Knowledge-Based Systems 78 (2015) 34–50

Contents lists available at ScienceDirect

Knowledge-Based Systems

journal homepage: www.elsevier.com/locate/knosys

Modeling semantic knowledge structures for creative problem solving: Studies on expressing concepts, categories, associations, goals and context

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ARTICLE INFO

Article history:
Received 9 December 2013
Received in revised form 20 December 2014
Accepted 23 January 2015
Available online 2 February 2015

Keywords:
Modeling
Knowledge structures
Semantic network
Creativity
Experimental studies

ABSTRACT

This paper presents a model for semantic network representation. According to the model, the main purpose of a semantic network is to help to correctly and quickly understand the features and structure of the solutions, and then make reliable predictions about their outcomes and rewards. These objectives are achieved under constrains like limited resources (e.g., memory size and access), time limitations, and variations of solution characteristics. The paper summarizes the elements of the model and presents a set of properties that describe the effectiveness of semantic networks in creative problem solving, including design. Six examples (based on three case studies from the related literature and three experimental studies conducted by the authors) discuss the model elements, characteristics, and properties.

1. Introduction

Creative solutions introduce features that address conceptual or implementation bottlenecks of the current solutions. We define bottlenecks as absent functions and performance limitations of existing solutions, contradictions and conflicts among problem requirements and solution features, and incapacity to derive more new features based on the characteristics of the current solutions. This definition implies that creative solutions have novel and useful features, as the traditional definition of creativity states [1]. However, in contrast to Amabile's definition, which declares the two defining characteristics of creativity, the above definition indicates the two major activities that are part of producing creative solutions: (i) identifying the bottlenecks of the current state-of-the-art and (ii) addressing the bottlenecks through specific features of the creative solution. The importance of knowledge entities in creative design must be discussed with respect to the two activities.

The effectiveness of creative activities is intrinsically related to the related knowledge structures (e.g., semantic networks) [56]. Numerous reports explain that domain expertise is a prerequisite for achieving high creativity [55]. This suggests that knowledge structures should cover a significant amount of relevant situations characterizing the problem domain. Also, experimental studies in cognitive psychology show that the organization of experts' semantic networks is significantly different than that of novices [9,13,50]. Experts' concepts are organized in categories distinguished based on structural and conceptual features (e.g., laws of physics, general principles) rather than physical (observed) properties, like for novices. Experts also utilize simpler networks [50] with less random associations. Therefore, it is plausible to assume that during problem solving experts focus more on principles and abstract concepts and less on specific details. This is important because research shows that reasoning with abstract concepts improves creativity [61]. Finally, the characteristics of semantic networks are related to the easiness of recalling information and gaining insight during problem solving [47]. Both tasks are important in identifying and tackling bottlenecks. For example, the capability of chess experts, like grand masters, to recall specific, meaningful chess positions is significantly higher than for beginners [25], even though both experts and beginners have similar recalling capabilities when random positions are used [13]. This observation suggests that experts have superior ability to organize complex yet important information, if they understand the implications (outcomes) of complex chess positions, including their advantages and limitations. This leads to superior decision making

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http://dx.doi.org/10.1016/j.knosys.2015.01.014
0950-7051/

because experts are able to anticipate (more) correctly the results of decisions. In conclusion, the effectiveness of knowledge structures in creative activities relates to its coverage of relevant information, information organization in categories (including associations), and correct anticipation of outcomes and their benefits.

The nature of memory organization has been studied through experiments on recall information. The average path lengths between concepts, including atypical associations, are used as predictor of the effectiveness of information recalling and insight gaining. Semantic network structures are produced from the observed proximity data between concepts, e.g., using Pathfinder algorithm [12,51,52,46]. Initial work focused on tree-like structures, which are good representations for typical, well distinguished concepts [11]. Recent studies focus on the statistical characteristics of semantic networks, like concept connectivity, average path lengths, and clustering of concepts [2,45,47,56]. Steyvers and Tenenbaum [56] suggest that small-world structure characterizes semantic networks that represent the meaning of new meaning through differentiation mechanisms. Concept connectivity follows a power law, according to which few concepts, acting as hubs, have large connectivities. Similarly, Schilling [47] suggests that semantic networks have small-world structure with short average path lengths between concepts. Petrou et al. [45] explain that idea networks are random (e.g., the number of a concept's connections follows a Gaussian distribution) and concept networks are scale-free (i.e. the number of a concept's connections follow a Poisson distribution). Other similar experimental studies are expected to offer more insight into the topological organization of semantic networks.

In this work, we call association path-based knowledge structure organization (using recall information) as *organization at the topological level* to distinguish it from the organization presented in the second paragraph, which we call *organization at the semantic level*. While the organization at the topological level serves as foundation for the organization at the semantic level, this paper does not explore the mechanisms for producing the second starting from the first. Instead, it discusses how the knowledge structure organization at the semantic level relates (during problem solving and decision making) to the posed problems and the semantics of the involved knowledge fragments. We think that this is a preliminary step to studying the emergency of the semantic level based on the topological level.

Given a problem, the dominant features and associations of the concepts at the level of semantic organization are significantly biased by the nature of the problem, e.g., its goals and requirements. These are part of the problem context. Barsalou [4] explains that ad-hoc concept categories are produced during problem solving depending on problem goals. Also, attention is geared towards features that are deemed (based on prior experience) to be relevant for solving the problem rather than any concept features. For example, studies indicate that the success in analytical problem solving depends on the ability to efficiently identify sub-requirements that act as stepping-stones (intermediates) for finding the more complex solutions [30,36]. Note that the features and associations of the selected sub-requirements are directly correlated to the solving strategy rather than being general-purpose. In contrast, experimental studies on memory organization often utilize experimental data, like word-associations and Roget's thesaurus, collected based on participants' input on word relatedness, but without considering the problem context or the meaning of the concepts as part of the overall solution. Moreover, network models express average statistical attributes but might discard measures about outliers. Still, outliers are important in creativity as they represent less frequent, hence potentially more novel, associations. The experimental data produced for WordNet database [16] incorporate some information on word meaning, like synonyms, polysems, antonyms, hypernyms, and meronyms. However, problem-specific details are not captured. Understanding the connection between semantic-level organization, problem description, and concept features is an important issue.

This paper presents an empirical set of properties for organizing semantic-level knowledge structures used in creative problem solving. The model assumes that knowledge structures, called semantic networks, serve to correctly understand and evaluate (predict) existing and novel solutions under the domain context (e.g., goals, objectives, and rewards), resource constraints (e.g., memory size and time limitations), and various variations (like feature and association variation in space, time and other). The paper summarizes the elements composing the model and offers a set of model properties that express correct, time efficient, robust, and flexible reasoning. The paper analyzes through six different examples how the properties are achieved through the specific model elements, like distinguishing features, categories, divergent elements, universal connectors, association sequences, and associations to goals, objectives, and rewards. The characteristics of semantic network organizations are also discussed for each case. The six examples include three case studies published in the cognitive psychology literature on creativity and three studies that refer to experiments conducted by our group. The case studies include general domain knowledge representation, open-ended problems, insight problems, well-defined problems, and analytical reasoning. For the case studies found in the literature, our analysis used the published knowledge structures. For the case studies based on our experiments, the semantic networks were manually constructed based on all design features present in the solutions produced by the participants. Features were clustered in categories based on similarity and roles, e.g., produced outcomes.

This study serves multiple purposes. It is based on problems of different kinds and from various domains. Therefore, the findings of the study have arguably a broader significance. The model expresses in a theoretical notation some of the main differences between semantic networks pertaining to different areas. This is important to understand whether the findings in a domain (e.g., what treats improve design creativity) can be transferred to other domains too. The model is also important in reasoning what semantic network elements are important in creativity-related activities, including conceptual combination and analogical reasoning, and then devising cognitive experiments to test such hypothesis. We think that this approach leads to more systematic devising of methodologies and strategies to improve design creativity. Third, the obtained insight on structure organization permits to construct broad sets of semantic network examples necessary to test and validate models that express various cognitive processes and activities [41,32]. Even though synthetic, such examples should include the characteristics of real semantic networks. Finally, the model can help towards understanding how knowledge structure organization at topological level originates organization at semantic level.

Different knowledge management representations have been proposed by the Artificial Intelligence community. Gero [27] suggests design prototype schema that includes functions, structures, expected behaviors, actual behaviors as well as relational, qualitative, computational and context knowledge. The using of schema for creative design is discussed. A metadata representation for case-based reasoning is proposed in [39]. Metadata store architectural patterns that are used to solve through analogy similar problems. Cash et al. [7] suggest a network representation that highlights the activities performed during problem solving. Patterns in the concept generation process are discussed in [57]. Other popular knowledge representations include ontologies [5,29,34], semantic web [53], and various rule-based systems [31]. Our work