Toward a Semantic General Theory of Everything

The notion of a universal semantic cognitive map is introduced as a general indexing space for semantics, useful to reduce semantic relations to geometric and topological relations. As a first step in designing the concept, the notion of semantics is operationalized in terms of human subjective experience and is related to the concept of spatial position. Then synonymy and antonymy are introduced in geometrical terms. Further analysis building on previous studies of the authors indicates that the universal semantic cognitive map should be locally low-dimensional. This essay ends with a proposal to develop a metric system for subjective experiences based on the outlined approach. We conclude that a computationally defined universal semantic cognitive map is a necessary tool for the emerging new science of the mind: a scientific paradigm that includes subjective experience as an object of study. © *2009 Wiley Periodicals, Inc. Complexity 15: 12–18, 2010*

ALEXEI V. SAMSONOVICH, REBECCA F. GOLDIN, AND GIORGIO A. ASCOLI

Alexei V. Samsonovich and Giorgio A. Ascoli are at Krasnow Institute for Advanced Study, George Mason University, 4400 University Drive, Fairfax, Virginia 22030 (e-mail: ascoli@gmu.edu)

Rebecca F. Goldin is at Department of Mathematics, George Mason University, 4400 University Drive, Fairfax, Virginia 22030

INTRODUCTION

Imagine that in a remote future all meaningful information is laid out in some abstract space based on its semantics. Let us call this space the *universal semantic space*, and the entire distribution of available *chunks** of information in it (which may look like stars in the galaxy on the cover illustration) the *universal semantic cognitive map*. The idea may sound intuitively familiar, as spatial analogies play a prominent role in human cognition and memory [1, 2]. However, the notion of a universal semantic cognitive map goes beyond mere indexing or analogy. The map in and by itself can be used as a language and a complete representation of all information that is ''indexed'' on it. Indeed, if each precise map location uniquely determines the associated meaning then, literally, one point of this map should be worth thousands of words. This representation of information, however, would make no practical sense, if map coordinates were assigned to chunks at random. Instead, as for a road atlas, a useful map would enable semantic inferences by virtue of geometric and topological inferences. Therefore, we assume that:

- semantic relations among chunks are captured by geometric and topological relations among their images in the map;
- points of the map and displacements on the map are associated with definite and consistent semantics; and

---

**By a ''chunk'' we refer to a coherent representation of meaningful information, in any format and in any medium. Examples: an utterance, a document, a sculpture, a movie, a traffic light. A message of any kind is also a chunk.*

DOI 10.1002/cplx.20293
Published online 25 November 2009 in Wiley InterScience
(www.interscience.wiley.com)

- the semantics of each map location can be obtained as a composition of semantics of finite displacements along a path leading to that location from some reference point on the map.

If this hypothetical construct is ever to materialize, it will in fact constitute a *General Theory of Everything*, once a dream of a great-grandfather of Ijon Tichy (a Stanislaw Lem's character). In comparison, we have a rather modest ambition to outline a more precise notion of this challenge from epistemological and mathematical perspectives. In this essay, we first address the critical question of how to measure semantics practically. Next, we introduce key distinctions and definitions of semantic maps. Then, we illustrate these concepts with a simplified example. Finally, we end with a discussion of the potential impact that semantic map may have on the evolution of science and the progress of humankind.

COGNITIVE-PSYCHOLOGICAL AND COGNITIVE-NEUROSCIENTIFIC UNDERPINNINGS

In this work, we treat semantics as potential experience of a human subject. In general, the notion of semantics and its definition have been a subject of perpetual philosophical debate ([3, 4]; see also the last section) to which we are not offering a conclusion. We will expand on our position in the last section with explanations and discussion of related background issues. For now, we just note that our choice allows us to measure semantics by measuring human experience and therefore to define all necessary concepts operationally. In this case, how should we measure the meaning of a chunk? The measurement of the meaning is not the measurement of the amount of information in the sense of Shannon [5], because in the current framework, we need to distinguish among various qualities or qualia rather than quantities of information. For this reason, e.g., it seems natural to expect that semantics should be measured by some sort of a vector rather than a scalar. Even the task of finding the number and semantics of the vector components seems too challenging. We start with an observation that could simplify the task substantially: to construct a meaningful multidimensional semantic map, we only need a measure of semantic dissimilarity of any two chunks that can be interpreted as distance with a direction, plus a chunk with known semantic measure. The latter is easy to ascribe: it could be the empty chunk, defined to have zero semantic "position."

To operationalize the notion of semantic dissimilarity, we interpret semantics as potential *average* human experience. If a representation is meaningful to a human subject then the subject understands its meaning (whatever this means) when he/she becomes aware of it. Building on this premise, the notion of the meaning of a chunk can be made precise by association with the mental state of awareness of the chunk, as follows. Assume that, in principle, it is possible to measure the dissimilarity of any given pair of mental states, using their neural (e.g., functional magnetic resonance imaging) and/or behavioral (e.g., introspective report) correlates. Of course, there are substantial technical issues here: how to filter out the noise and effects of unrelated factors, how to overcome cultural differences, etc. We skip their discussion for now and assume that there is a protocol according to which measurements can be repeated with a sufficient number of subjects yielding consistent results. In this case, we could say that the notion of dissimilarity of two mental states is operationally defined, and so is the notion of dissimilarity of two chunks. At this point, it is only an assumption that these general operational definitions exist.

The next question refers to the notion of semantic space that provides an infrastructure for the map. In cognitive psychology and linguistics, there were many limited attempts (and associated criticisms: [6]) to make the idea of semantic space mathematically precise. For example, Russell [7] introduced a two-dimensional circumplex model to represent feelings, Osgood et al. [8] introduced a three-dimensional semantic differential, Gärdenfors [4] developed the notion of a conceptual space, etc. The state of the art in linguistics related to the semantic space idea is represented by latent semantic analysis (LSA; [9]) and its variations, including the probabilistic topic model [10], association spaces [11], and other techniques. We eschew any requirement to give a comprehensive review here.

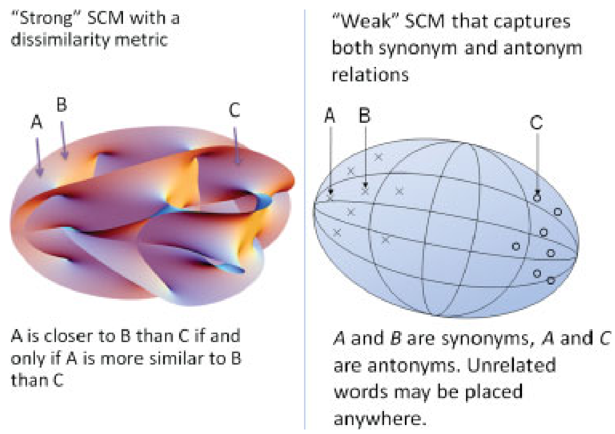
The growing success of LSA and related examples supports our central assumption that the idea of the universal semantic cognitive map can be given a precise mathematical sense in general, and not only in those limited special cases. Specifically, we assume that it is possible to map any given set of chunks to points in a universal semantic space endowed with a metric that captures semantic relations among chunks.

KINDS AND PROPERTIES OF SEMANTIC COGNITIVE MAPS

In this text, we use the word "map" to mean both a **map of sets** from the chunks to a metric space, as well as its **image**. Semantic relations among chunks captured by the map image may include dissimilarity, antonymy, and synonymy. For example, the ambient space in which the map lives may have a metric that captures dissimilarity (called *dissimilarity metric*): the more dissimilar two chunks are the greater is the distance between them on the map. Naturally, zero distance should imply identity of meaning and vice versa. In this case, we call the

DOI 10.1002/cplx

FIGURE 1



Kinds of semantic cognitive map: strong (left: modified with permission from http://en.wikipedia.org/wiki/File:Calabi-Yau.png) and weak (right).

map a *strong* semantic cognitive map. As an alternative, a map may tend to pull all synonyms together and all antonyms apart, with a soft constraint on the spread of the entire distribution and without representing dissimilarity per se [12]. In this case, we call the map a *weak* semantic cognitive map (Figure 1).

A proposal to build a universal semantic cognitive map capable of accommodating all possible human knowledge and experiences would imply a huge program for many generations to come. Today, we are far from the final goal, yet it could make sense to address one relatively simple question about the final product. Assuming that the universal semantic cognitive map can be constructed, what can we say a priori about its geometric and topological properties?

We propose to narrow this question down to two issues that in our view can be addressed today. One has to do with geometric representation of antonymy on a strong semantic cognitive map. How can one introduce synonymy and antonymy into the geometrical framework outlined above in which only the notion of dissimilarity is initially assumed to be represented by distances? To the best of our knowledge, this is an open problem [13].

Another issue concerns the semantics of the coordinates of the ambient space in which the map image lives. A recognized limitation of LSA and related approaches is that semantic dimensions cannot be clearly identified: "*The typical feature of LSA is that dimensions are latent. That means there are no explicit interpretations for the dimensions*" (Ref. 14, p. 414). Is it possible to construct a semantic cognitive map, the dimensions of which have clearly identifiable, general semantics?

For now, we assume that the ambient space of the cognitive map is a vector space $\mathfrak{R}^n$, and therefore chunks are associated with vectors under any semantic map of chunks to $\mathfrak{R}^n$. According to the above assumptions, the semantics of a given chunk are given by a composition of semantics of elements of a path leading to it from 0, representing the empty chunk.

We also assume that with a sufficiently large set of chunks, elements of a path can be made small enough so that semantics of a path element would approach an "elementary semantic difference." In other words, our hope is that as the difference of meaning of two chunks becomes smaller and smaller, it should also become simpler and easier to grasp. Indeed, when the necessary level of precision is specified, the difference between two similar items is usually easier to characterize than the difference between items of different kind. Consider, for example, the following pairs of chunks: "a new car" and "a used car," "the number 4" and "the number 5," "a new car with a scratch" and "polysemy." Consistent with this observation, we assume that the notion of an *elementary semantic flavor* makes sense, understood as the meaning of a finite semantic difference that cannot be further reduced to a composition of smaller differences. Based on this definition, elementary semantic flavors must differ from each other qualitatively, implying that two different flavors cannot correspond to the same direction in $\mathfrak{R}^n$. On the other hand, every direction in $\mathfrak{R}^n$ associated with a pair of chunks that are separated along this direction should be representable by a composition of elementary semantic flavors. Based on these considerations, we assume that any point on the map has local coordinates associated with elementary semantic flavors.

We shall continue this consideration in the next section using a simple example (which is not representative of today's state of the art in computational or cognitive linguistics). Specifically, we restrict chunks to English documents, replace elementary semantic flavors with English words, neglecting their ambiguity and context-dependence, and assume that coordinates given by these words on the map are global Cartesian coordinates. Although these simplifications may introduce

DOI 10.1002/cplx

inconsistencies, this toy example is useful to illustrate our ideas.

A TOY EXAMPLE

Let us start with a finite set X consisting of the set of documents currently existing in the literature. We are setting out to present a mathematical framework in which X can be given geometrical structure, and that structure can be studied to understand more about the structure of language and human knowledge. As a first step in this process, we would like to consider a map

$$A : X \to \Re^n \tag{1}$$

in which X is represented in a vector space $\Re^n$ by its image under the map A. There are many choices for this map A and, depending on the aspect of X that is under consideration, it may be useful to vary the choice of A. Indeed, a geometric representation of X using LSA can be viewed as an example of a choice of A.

Ideally, we should be able to learn about semantic characteristics of X by measuring geometric characteristics of $A(X)$, given the right choice of A. Many useful geometric characteristics (e.g., a nonzero Hausdorff dimension [15]) require an infinite set of points in $\Re^n$. Therefore, we need to take an extension of the set X to an infinite set. A possible example is the set of all *possible* documents, without restrictions on the document length. The advantage of an infinite set is that one can construct infinite sequences and make conclusions about how they converge under the map A in the topology of $\Re^n$. In this heuristic picture, the properties that would ideally be satisfied by X and by A include:

- A is injective, and hence no two documents are represented by the same point in $\Re^n$,
- the image $A(X)$ is dense in (a subset of) $\Re^n$,
- $A(X) \subset \Re^n$ has interesting geometric properties,
- the coordinates of $\Re^n$ have definite semantics,
- $A(X)$ records dissimilarities among elements of X by distances in $\Re^n$ (with an appropriate choice of metric): the more distant two documents are, the less similar are their meanings, and vice versa.

It may not be possible to satisfy all these properties at once, but we begin by noting that a part of this general framework has been used already in LSA. Attempts to improve on this analysis will not only rely on changing parameters but also on varying A and (correspondingly) the value n.

To clarify this concept with an example, we consider a simple model, in which a basis $\{w_1, w_2, \ldots, w_n\}$ of $\Re^n$ is associated with a set of n dictionary words W, $n \approx 10{,}000$, each word $w_i \in W$ representing an elementary semantic flavor. For each document $x \in X$, we have

$$A(x) = \sum_{i=1}^{n} b_i a_i(x) w_i, \tag{2}$$

where $a_i(x)$ is the number of times the word w_i occurs in x, and $b_i \in \Re$ is a real number indicating a "weight" that the word w_i is given. This model to study X is used as a starting point of LSA, followed by an SVD-rotation and truncation of extra spatial dimensions [16].

There are some clear limitations to the particular choice of A in (2). Specifically, if two documents have the same words but in a different order, they would be mapped to the same place in $\Re^n$. The model would make no distinction between a document which reads "The dog ate the shark," and "The shark ate the dog," even though the context in which either could occur is clearly very different (one suggesting land, and the other suggesting water; one suggesting the shark was already dead, whereas the other suggesting that the shark attacked the dog, etc.). Below we assume that this and other difficulties are resolved with a better choice of A [17]. Our present goal is not to find the best representation of documents, but rather to introduce a framework in which such maps could be explored.

The first question that we address here is how to incorporate the notions of synonymy and antonymy into this geometrical framework. This question relates to the issue of translating relationships among words and documents into relationships among documents.

We posit the existence of two functions (defined operationally):

applicability g: $X \times W \to [0, 1]$, and
agreeability f: $U_X \to \Re$,

where U_X is a subset of $X \times W$ consisting of pairs (x, w) such that $g(x, w) = 1$. Intuitively, applicability is a measure of the sensibility of applying the word w to a document x, and it takes only two values: applying the word either makes sense or not. Agreeability can be intuitively understood as a rating of a document along the semantic dimension given by a word. Operationally, to measure agreeability $f(x, w)$ of a document x and a word w, we would ask subjects to evaluate how strongly they agree/disagree with one of the following sentences:

- "x is w" (if w is an adjective, e.g., "hot," "cool," "boring").
- "x ws" (if w is a verb, e.g., "sounds," "rocks," "flies").
- "x is like w" (if w is a noun, e.g., "hummer," "wave," "tree").

Then, we would ask the same subject to evaluate whether the question makes sense or not. The result of the second answer is the value of applicability. Therefore, for each word w, we have a domain of applicability on the map, denoted by F_w: the set of all documents x such that $g(x, w) = 1$. Alternatively, the domain of applicability can be described as the fiber over w of the projection $U_X \to W$ onto the second coordinate. The function f allows us to construct functions f_A and

DOI 10.1002/cplx

g_A on $A(X) \times W$, where $A(X)$ is the image. In particular, we let $f_A(p, w) = f(x, w)$ and $g_A(p, w) = g(x, w)$, where $p = A(x)$. On each fiber, F_w, we then extend $f_A(., w)$ and $g_A(., w)$ to smooth functions on an open neighborhood of the image $A(F_w)$. Such extensions are clearly not unique, but we choose one to be as simple as possible, i.e. such that it does not vary wildly in regions not containing points in $A(X)$. We abuse notation and denote the extensions by f_A and g_A as well. Thus, the domains of $f_A(., w)$ and $g_A(., w)$ are subsets of $\Re^n$. Then, for each word w, we may associate a vector to each point in its domain of applicability: the gradient of $f_A(., w)$ at that point.

The notions of synonymy and antonymy that conform to a common intuitive understanding can be now introduced as follows. We compute gradient vectors at p for all words that apply to documents at p. Then, we define *synonyms* and *antonyms* to be pairs of words such that gradient vectors at p are nearly parallel for synonyms and nearly antiparallel for antonyms; the notions "nearly parallel" and "nearly antiparallel" are made precise with a threshold angle, which is a parameter of the theory. Note that if $A(X)$ satisfies an appropriate density property near p in $\Re^n$ then the gradients at p will be independent of the extensions of f_A and g_A to a neighborhood of $A(X)$.

Assuming that it is possible to generalize this toy example to the universal semantic cognitive map considered above, we relate the local coordinates on the universal semantic cognitive map to the above notions of synonyms and antonyms. A pair of antonyms should correspond to opposite directions along a coordinate that captures their semantics, two synonyms should correspond to nearly the same direction, and semantically different pairs of antonyms should correspond to different local coordinates on the map. This approach allows us to estimate the dimension of the map by analyzing the system of synonym–antonym relations.

We have previously demonstrated by example the possibility of simultaneous geometric representation of synonym and antonym relations in W using a *weak* semantic cognitive map [12]. Our example constructed by numerical optimization of a certain energy function was a map from W to a vector space V:

$$\sigma : W \rightarrow V \tag{3}$$

i.e., words were represented as vectors in V, such that almost every antonym pair had an obtuse angle between their vectors, whereas almost every synonym pair had an acute angle between their vectors (exceptions from this rule constituted only 1% of synonym and antonym pairs and could be due to inconsistencies of the dictionary itself). In contrast to $\Re^n$, the vector space V is low dimensional, with most of the data captured in just four dimensions (95% of the variance of the data is captured in three dimensions; the fifth and higher dimensions have negligible variance). Moreover, the first three principal components (PC) of the emergent distribution of words in V had clearly identifiable semantics: "good-bad" (PC 1), "calming-exciting" (PC 2), and "open-closed" (PC 3). This result suggests that in the case outlined above of a strong semantic cognitive map, it will be possible to select a semantically meaningful local coordinate system using these same general semantics (possibly producing similar PC characteristics for the local density of the universal semantic cognitive map).

WHY SEMANTIC COGNITIVE MAPPING MATTERS TO SCIENCE

The brain creates the Universe as we know it, and the only Universe that we know directly: the mind. It all starts from humans being aware of their own subjective experiences. Scientists call some of these experiences "observations" and attribute their origin to the physical world "out there." This belief allows us to develop phenomenological knowledge of the World which, together with precise metrics, logic, and experimentation, leads to progress, including tools to modify the World itself. Paradoxically, however, in this circle of empirical science experiences themselves are left out as a hard problem. We recently proposed a scientific approach to study experiences, because humans observe them just as they observe other real phenomena [18]. Because experiences are subjective, their phenomenological knowledge must be developed via introspection rather than with psychophysiological measures. To yield consistent scientific results, however, those observations must become objective, in the sense that they can be reliably repeated by, and quantitatively communicated among, independent researchers (see the cover illustration of this issue). The key missing elements for this purpose are precise metrics and measuring tools for human subjective experiences, such as Cartesian coordinates of the mental space. Logic and experimentation, applied to measures of subjective experiences, will lead to more progress, including tools to engineer artificial minds.

A long time has passed since scientists were satisfied with the belief of a world made of particles and fields. Today physicists are preoccupied with interpretation of far more abstract concepts, while even the century-old quantum mechanics lacks interpretation [19, 20]. Brain scientists are similarly puzzled with developing a scientific description of the brain at the higher cognitive level. In particular, there is no general consensus on how to introduce subjective experience into natural science [21]. The new scientific paradigm [18] should be based on the classical scientific method [22–24], while at the same time it needs to be (a) semantically oriented and (b) subject-oriented, i.e. it needs to include subjective experience as a subject of study. The

DOI 10.1002/cplx

explicit connection between semantics and subjectivity can be ensured by selecting an operational definition of semantics based on subjectivity, and this is the choice we made in this work.

To better understand what semantics are, how to measure and to quantify semantics, and how to build quantitative theories in semantic terms, it would be useful if we could represent semantics geometrically and apply powerful tools of geometry to (real rather than latent) semantic analysis. The notion of semantics, or the meaning of a representation, has many definitions and interpretations. Major philosophical, linguistic, and mathematical movements have been founded on trying to articulate these notions [25, 26]. The long and numerous controversial discussions of semantics in the literature from ancient to modern times justify the freedom of our choice, which is to define semantics in terms of subjective experience: in other words, we say that "meaningful" equals "meaningful to a subject". In this case, the notion of *semantics* and the notion of *potential experience* become synonymous.

Although the new scientific paradigm needs to include subjective experience as a topic of investigation, no conceptual and mathematical tools are yet available to represent and study subjective experiences quantitatively with adequate accuracy, completeness, and generality. We need a powerful apparatus to deal with semantics of experience, and therefore, with semantics in general: the word "experience" does not add a restriction in this context. Accordingly, we expect implications of semantic cognitive maps for the entire natural science, not just for the new science of the mind. In conclusion, to develop a unified semantic theory applicable to subjective experience and to objective physical reality, we need to better understand semantics itself, from a conceptual to a computational level. This sort of knowledge can be extracted from natural language and all documents, viewed as a collective product of all human minds of all generations.

ACKNOWLEDGMENTS

The authors thank Dr. Harold J. Morowitz for his continuous encouragement.

REFERENCES

1. Lakoff, G.; Johnson, M. Metaphors We Live by, 2nd ed.; University of Chicago Press: Chicago, IL, 1980.
2. Samsonovich, A.V.; Ascoli, G.A. A simple neural network model of the hippocampus suggesting its pathfinding role in episodic memory retrieval. Learn Memory 2005, 12, 193–208.
3. Baldinger, K. Semantic Theory: Towards a Modern Semantics; Brown W.C., Wright, R., Transl.; St. Martin's Press: New York, 1980.
4. Gärdenfors, P. Conceptual Spaces: The Geometry of Thought. MIT Press: Cambridge, MA, 2004.
5. Shannon, C.E. A mathematical theory of communication. Bell Syst Technical J, 1948, 27, 379–423, 623–656.
6. Tversky, A.; Gati, I. Similarity, separability, and the triangle inequality. Psychol Rev 1982, 89, 123–154.
7. Russell, J.A. A circumplex model of affect. J Pers Soc Psychol 1980, 39, 1161–1178.
8. Osgood, C.E.; Suci, G.; Tannenbaum, P. The Measurement of Meaning. University of Illinois Press: Urbana, IL, 1957.
9. Landauer, T.K.; Dumais, S.T. A solution to Plato's problem: The latent semantic analysis theory of acquisition, induction, and representation of knowledge. Psychological Rev 1997, 104, 211–240.
10. Griffiths, T.L.; Steyvers, M. A probabilistic approach to semantic representation. In: Proceedings of the 24th Annual Conference of the Cognitive Science Society; Gray, W.D.; Schunn, C.D., Eds.; Lawrence Erlbaum Associates: Hillsdale, NJ, 2002; pp 381–386.
11. Steyvers, M.; Shiffrin, R.M.; Nelson, D.L. Word association spaces for predicting semantic similarity effects in episodic memory. In: Experimental Cognitive Psychology and Its Applications: Festschrift in Honor of Lyle Bourne, Walter Kintsch, and Thomas Landauer; Healy, A., Ed. American Psychological Association: Washington, DC, 2004; pp 237–249.
12. Samsonovich, A.V.; Ascoli, G.A. Cognitive map dimensions of the human value system extracted from natural language. In: Advances in Artificial General Intelligence: Concepts, Architectures and Algorithms.Proceedings of the AGI Workshop 2006. Frontiers in Artificial Intelligence and Applications, vol. 157; Goertzel, B.; Wang, P., Eds. Amsterdam, The Netherlands: IOS Press, 2007; pp 111–124. ISBN 978–1-58603-758-1.
13. Schwab, D.; Lafourcade, M.; Prince, V. Antonymy and Conceptual Vectors. In: Proceedings COLING 2002: The 19th International Conference on Computational Linguistics. http://www.aclweb.org/anthology-new/C/C02/C02-1061.pdf; 2002.
14. Hu, X.; Cai, Z.; Wiemer-Hastings, P.; Graesser, A.C.; McNamara, D.S. Strengths, limitations, and extensions of LSA. In: Handbook of Latent Semantic Analysis; Landauer, T.K.; McNamara, D.S.; Dennis, S.; Kintsch, W., Eds.; Lawrence Erlbaum Associates: Mahwah, NJ, 2007; pp 401–425.
15. Mandelbrot, B. The Fractal Geometry of Nature. Lecture notes in mathematics 1358. W. H. Freeman: New York, NY, 1982. ISBN 0716711869.
16. Martin, D.I.; Berry, M.W. Mathematical foundations behind latent semantic analysis. In: Handbook of Latent Semantic Analysis; Landauer, T. K.; McNamara, D.S.; Dennis, S.; Kintsch, W., Eds.; Lawrence Erlbaum Associates: Mahwah, NJ, 2007; pp 35–55.
17. Dennis, S. Introducing word order within the LSA framework. In: Handbook of Latent Semantic Analysis; Landauer, T.K.; McNamara, D.S.; Dennis, S.; Kintsch, W., Eds.; Lawrence Erlbaum Associates: Mahwah, NJ, 2007. pp 449–464.
18. Ascoli, G.A.; Samsonovich, A.V. Science of the conscious mind. Biol Bull 2008, 215, 204–215.
19. Bell, J.S. On the problem of hidden variables in quantum mechanics. Rev Mod Phys 1966, 38, 447.
20. Feynman, R.P. Simulating physics with computers. Int J Theoretical Phys 1982, 21, 467–488.

DOI 10.1002/cplx

21. Chalmers, D.J. The conscious mind. Search of a Fundamental Theory. Oxford University Press: Oxford, UK, 1996.
22. Popper, K.R. The Logic of Scientific Discovery. Unwin Hyman: London, 1934/1959.
23. Kuhn, T.S. The Structure of Scientific Revolutions. University of Chicago Press: Chicago, IL, 1962.
24. Lakatos, I. Falsification and the methodology of scientific research programs. In: Criticism and the Growth of Knowledge; Lakatos, I.; Musgrave, A., Eds.; Cambridge University Press: Cambridge, UK, 1970.
25. Katz, J. Semantic Theory. Harper & Row: New York, 1972.
26. Putnam, H. Is semantics possible? In: Concepts: Core Readings; Margolis, E.; Laurence, S.; Eds. The MIT Press: Cambridge, MA, 1999; pp 177–187.

DOI 10.1002/cplx