionary (The American Heritage Dictionary of the English Language) meaning of substrate is:

1. The material or substance on which an enzyme acts.
2. Biology. A surface on which an organism grows or is attached.
3. An underlying layer; a substratum.

The second and third meanings express very well what we want to emphasize, viz. the underlying layer in/on which a system or structure grows such that the layer qua environment influences how the system develops.

Mapping from Complex Adaptive System to Information System. Given what we have said about Cas and IS, we explain in this section how the mapping from Cas to IS works leading to the proposed concept of Cais. What we need to do is to specify the agents of the information system, and the nature of their interaction and adaptation as well as how the system interacts with the environment (otherwise it would be a closed system).

The mapping from CAS to information systems goes thus. We can characterize information systems by saying that they take bits of information (or knowledge) in, processes and stores these bits of information, and serve/return bits of information in response to queries from the environment. So we let bits of information be the agents of the system and call them memes as justified above. To realize a Cais, we need to implement a substrate that takes in memes from the environment, processes and stores them. Memes must be represented in such a way as to allow local interaction and adaptation between them. The meme system adapts to changes in the environment that is changes in user interactions. Changes in the meme-structure of a Cais must in turn influence how is works as an IS.

The interaction between memes relies on the *laws embodied in the substrates*. We believe that the prime interaction of memes is that of mutual activation. Memes, just like neurons in the brain, form excitatory and inhibitory links, via which the activation of one spreads to those connected to it. Thus, memes form networks, which must be made to self-organize in the substrate. Since memes interact via activation spreading, the only adaptation they are capable of is to change the activation strengths to other memes. Memes must be given a place where this interaction can happen such that it is locally confined and such that a meme doesn't only interact with the memes it has already connections to, for else the memenet as a whole would not grow. So, memes adapt by changing their links to other memes and this in turn changes their behavior, as the amount of spread activation changes.

The interaction with the environment is realized by active sites of the substrate that take in meme from the environment and let them interact with memes already in the system. A structural coupling with the environment is realized, when both sides influence each other in appropriate ways. Since the environment of a Cais is a large number of (mainly) human users, the users interacting with a Cais are themselves a Cas in which humans are the components who interact via the exchange of memes. The user Cas and the information system are also structurally coupled via the exchange of memes.

For a Cais, it is necessary to interact with a large number of users. Via this interaction a Cais stays alive. A Cas that is not constantly perturbed by the environment soon falls into equilibrium and dies. This is why we are stressing the fact that an information system be an online or mobile information system. Thus by definition, Cais are large-scale systems that need to deal with huge numbers of memes and interact with huge number of user. Just like a hand-full of ants doesn't make an ant-colony or a hand-full of neurons a brain, so a small-scale information system cannot be a Cais. In Cais, scale matters.

The *Substrate* is the place of the Cais where memes form structures organizing into meme networks. The substrate as a simulation of the environment where these structures form, as mentioned before, must determine a number of laws that govern the interaction. We currently have three sets of rules responsible for lifting, activation spread and adaptation (see below). The necessity and meaning of these rules will become clear below. Users and Cais need to exchange something for a structural coupling between the systems to be realized. Since information is all that can be passed in and out of computational information systems, memes need to be exchanged. This exchange is mediated by active sites, called *Workspaces*. Workspaces are *active* because in them certain memes are activated. This activation is passed via links to other memes; this is governed by the activation spreading rules. When a meme is put into the workspace, memes that are connected to it are given a change to take part in the interaction, by being lifted from the substrate in the workspace; the lifting rules regulate this. Activation can only spread to memes in the workspace. *Lifting* makes sure that only rotationally relevant memes are lifted, thus keeping the number of memes engaging in a workspace way below the number of all memes in the system. The workspace thus creates a *context for interaction* with the user, as well as for creating new links and changing the strength of old links; this is governed by *adaptation rules*.

Memes coming from the user determine what gets lifted and by activating those activation spreading is also influenced. These are constraints that guide the development of the system. To a certain extents, it is not in spite of constraints, but *because of constraints* that systems exhibit creativity.

Links between memes represent *cognitive* links, be they associations or otherwise. As such they model *interaction* between memes. Agents in Cas interact by exerting some causal influence on each other, in Cais this is done by links. We model these links by directed links that have a strength value in the interval [-1..1]. A positive link means the link is activatory; negative represents an inhibitory relations between two memes. Links also have an attached meme, called the *link meme*. The link meme influences the amount of activation that can be passed over it by its own activation value. If the link meme is not active, the link is effectively off. If the link meme is fully active the link works at full capacity. Intermediate activation values of the link meme realize intermediate strengths of the link. Thus, the strength of links is context dependent.

We call our meme structure *meme network*, or memenet for short. Memenets look like semantic nets, but they differ from them in that they are not comprised of nodes that stand for concepts, but of meaningless entities. Memenets, abstractly viewed as graphs, exhibit a number of the same properties that are known from investigations into natural occurring network structures. For a popular account of the field of research see [1]. We review here some network properties that are important in the present context. It will turn out, that all three rule sets depend to a large extent on these network properties, that is not semantic properties, i.e., the meaning of what memes represent, but structural properties of their agglomeration is important.

The *memenet needs to be grown rather than created by hand*, because as we have pointed out above with the problems KAP, UP nad EP, the kind of knowledge or information they need to capture can only be indirectly be captured in an implicit way. The meaning of vague terms cannot be explicitly formalized by a formal language and the change of meaning can only be captured in a system that changes itself all the time.The laws of lifting, adaptation and activation spread in conjunction with the interaction of the system with users are responsible for directing the evolution of the memenet. What we gain from such an approach is that we are able to capture knowledge that cannot be gotten by traditional AI techniques because we cannot even ask for it.
Modeling Interaction via Activation Spreading

Conclusion

Our conception of the information system as a whole and the role we ascribe in the information system to concepts such as knowledge, semantics or meaning and retrieval, learning, etc., has important consequences on our ability solve the problem (even conceive of solutions) of vague personalized content retrieval based on context. What current information systems (viewed as whole systems) are lacking are concepts of context, adaptation, interaction, evolution and self-organization.

We showed how there is a meaningful mapping between information systems and what has been termed complex adaptive systems. *We propose to take the analogy seriously by letting it guide our construction of whole information system that show a coherency lacking in current information systems.* This new way of looking at information systems as complex adaptive information systems, as we call the new systems, is an important conceptual aid by which we show how to come up with a system architecture, that not only resembles natural complex adaptive system to be called a simulation thereof, but whose properties, inherent in the model, solve above-mentioned problems almost automatically. Trying to solve these problems from within the current understanding of information systems is futile. What is needed is a new metaphor, one that, so we argue, is best based on complex adaptive systems.

The meaning of information in an information system cannot be captured in the system; it must remain in the users of the system. Trying to capture this meaning within the information systems by is impossible. Complex adaptive information systems acknowledge this fact from the outset. They do not even attempt to capture any meaning; what they try to do is to co-evolve in a meaningful way with the humans who use the system merely by interacting with them. There intelligence emerges from the memenet, the network of pieces of information. The growth of the network and the adaptation of the memes are based solely on structural properties of the network and don't involve any semantics. The intelligence of the system is in its interactive behavior, not in any classical representation, which needs an interpreter but tries to ignore this fact.

The proposed model for information systems based on the analogy to complex adaptive systems includes the following important characteristics that are all *part of the model or immediate ramifications of it.*

- Emphasis on iterated interaction that leads to shared understanding between user and system.
- All interactions between user and system happen in context created by a workspace (this solves the personalization problem)
- Mediation of exchange of information between user and information system by the workspace and constant adaptation of the content lead to perpetual novelty in the information system and realize overall adaptation of the system to the single user and the user community as a whole
- Vague terms' meaning is learned by wittgensteinean language games
- Interfaces realize what we term *context browsing with cueing*
- Users and contents are part of a single information store as is the language to talk about the contents

Since the rules for lifting, activation spreading and adaptation are all based solely on structural properties of the memenet work and activation value distributions, meaning of word doesn't play a role. This emphasis on meaning is replaced in our proposal by an emphasis on context and interaction.

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References

[1] A.-L. Barabási. *Linked.* Perseus Publishing, Cambridge, MA, 2002.

[2] Y. Bar-Yam. *Dynamics of Complex Systems.* Perseus Books, Reading, MA, 1997.

[3] S. Blackmore. *The Meme Machine.* Oxford University Press, Oxford, 1999.

[4] T. Chklovski. *Using Analogy to Acquire Commonsense Knowledge from Human Contributors.* PhD thesis, MIT, February 2003.

[5] D. Dennett. *Consciousness Explained.* Penguin Books, London, 1991.

[6] G.W. Flake. *The Computational Beauty of Nature.* MIT Press, Cambridge, MA, 1998.

[7] J. Holland. *Hidden Order.* Perseus Books, Cambridge, MA, 1997.

[8] S. Kauffman. What is Life?. In: J. Brockman (ed.), *The Next Fifty Years*, pp. 126-141, Phoenix, London, 2003.

[9] A.I. Kovács, *Actions in Situation Theory - And a Novel Solution to the Frame Problem*, Unpublished M.Sc. Thesis, University of Leipzig, January 2003. [http://dol.uni-leipzig.de/pub/2003-1/en/]

[10] A.I. Kovács and H. Ueno, Towards complex adaptive information systems, Proc. of the 2nd ICITA 2004, Harbin, China, January 2004.

[11] A.I. Kovács et al. *Knowledge Management in the Gourmet Advisor.* Technical Report of IEICE, 103(709):37-42, 2004.

[12] コバチ・アレクサンダー、上野晴樹. 複雑適応情報システムの概念に基づくグルメ・アドバイザー. *人工知能学会 2004 年全国大会予稿集*, 金沢, 2004 [in Japanese].

[13] M. Mitchel. Analogy-making as a complex adaptive system. In Segel et al. [16].

[14] Munnecke T., The World-Wide Web and the demise of the clockwork universe, Proc. of the 2nd International Conference on Mosaic and the World Wide Web, Chicago, October 1994.

[15] L. Rocha and J. Bollen. Biologically motivated distributed designs for adaptive knowledge management. In Segel and Cohen [16].

[16] L. Segel and I. Cohen, editors. *Design Principles for the Immune System and Other Distributed Autonomous Systems.* Santa Fe Institute Series in the Sciences of Complexity. Oxford University Press, New York, 2001.

[17] M. Waldrop. *Complexity*, London, Penguin Books, 1994.