A Theory of Communication for User Interface Design of Distributed Information Systems

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Abstract : We explore the phenomena of communication and computer-mediated communication. Concepts from information theory, user interface design, and semiotics are surveyed. Aspects of the cognitive and social dynamics of communication are discussed. A novel communication theory is proposed, and a pilot study is made to conceptually validate some of the principal postulates of the theory. Related work is given, and future plans are outlined.

Key words : User interface design, Distributed information systems, Communication, Semiotics

1. INTRODUCTION

It may seem quite natural that while interacting with artificial systems, particularly – with computer systems, people tend to humanize their counterpart, by default delegating to it an active rôle of guiding the process of interaction and anticipating from the system an "intelligent" (often seen as flexible and adaptive rather than knowledgeable) or even "conscious" (able to assess itself) behaviour. The evidence for this is everywhere – not only in users' descriptions of their related experiences (e.g. "The system explained me that..."),

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but also in the domain terminology and commercial slogans advertised (e.g. "intelligent agent," "office assistant," "avatar," and the like). It should be noted, however, that software designers and developers till recently kept themselves away from the very complicated task of modelling human-like personality at any scale of interest, maintaining the thesis that anthropomorphic characterizations of computers should only metaphorically be understood and be related not so to a system or its interface but indeed to the people "hidden behind" the system. Given the complexity of human behaviour and the existing poor understanding of the "mechanisms" governing human-human interaction (i.e. intelligence and consciousness), it nevertheless appears interesting as to explore whether and to what extent straightforward anthropomorphic modelling of human-computer interaction can resolve the evident conflict between users' expectations about the system's rôle and its actual, designed and implemented capabilities.

There are a number of possibilities for modelling human-like behaviour in user interface design arising from various assumptions made about the fundamental processes underlying human-computer interaction, including the modelling of the user's perspective on the system's functioning and reaction (as in the so-called interaction models, e.g. Beaudouin-Lafon, 2000). In this paper, we address a different viewpoint on the interaction, one that arises from considering the interface as an active communication device. We thus aim to specify human-computer interaction, based on a fundamental biological view of human communication, as a complex process of semiosis developed from the interaction of two or more self-organizing systems.

We describe digital cities, a class of computer systems that comprise different media and information resources and serve to facilitate social or spatial navigation of its users in an abstract or physical space. It is argued that communication is a critical issue in the digital city development, and that none of the classical models of communication is adequate to elaborate comprehensive guidelines for designing digital city user interfaces. We then provide an axiomatic basis and introduce a system-theoretic semiotic model of communication. We also describe a pilot study of the implementation of an active (adaptive) user interface for a digital city that partially realizes the developed model.

2. BACKGROUND

2.1 Digital City and User Interface

A digital city usually comes as a distributed collaborative system comprising a range of information resources associated with a certain geographical place or a specific human activity (see Ishida and Isbister, 2000). The principal function of a digital city is to support navigation of its users in the physical (geographical) or abstract (activity) space by providing relevant information in a timely manner. To do this, the digital city enables various (social) interactions between users and information resources. These interactions can roughly be classified into three groups: communication of the user's need or goal (e.g. sightseeing or shopping), the location of a source of relevant knowledge (e.g. a database or another user), and communication of the knowledge (e.g. as a text, photograph, or diagram). A typical scenario for the interaction is that the user submits a query representing his or her goal to a search engine, which is part of the digital city, and then browses across hyperlinks generated by the system in reply to the query, interprets, finds, and retrieves information of interest. Otherwise, to locate a particular resource, the user can browse through a pre-defined hyperlink tree or network that reflects the digital city organization.

To illustrate major difficulties in designing and using digital city interfaces, let us consider a typical situation where a user of a digital city interacts with the system (through its interface), having in mind to find and, perhaps, buy "a good book on interface design." The first problem on the user's side is to formulate his or her goal in terms, which can effectively and correctly be understood by the system. There may or may not be an appropriate pre-defined hyperlink (e.g. to an e-bookstore), while submitting a query (e.g. "interface design"+"book") to the search engine typically results in returning hyperlinks of arbitrary relevance to the user's goal (that would, in our case, be metaphorically thought of as window-shopping). The user has yet to explicate to the system his or her subjective notion of the "good book" (for instance, the same volume would be fairly good for a housewife but of little help for a Web-designer). To be effective, the system has to develop and/or utilize a (cognitive) model of the user's goal-state and/or behaviour.

Having chosen a hyperlink, the user may access a component of the digital city (e.g. a digital library or a site representing a "physical" bookstore); the semantics of the original query may then change, owing to the component design (e.g. book as a digital document *vs.* some data about an ordinary paperback) and/or experience and practice currently prevailing in the society of the system's users (e.g. a digital document may be considered "good" – i.e. popular – just because it is freely available and/or the corresponding hyperlink is, at the moment, most strongly associated with the query, based on feedback from the previous users). Besides, while browsing, the user may refine or even change his or her goal (e.g. to "to find a text-book on communication theory"), owing to information learnt from the different recourses. Thus, to successfully communicate, the user has dynamically to adjust her or his language (seen as behaviour) and reconcile her or his subjective semantics with semantics implemented in the different parts of the system. It is obvious that the efficiency of this adaptation process (and, therefore, the effectiveness of human-computer interaction) depends on both the individual (cognitive) and the social (community) dynamics of communication.

2.2 Communication Models and Interface Design

There are two major approaches to understanding and modelling communication processes (Lewis and Gower, 1980): statistical "signal-oriented" and interpretive "meaning-based." The Shannon-Weaver theory with its conveyor tube model (Shannon and Weaver, 1963) represents the former class of the approaches (see Figure 1). By the model, the interface is composed of messages allowing for and explaining the control and operation of the system (e.g. a physical mechanism).

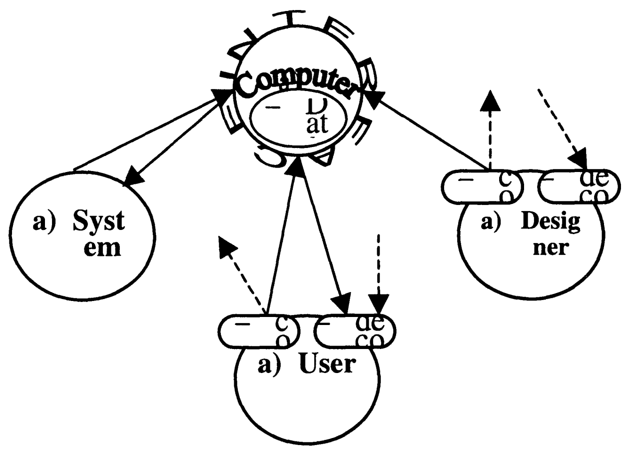

Figure 1. User interface and the transmission of messages

The messages can be about the system domain, computational domain, and user-computer possible interactions. Both, the user and the system can send and receive information, and a computational data model implemented in the computer program determines the "correct" messages and interactions. This data model reflects the designer's understanding of the controlled system structure and functioning encoded and sent to the user through the interface. The designer and the user can also exchange information directly, e.g. through interviews, questionnaires, or any other feedback, bypassing the computer.

Although being frequently criticized, the Shannon-Weaver theory currently dominates over any other theory of communication in terms of its conceptual development and significance for practice. Among the most noticeable shortcomings of this model, we should mention its inability to deal with semantic issues. More significant for us, however, is the fact that the Shannon-Weaver theory can contribute little, if anything, to clarifying and coping with the complexity of communication in a social context (Di Paolo, 1998).This makes the signal-oriented statistical approach ineffective for the design and development of user interfaces.

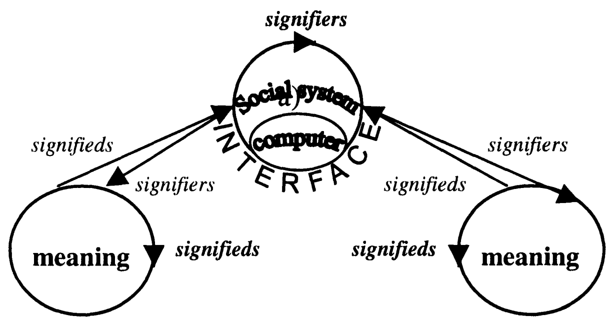

Figure 2. User interface and the interpretation of signs

Communication models of the second – interpretive – class are usually associated with the Peircean conception of a semiotic triad (Peirce, 1998) connecting a sign with its object by meaning, which may or may not be another sign, that is the sense made of the first sign. In user interface design, the application of such a model (frequently simply called semiotic model) is concerned with the generation and exchange of meaning, when the divergence of meaning is not a failure but a natural attribute of communication. In a semiotic model, communication is defined as the development and re-interpretation of signs that are representations of the world (see Figure 2). By the model, the interface is composed of signs – signifiers, which are to represent "meaning" created by psychic or/and physical systems. These systems externalise meaning by producing signifieds (generally seen as behaviours), which may activate the "generation" of signifiers (i.e. signs standing for something) through the interaction with the social system. The interface is a realization of the social system, while signs are individually interpreted but still have socially (culturally) induced meaning. There can be more than one social system, but no communication is possible beyond a social system. All the systems involved have internal dynamics affecting their outputs – signifieds (in the case of physical/psychic systems) and signifiers (in the case of social systems).

In its classical stating (see Andersen, 2001), the model tells little about mutual influences of the social and psychic systems and about the dynamics of these systems. The major drawback of the "meaning-based" model is, however, its conceptual vagueness and, as a

consequence, poor formalisation.
Thus, as none of the popular communication models provides comprehensive guidelines for user interface design of distributed information systems, such as digital cities, new approaches to modelling communication need to be found.

3. THE APPROACH

Most of the theory referred to in papers and books on human-computer interaction has a strong propensity to concentrate on either cognitive or social aspects of communication. The analysis of the different approaches to user interface design presented in the previous sections convinces us that the development of an adequate model of human-computer interaction requires the provision of a more broad, *socio-cognitive* perspective on communication phenomena. In this section, we will describe a model of human-computer (and human-human) interaction derived from a general definition of communication made in terms of autopoiesis theory.
Autopoiesis is a theory of the organization of complex systems, such as living organisms (Maturana and Varela, 1980). An autopoietic system is a form of self-organization: it consists of a network of processes, which recursively produces and reproduces its own components and boundary to ensure the survival of the system, and which have a particular physical embodiment – structure. The principal property of an autopoietic system is its autonomy in respect to the environment: the inner state of the system at any time is determined solely by its structure and a previous state. All observed behaviours – the output – of an autopoietic system is a result of its inner state and history. Through behaviours, the system can interact with the environment that may lead to changing its structure. If this changing does not break autopoiesis, the system is called structurally coupled with the environment. An important case is when the environment has a structural dynamics (e.g. is in itself a self-organizing system): the coupled system and the environment may begin to mutually trigger their inner states so that the system undergoes self-adaptation. The self-adaptation processes of several autopoietic systems embedded in the same environment may become coupled, recursively acting through their own states. All the possible

changes of states of such systems, which do not terminate this coupling, establish a consensual domain. Behaviours in a consensual domain are mutually orienting. Communication can fundamentally be defined as *the observed behavioural coordination developed from the interactions between autopoietic systems in the consensual domain* (Di Paolo, 1998).

3.1 Theory

We will assume that all the psychic (or any other) systems involved into communication are (higher order) autopoietic systems acting in the consensual domain. Each of these systems "belongs" to at least one self-organizing social system understood as a projection of the consensual domain. We will also assume that the psychic system is composed of interpretants (meanings) and is observationally equivalent to (i.e. is interpreted as) the totality of subjectively (i.e. experientially) effective behaviours called *objects*. The social system is composed of *signs* and is equivalent to the totality of socially valid (i.e. maintaining the social system) behaviours. (The reader with a semiotic background should be warned that our treatment of the semiotic triad *object-sign-interpretant*, although does not generally contradict to the concept of infinite semiosis (Peirce, 1998), moves forward from the canonical Peircean definition by elaborating the ideas originally formulated in Andersen, 2001.)

We will consider communication a (usually finite) partial time-sequence of interdependent – through signs seen as behaviours and in the sense of the behavioural coordination revealed as relations on the signs – semiosis processes $C=\{S_1,S_2,\ldots,S_K\}$, where $S_t=\{Object_t,Sign_t,Interpretant_t\}$ is a single semiosis process specified through its manifestation (that is an interpreted sign), and t is a discrete time-mark.

The dynamics of a self-organizing system can generally be described as follows:

$$\begin{cases} \mathbf{x}(t+1) = \mathrm{f}(\mathbf{x}(t), y(t)), \\ y(t+1) = \mathrm{g}(y(t), \mathbf{x}(t+1)), \end{cases} \tag{1}$$

where $y(t)$ is the state of the system at time t, $\mathbf{x}(t)$ is the vector of states of the system parts, which constitute its structure, and f and g are some operators specifying the behaviour of the system parts and the system as a whole, respectively. The dynamics of the communication process is then described by the following equations:

$$\begin{cases} \mathbf{Objects}_{t+1} = \text{Externalizing}(\mathbf{Objects}_t, \mathit{PsychicState}_t), \\ \mathit{PsychicState}_{t+1} = \text{Interpreting}(\mathit{PsychicState}_t, \mathbf{Signs}_{t+1}), \end{cases} \quad (2.1)$$

and

$$\begin{cases} \mathbf{Signs}_{t+1} = \text{Authorizing}(\mathbf{Signs}_t, \mathit{SocialState}_t), \\ \mathit{SocialState}_{t+1} = \text{Evolving}(\mathit{SocialState}_t, \mathbf{Objects}_{t+1}), \end{cases} \quad (2.2)$$

where "**Objects**" is a state vector representing the behaviours (i.e. psychic states as observed), which are subjectively effective, and "**Signs**" is a state vector representing the behaviours socially valid. "Externalising" and "Interpreting" are operators that represent the uttering and the understanding processes, respectively; likewise, "Authorizing" and "Evolving" represent the corresponding (implied) processes of social dynamics. (In these formulas, neither "social" nor "personal" time is given explicitly, but by the effect they have on the semiosis processes.)

The simultaneous equations of (2.1) and (2.2) allow us to conceptually characterize communication as a complex semiosis process. It should be understood that the number of equations of the form (2.1) and (2.2) necessary to define a particular communication depends on the number of the psychic and social systems involved. It is also to note that for all the systems, the state at time t does not necessarily differ from the state at time t+1, and for a psychic system involved into communication, it is not necessarily to produce *Objects* to receive *Signs*.

To refine and make the proposed conceptual framework formal, i.e. appropriate for computer treatment, the apparatus of algebraic semiotics can be used (Goguen, 1999). For the purposes of this paper, it will suffice to consider a sign system Ξ as a logical theory that consists of sets of signs (that are not the same as *Signs*, and that are usually understood as symbols), which have sorts, together with some operators used to build up new signs from signs already existed, some partial orderings on sorts (by sub-sort and by level) and operators (by

level and by priority), and relations and axioms that constrain the possible signs. We will call a semiotic morphism $\mu:\Xi \rightarrow \Xi'$ a mapping (translation) from a sign system Ξ to a sign system Ξ'. This mapping is composed of partial functions defined on the sign system elements, and it preserves some of the structure of the first system (for formal details, see Goguen, 1999).
Let us introduce the notion of basic semiotic component as follows:

$$\mu_{t+1} : f_t[\Xi_t] \xrightarrow[P_{t+1}]{} \Xi_{t+1}, \tag{3}$$

where f_t is a (composition of) semiotic morphism(s) that specifies the dynamics of signs in Ξ_t, and μ_{t+1} is a *probabilistic semiotic morphism* that represents a set of L_{t+1} possible translations from Ξ_t to Ξ_{t+1} with probabilities $P_{t+1} = \{p_1, p_2, \ldots, p_{L_{t+1}}\}$, one for each translation.
We will now introduce an axiomatic basis for a semiotic theory of communication as follows.
Axiom I. Each psychic system can be represented by a sign system Ξ. The state of the psychic system – the psychic state – is completely described by a set of related signs in Ξ. ♦
Definition 1. Two states of the psychic system, α and β, are called orthogonal, written $\alpha \perp \beta$, if α implies the negation of β, or vice versa. ♦

Definition 2. For a subset of states $A \subset \Xi$, its orthogonal complement is $A^{\perp} = \{\alpha \in A \mid \forall \alpha' \in A^{\perp} : \alpha \perp \alpha'\}$. ♦

Definition 3. $A \subset \Xi$ is orthogonally closed if $A = A^{\perp\perp}$. ♦
Similarly with a quantum system, the psychic system is *normally in multiple states at once* and, therefore, it cannot uniquely be interpreted: at every single moment, there can be made more than just one interpretation of the psychic system state. This postulated with the following *context principle*:
Proposition I. For every two distinct psychic states $\alpha \neq \beta \subset \Xi$, there exists a context state $\alpha \cup \beta = \gamma \subset \Xi$ such that $\forall \delta \subset \Xi$, if $\delta \perp \alpha$ and $\delta \perp \beta$, then $\delta \perp \gamma$. ♦

Axiom II. Each interpreted psychic state can be represented in a unique way by a probabilistic semiotic morphism μ with

$P = \{p_1, p_2, ..., p_L\}$ on Ξ. The probabilities of the morphism correspond to the possible interpretation results.♦

Definition 4. We will call *Object* an orthogonally closed set of psychic states with a single *Interpretant* understood as a distinction. ♦

An interpretant is hence a psychic state but also the result of interpretation.

Axiom III. Right after an interpretation of an *Object* standing for some psychic states γ, which resulted in α, the psychic system is represented by α, i.e. the original states γ are translated to the *Interpretant* α by the interpretation.♦

Hence, an interpretant exists always only to the extent as the corresponding psychic states are accessible for interpretation.

Axiom IV. For a psychic system engaged into communication within a social system, the dynamics of the communication process is given by a pair of sequences of basic semiotic components defined recurrently as follows:

$$A = \{M^A, P^A, F^A, \Xi_{objects}\}, \tag{4.1}$$

and

$$\Omega = \{M^\Omega, P^\Omega, F^\Omega, \Xi_{signs}\}, \tag{4.2}$$

where A is the model of the psychic system that includes M^A a set of semiotic morphisms μ_{t+1}, P^A a set of probabilities for each μ_{t+1} in M^A, F^A a set of semiotic morphisms f_t, $t=1,\ldots,K$, and $\Xi_{objects} = \bigcup_{m=1}^{M} Object_m$, M is the number of the interpretants by the psychic system prior to the communication. Ω is the model of the social system with analogously defined M^Ω, P^Ω, and F^Ω, and $\Xi_{signs} = \bigcup_{n=1}^{N} \Xi_{objects_n}$, where N is the number of psychic systems constituting the social system. ♦

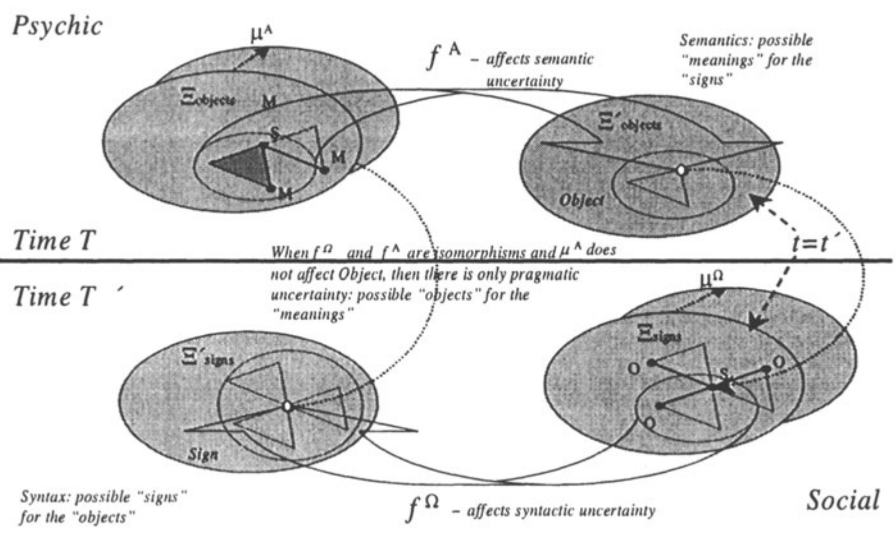

Figure 3. Semiosis of communication

It can be seen that A and Ω correspond to the representations of (2.1) and (2.2), respectively (also see Figure 3). μ-type morphisms are to define the internal dynamics – state transition – of the psychic (social) system caused by interpretation (evolving, in the case of social systems), and P is to reflect the indirect character of the state representation (e.g. potentially multiple meaning of the same object or potentially multiple objects of the same sign). f-type morphisms are to specify the process of "externalising" the system inner state. $\Xi_{objects}$ is, in effect, the psychic system's language that reflects the individual's communication experience, and Ξ_{signs} is the language of the social system. The cognitive and social dynamics of the communication process are specified with the morphisms of A and Ω, respectively.

Axiom V defines communication as the interaction – coupling – between the two self-organizing systems, where one system – psychic – may be perturbed by signs and produces objects (behaviours), and another system – social – may be perturbed by objects and produces signs. Both systems are defined in a quite deterministic manner, but their numerous constituents and sensitivity to the initial conditions (i.e. the history given with $\Xi_{objects}$ and Ξ_{signs}) make the communication process, although controllable in principle, hard to model and predict. The coupling of the systems is specified with M^{A} (the psychic) and F^{Ω} (the social) semiotic morphisms. The rôle of the social system is seen to filter – authorize – communications out of behaviours and, on the other hand, to buffer behaviours against the uniformity of socio-cultural norms. The social system is not to impose a "standard" of communicative behaviour, but rather to propagate regularities accounting for the possibility of coordinated behaviour.

(Closure) Theorem. A communication is orthogonally closed:

a) *pragmatically* through the laws of nature in the sense that given an interpretant $Interpretant_t$, it is only the physical laws that determine its object $Object_t$ so that $Object_t = Object_t^{\perp\perp}$;

b) *semantically* through the psychic system in the sense that $\Xi_{objects} = \Xi_{objects}^{\perp\perp}$, and

c) *syntactically* through the social system in the sense that $\Xi_{signs} = \Xi_{signs}^{\perp\perp}$.

Proof:

a) If there is exactly one object *Object* with a single interpretant, the closure is self-evident. Let us then consider two psychic states $\alpha \neq \beta$ characterized by two objects $Object_1 \neq Object_2$ with the same interpretant *Interpretant*. Whenever physically possible, one can define $Object_3 \subset Object_1 \cup Object_2$ characterizing some γ, $\gamma \neq \alpha$ and $\gamma \neq \beta$, that has the same interpretant. Since $Object_3 \cap Object_1 \neq \varnothing$ and $Object_3 \cap Object_2 \neq \varnothing$, the state γ cannot be determined orthogonal to α or to β. Furthermore, for all the states δ, $\delta \perp \alpha$ and $\delta \perp \beta$, with objects $Object_4$ having interpretants different from the *Interpretant*, $Object_4 \cap (Object_1 \cup Object_2) = \varnothing$, $\delta \perp \gamma$ as $\delta \cap \gamma = \varnothing$. Hence, extending to an arbitrary number of *Objects*, given a set of psychic states and a distinction of these states by an interpretant, it is (ultimately) only the physical laws determining the psychic states – the (ultimate) *pragmatics* of the situation – that limit the possible *Objects* for the interpretant.

b) Provided that $Object_m = Object_m^{\perp\perp}$ for $m=1,\ldots,M$, then $\Xi_{objects} = \Xi_{objects}^{\perp\perp}$, as $\Xi_{objects} = \bigcup_{m=1}^{M} Object_m$ by definition. Hence, given a psychic system and a distinction classification of its states by interpretants, it is only this classification – the *semantics* of the *Objects* – that determines the objects for the psychic system.

c) Provided that $Object_m = Object_m^{\perp\perp}$ and $\Xi_{objects} = \Xi_{objects}^{\perp\perp}$, then $\Xi_{signs} = \Xi_{signs}^{\perp\perp}$, as $\Xi_{signs} = \bigcup_{n=1}^{N} \Xi_{objects_n}$, $n=1,\ldots,N$, by definition.

Hence, tautologically, the possible signs for the social system – the *syntax* of the *Signs* – are determined by the (*Objects* of the) psychic systems constituting it. ♦

It follows directly from the above theorem that the psychic state corresponding to every (physically) possible *Object* can uniquely be determined, but also that the *Object* corresponding to each psychic state does not have to be unique. Besides, the theorem dictates that every single communication is closed only to a degree. Indeed, given a psychic state, its pragmatic closure is reachable when one considers a (frequently huge) number of *Objects* – in fact, all the possible *Objects* – characterizing the state, which are to express the physical frames of the situation (e.g. a perception or emotion) associated with the psychic state and to establish the interpretant. The latter is not a practical case (unless we consider learning by trial and error or the like cognitive processes), and *Objects* are results of some relations (which are not necessarily conventions) developed from individual experience rather than exhaustive representations of the psychic state. Furthermore, semantic closure is hardly reachable, because to hold, it requires the definition of all the *Objects* for all the psychic states that is unrealistic, owing to (at least) the spatio-temporal dynamics every time uniquely allocating each psychic system, the indirect character of interpretant assessment, and the natural cognitive limitations (e.g. the memory limits). This, as well as the fact that social systems are generally dynamic in respect to their psychic constituents, hampers calculation of syntactic closure, too. Thus, *every communication is uncertain.*

The goal (or motivation) of a communication for a psychic system can be understood as to reach a certain psychic state through perturbations by signs. Normally, to initiate communication, the psychic system must possess a "model" of the corresponding social system – i.e. it must make some assumptions (in other words – anticipations) about the social language, as well as a "plan" or "strategy" for the interaction; it must also interpret some of Ξ_{signs}. On the other hand, as soon as the psychic system is involved into communication, it becomes part of the social system so that some of its *Objects* may be interpreted and thus turn out to be part of Ξ_{signs}. It can be shown that having defined the orthogonal syntactic (semantic) closure, one can always reconstruct the state(s) of the social (psychic) system (though not the system itself, as there will always be an uncertainty caused by the "externality" – in respect to the social (psychic) system – of the pragmatic closure). The better the reconstruction, the more precise the corresponding model of Ξ_{signs} ($\Xi_{objects}$) and, naturally, the more efficient – for the psychic system and in the sense of minimizing the requisite interaction – the communication process built on the model.

Lemma I. Given a communication situation with a pragmatic uncertainty *Const* independent of time, the natural limitation on the minimal (communication) requisite interaction for a psychic system engaged into the communication is determined by the communication uncertainty $E_{O,M}$ that can be estimated using the following formula ($E_{O,M} \in [0,1]$, $E_{O,M}=1$ is for the absolute certainty):

$$E_{O,M} = k_s \sum_{i=1}^{M} \left(\sum_{j=1}^{M} \frac{N_{Int}(Object_i \cap Object_j)}{N_{Int}(Object_i) + N_{Int}(Object_j) - N_{Int}(Object_i \cap Object_j)} - 1 \right) + k_c \sum_{i=1}^{O} \left(\sum_{j=1}^{O} \frac{N_{Int}(Sign_i \cap Sign_j)}{N_{Int}(Sign_i) + N_{Int}(Sign_j) - N_{Int}(Sign_i \cap Sign_j)} - 1 \right) - Const, \quad (5)$$

where M is the number of *Objects* produced by the psychic system, O is the number of *Signs* received by the psychic system, $N_{Int}(Object_i)$ is the number of interpretants by the psychic system for the same object $Object_i$, $N_{Int}(Object_i \cap Object_j)$ is the number of interpretants for both $Object_i$ and $Object_j$, $N_{Int}(Sign_i)$ is the number of interpretants of the same sign $Sign_i$ in the social system, $N_{Int}(Sign_i \cap Sign_j)$ is the number of common interpretants of $Sign_i$ and $Sign_j$, k_c and k_s are normalizing coefficients, and *Const* is a constant determined by the degree of pragmatic closure. Note that generally, $M \neq O$. (The proof is omitted to kept he paper short.)

It is understood that $E_{O,M}$ as an estimation of the minimal requisite interaction is not generally applicable to an on-going communication unless the principal parameters of the social and psychic systems remain constant from the time of estimation through the time of communication.

The probabilities necessary to define the dynamics of the psychic system (see Axiom IV) can be estimated based on the following axiom:

Axiom V. For a psychic system in a state $\gamma \subset \Xi$, the real number $\Pi(\gamma,\alpha)$, where Π is an operator measuring the semantic distance and α is resultant of μ, is inversely proportional to and, in this way, determines the probability to obtain the interpretation α when μ. For $\alpha \not\subset \Xi$ and $\alpha \perp \gamma$, $\Pi(\gamma,\alpha)=\infty$; furthermore, $\Pi(\gamma,\alpha)=0$ for $\alpha=\gamma$.♦

If disregard the dynamics of the psychic system (i.e. the meaning change) and for a sufficiently large number of observations (i.e. interpretation trials) M, the semantic distance can be estimated using the notion of semantic close:

$$\Pi(\gamma,\alpha) \cong \frac{1}{M}\sum_{i=1}^{M}\left(\frac{N_{Int}^{i}(Object_{\gamma}) + N_{Int}(Object_{\alpha})}{N_{Int}^{i}(Object_{\alpha} \cap Object_{\gamma})} - 2\right). \quad (6)$$

The probabilities for the model of the social system can analogously be estimated.

Given $C=\{S_1,S_2,\ldots,S_K\}$ a time-sequences characterizing semiosis processes of a communication, the behavioural coordination *COR* of the involved psychic systems can be estimated using the following formula:

$$COR(t) = k_b \sum_{i=1}^{K} \frac{N_{Int}(Sign_t \cap Sign_i)}{N_{Int}(Sign_t) + N_{Int}(Sign_i) - N_{Int}(Sign_t \cap Sign_i)} - 1, \quad (7)$$

where $t=1,\ldots,K$, and k_b is a normalizing coefficient. *COR(t)* shows how the syntactic uncertainty is changed through communication: as behavioral coordination produces relations on signs, it should reduce the number of distinct psychic states associated with the given communication situation.

4. PILOT STUDY

In this section, we will present a pilot study conducted to explore if and to what extent a partial implementation of the communication model (4.1 – 4.2) with an adaptive user interface would increase the efficiency of communication.

Figure 4 shows an interactive Web page filtering process with an adaptive interface, which utilizes relevance feedback from its users to increase the efficiency of user-computer interaction. A user initiates communication by inputting a query (i.e. *Object*) to a search engine (seen as the interface of the World Wide Web) and then receives a hit-list that is composed of hyperlinks to Web pages that contain *Signs*, which may bring the user's psychic system to its goal or preferred state. This hit-list is to reflect the user's interest but, on the other hand, it also represents the state of the social system associated (or modelled) with the search engine at the time of the query. When the number of received pages is too large for the user to check all of them, the interface attempts to develop a model of the goal state using appropriate signs of the social system to consequentially estimate the relevancy of each page from the list. In Figure 4, the model is represented in the form of rules, which are derived from training examples of relevant and non-relevant pages given by the user. The rules are used to select (from the hit-list) pages that are likely to be relevant. If the number of selected pages is still too large, the user can repeat the training-filtering cycle until she or he obtains a manageable volume of information.

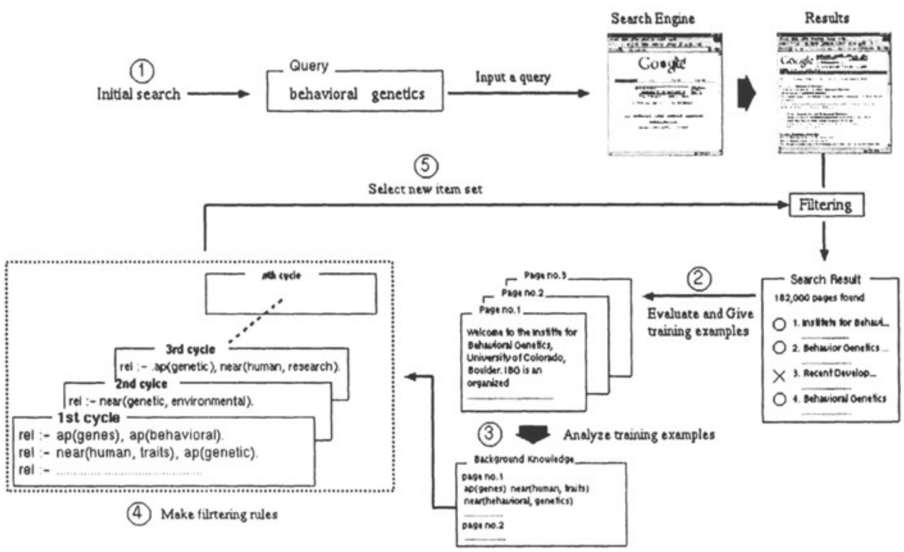

Figure 4. Adaptive user interface

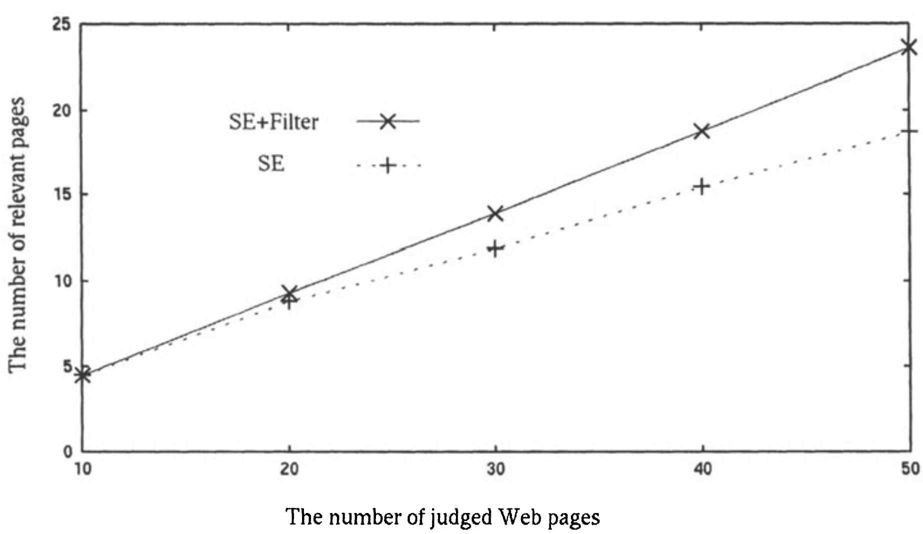

Figure 5. The average number of relevant pages found

To estimate the efficiency of the developed adaptive interface, several retrieval experiments have been made. In one experiment, 50 pages from the top of a hit-list returned by a conventional search engine (SE) were first judged against their relevancy to the goal-state. 4 iterations were then made, using the search engine and the adaptive interface (SE+Filter), every time collecting 10 pages from the top of the hit-list to provide for feedback and to build filtering rules, and 50 pages from the resultant hit-list were evaluated for their relevancy to the goal-state. Google (http://www.google.com) was used as the test search engine SE. 20 topics (no. 401 through 420) were selected as *Interpretants* from the small web track collection TREC-8 (http://trec.nist.gov). The title words in every chosen topic were used to form queries for the search engine. Relevance judgment for each page was made by the same person according to the narrative part of each topic.

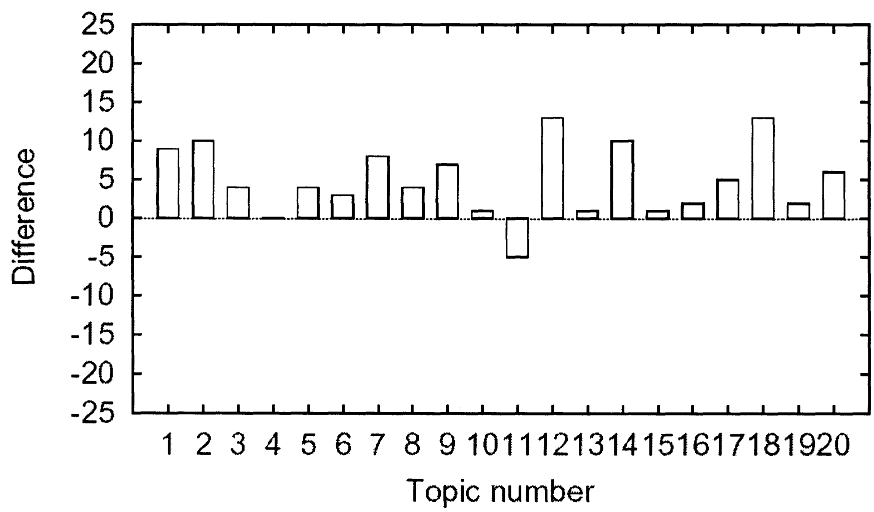

Figure 6 The difference in the number of relevant pages after the 4th feedback: SE *vs.* SE+Filter

Figure 5 shows the results of the experiment. The number of relevant pages is the average value over 20 topics. After four feedbacks, "SE+Filter" got about 5 relevant pages more than "SE". However, the change in the number of relevant pages differed for every topic (see Figure 6).

The second experiment was conducted one year later from the time of the first. We have applied the "old" model of the user's goal state (for each topic) obtained in the first experiment to search relevant pages. Figure 7 displays the difference in the number of relevant pages found in the first and second experiments. The decline in relevant pages was, most probably, caused by the social dynamics revealed as an increase in the degree of syntactic closure of the corresponding social system. (To reduce the influence of the cognitive dynamics to the minimum, the relevance judgment was made by the same person as in the first experiment and strictly following the narrative part of each topic description.)

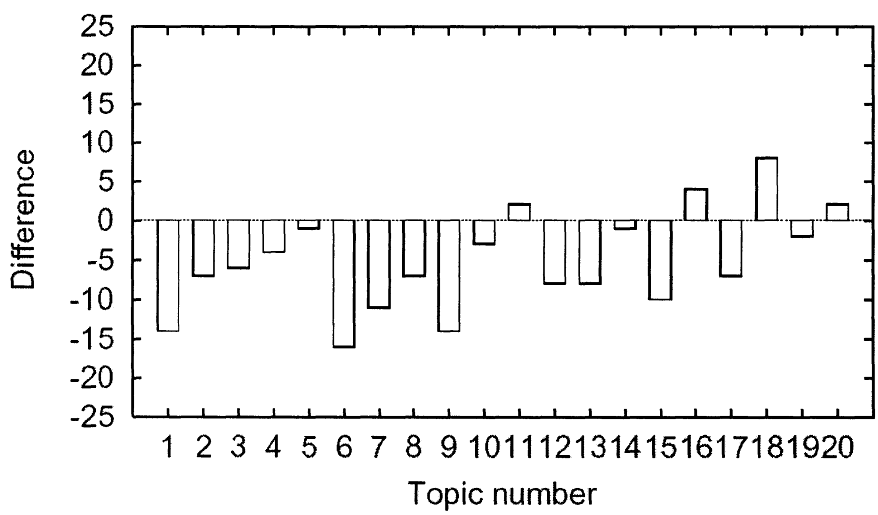

Figure 7. One year later: the decline in relevant pages by Google+Filter

The application of the "old" model with the AltaWista search engine (http://www.altavista.com) resulted in slightly better results (see Figure 8) than in the case of the present Google (compare with Figure 7) but, though expectedly, worse than in the case of the "old" Google. This may be due to the fact that the social system, which AltaWista stands for, has a significantly less ($P<0.001$) degree of syntactic closure for the given interpretants (topics) than the one associated with current Google, and this system is closer (in the sense of syntactic closure) to the social system realized by Google one year ago

(corresponding estimations were made using the "syntactic" component of formula (5)).
Figure 9 shows the behavioural coordination (for the first 5 semiosis processes and averaged over the 20 topics) calculated with formula 7 (keywords as *Signs* and the indexed documents as *Interpretants*) for AltaVista and Google. It can be seen from the figure that AltaVista+Filter provides for a better behavioural coordination and, thus, more efficient communication than Google+Filter in the given communication situation.

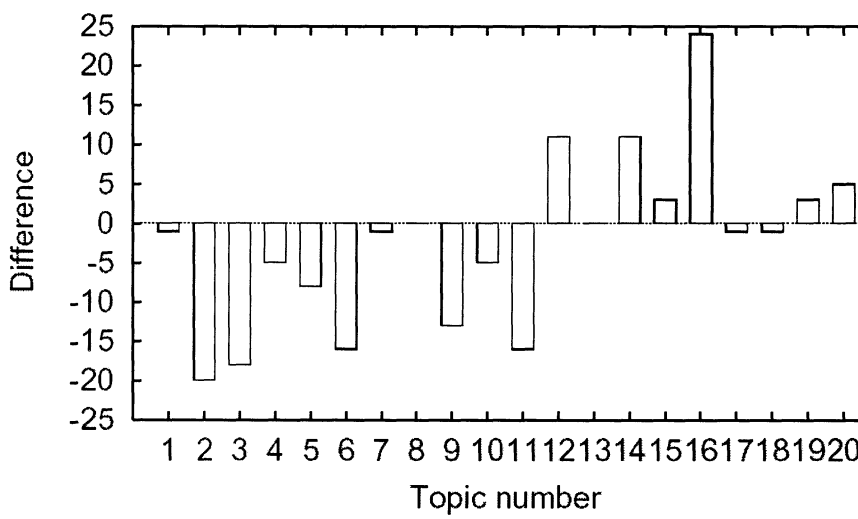

Figure 8 "Old" Google+Filter against present AltaWista+the same Filter

The experiments clearly indicated that *a*) the efficiency of communication can be improved by implementing the social and psychic system models with an adaptive interface, *b*) a model of the psychic system state (e.g. a user profile) alone may not be sufficient to ensure efficient communication, and an appropriate dynamic model of the social system (or, at least, a model of the social state) should be utilized, and *c*) the degree of syntactic closure and behavioural coordination are important parameters that may be used to detect social systems fitting to a particular model of a psychic state.

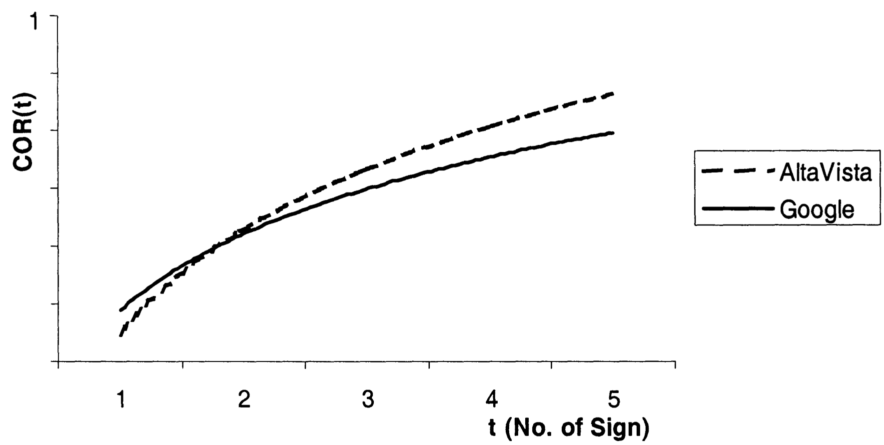

Figure 9 Behavioural coordination: AltaVista+Filter *vs.* Google+Filter

5. RELATED WORK AND CONCLUSIONS

The system-theoretic semiotic model of communication resembles the conceptual framework introduced in (Andersen, 2001): we formalized the key concepts of the dynamic semiotics – signifiers/signs and signifieds/objects – and made them applicable for the practical purposes of user interface design. We in fact proposed a novel theory for the studies of communication, and the work (Heylighen, 1990), which discusses representation problems in modern physics, has inspired us to formulate the basics of the theory in a way similar to the axioms of quantum physics. The work (Luhmann, 1995) on social autopoiesis as a general form of system development drawing on self-referential closure gave us the core idea about the rôle of a social system in the communication process.

Other closely related studies include the work (Sonesson, 2002) on interpretation phenomena, a series of works on organizational semiotics with its "allowances" and "norms" as conceptual analogues of our objects and signs (e.g. see Stamper, 1996), and the works (Prestschner and Gauch, 1999) and (Terveen and Hill, 2001) surveyed the current trends and problems in user interface design and development of distributed information systems.

It follows from the presented study that in the case of distributed information systems, the semantics of the communication language (and, therefore, the structure of the human-computer interactions) is determined, both individually and socially, by the system users rather than by some "objective" laws or by the structure/contents of the system. The system interface should thus be able to dynamically adjust the semantics as it evolves, instead of building on a pre-defined and fixed "universal semantics" (e.g. keyword indices or an ontology). The latter may put in question the efficiency, in the long-term perspective, of the technological solutions of some of the recently popular "Web-paradigms," such as the Semantic Web (Berners-Lee and Hendler, 2001).

While the presented axiomatic basis mainly focuses on and provides for the description of the communication phenomena at the "micro" (i.e. as for a psychic system) level, in our future research we plan to elaborate it so as to statistically (i.e. at the "macro" level) define the time-development of the social system. Formulation of a methodology and principles for a large-scale experiment to measure parameters of the whole World Wide Web as a social system is another direction for future work.

6. ACKNOWLEDGEMENT

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7. REFERENCES

Andersen, P.B.: Dynamic semiotics. Semiotica (2001)

Beaudouin-Lafon, M.: Instrumental Interaction: An Interaction Model for Designing Post-WIMP User Interfaces. In: T. Turner, G. Szwillus, M. Czerwinski, and F. Paterno (eds), Proceedings of the CHI 2000 Conference, The Hague, Amsterdam (2000) 446-453

Berners-Lee, T. and Hendler, J.: Publishing on the semantic web. Nature 410 (2001) 1023-1024

Di Paolo, E.A.: An investigation into the evolution of communication. Adaptive Behavior. 6(2) (1998) 285-324

Goguen, J.A.: Social and semiotic analyses for theorem prover user interface design. Formal Aspects of Computing (Special issue on user interfaces for theorem provers), 11 (1999) 272-301

Heylighen, F.: Classical and Non-Classical Representations in Physics II: Quantum Mechanics. Cybernetics and Systems, 21 (1990) 477-502

Ishida, T. and Isbister, K. (eds): Digital Cities: Experiences, Technologies and Future Perspectives. Lecture Notes in Computer Science, Vol. 1765. Springer-Verlag (2000)

Lewis, D.B. and Gower, M.D.: Biology of Communication. Blackie, Glasgow (1980)

Luhmann, N.: Social systems. Stanford University Press, Palo Alto (1995)

Maturana, H. and Varela, F.J.: Autopoiesis and Cognition: The Realization of the Living. D. Reidel Publishing Company, Dordrecht (1980)

Peirce, C.S.: The essential Pierce: Selected philosophical writings, Vol. 2. Indiana University Press, Bloomington (1998)

Pretschner, A. and Gauch, S.: Personalization on the Web, Technical Report ITTC-FY2000-TR-13591-01, Information and Telecommunication Technology Center (ITTC), The University of Kansas, Lawrence, KS (1999)

Shannon, C.E. and Weaver, W.: The Mathematical Theory of Communication. University of Illinois Press, ILL (1963)

Sonesson, G.: The act of interpretation. A view form semiotics. Galáxia, Sâo Paolo (2002, to appear)

Stamper, R.: Signs, Information, Norms and Systems. In: Holmqvist, B., Andersen, P.B., Klein, H., Posner, R. (eds): Signs of Work, pp. 349-399. De Gruyter, Berlin (1996)