An Information Foraging Model of Interactive Analogical Retrieval

Swaroop S. Vattam & Ashok K. Goel
Design & Intelligence Laboratory, School of Interactive Computing, Georgia Institute of Technology
Atlanta, GA 30332 USA

Abstract

An essential first step in analogy is retrieval of a source analogue appropriate for the target situation. In this paper, we focus on the phenomenon of *interactive analogical retrieval (IAR)* wherein the source analogues are obtained through interaction with online information environments. We first provide a descriptive account of IAR based on two *in situ* studies. We then describe an information-processing model (called PRISM) that provides an explanatory account of IAR. We conclude with a discussion of some of the theoretical and technological implications of this work.

Keywords: analogy, analogical retrieval, biologically inspired design, design cognition, information foraging.

Introduction

Analogy appears to be ubiquitous in human cognition and thus has received much attention in cognitive science (e.g., Burstein 1986; Carbonell 1986; Clement 2008; Gentner 1983; Davies, Goel & Nersessian 2009; Dunbar 2001; Gentner & Markman 1997; Hofstadter 1995; Holyoak & Thagard 1989; Indurkhya 1992; Keane 1988; Kokinov & Petrov 2001; Kunda, McGreggor & Goel 2013; Nersessian 2008). An essential first step in analogical reasoning is the retrieval of a source analogue appropriate to the target situation. Here we focus on *situated analogy* wherein source analogues are obtained through interactions with an external environment rather than being recalled from internal long-term memory. In particular, we focus on the phenomenon of *interactive analogical retrieval (IAR)* wherein source analogues are accessed from Web-based online information environments.

In this paper, we first present a descriptive account of IAR based on two *in situ* studies of cross-domain analogies in biologically inspired design. Then, we develop an information-processing model that provides a partial explanation of IAR in terms of its underlying cognitive processes. Our model builds on Pirolli's (2007) *information foraging theory* of human online information-seeking behavior and Thagard et al.'s (1990) model of *analogical retrieval by constraint satisfaction*.

Interactive Analogical Retrieval (IAR)

We investigate IAR in the domain of *biologically inspired design* (Benyus, 1997; Vincent & Mann, 2002), the practice of developing innovative technology using analogies to biological systems. Some well-known examples of products of biologically inspired design include Velcro (inspired by the attachment mechanism of burr seeds), high-performance wind turbines (inspired by the pectoral fins of humpback whales), self-cleaning surface coatings (inspired by the super-hydrophobic effect of lotus leaves), and fog harvesting devices (inspired by the arrangement of hydrophobic and hydrophilic surfaces on Namibian beetles).

From a cognitive standpoint, biologically inspired design entails cross-domain analogies for solving a target design challenge in, say, engineering, by transferring elements of a source analogue from a different domain (biology). In biologically inspired design, designers (often from engineering) typically are novices in biology: they know of only a small fraction of the vast space of biological systems that comprise the source domain. Thus, in practice the designers often try to access biological analogues from the Web. We call this phenomenon *interactive analogical retrieval.* (Due to limitations of space, our discussion of the *in situ* studies below is very brief; Vattam (2012) provides more details.)

Study Context and Methodology

We conducted two *in situ* studies of designers engaged in biologically inspired design in Fall 2006 and Fall 2008 respectively. Both studies were conducted in the context of an interdisciplinary, senior-level, project-based course on biologically inspired design taught at Georgia Tech. The most important element of the course for us was the semester-long design projects. Each design project grouped an interdisciplinary team of 4-6 engineers and biologists based on similar interests. Yen et al. (2011) provide details of the teaching and learning in this course.

As external observers in the Fall 2006 study and participant observers in the Fall 2008 study, we attended almost all the classroom sessions, collected all the course materials, documented lecture content, and observed teacher-designer and designer-designer interactions in the classroom. We documented a total of ten biologically inspired design projects in the two studies. We attended the design meetings of selected teams many times to observe firsthand how the design process unfolded. We took field notes, collected all the design related documentation produced by the teams, and also collected their idea journals. We analyzed the gathered data focusing on the processes and the products of the designers. In terms of the practices, we observed and documented frequently occurring problem-solving and representational activities of designers. In terms of the design products, we observed and documented their "design trajectory" – the evolution of the conceptual designs over time.

Main Findings

We found that designers often searched online for biological systems that are analogous to their target design problem. In fact, this was one of the dominant approaches for finding biological analogues. Designers reported using a range of Web-based information environments, including (1) online libraries of scholarly articles such as the Web of Science, Google Scholar, ScienceDirect, etc., (2) online encyclopedias like Wikipedia, (3) popular life sciences blog sites like Biology Blog, (4) biomimicry databases like AskNature, and (5) general search engines like Google. Online libraries like Web of Science and Google Scholar were the most frequently used websites.

We noted that designers used several heuristics in order to find relevant biology articles, including "biologizing" the problem, problem reformulation, functional decomposition, and using domain-bridging abstractions such as functions, mechanisms, physical principles, etc.

We noted that online information environments on which the designers relied upon did not adequately support the task of finding useful biological analogues. In particular, the designers reported that the online search for analogies was not only time consuming, but often also work intensive, tedious and frustrating.

Our analysis of the designers' online search activity identified three main challenges. The first challenge is *findability.* The relative frequency of encountering relevant articles containing biological analogues was very low. Designers often went for long periods without finding a single source analogue in a retrieval process that typically extended over several weeks. A rough calculation suggests that designers spent approximately three person-hours of search time on the Web in order to find a relevant article.

The second challenge is *recognizability*. The designers were prone to making errors in judgment about the true utility of the information resources that they encountered. In almost all online environments, search queries brought back a ranked list of search results. An important aspect of the search process was assessing and selecting promising information resources from this list for further consumption. However, this decision had to be made based on limited information, (e.g., titles, keywords and abstracts of biology articles). In many instances, designers picked up on low-utility articles and spent a lot of time and effort trying to understand its contents, only to realize later that they were not actually very useful (false positives). False positives have both resource and opportunity costs. Conversely, there were situations where designers dismissed a resource that they encountered during the search as having low utility even though it actually contained useful information about a relevant biological analogue (false negatives). The false negatives represent missed opportunities.

The third challenge is *understandability*. The designers often found it challenging to understand the contents of the biological cases described in the online information resources and develop the knowledge required to transfer to their target problems. This was in part due to the scholarly nature of the biology articles that were encountered and partly because the articles often did not explicitly describe how a biological system worked from a design perspective.

PRISM: A Model of Interactive Analogical Retrieval

We now present an information-processing model of IAR. Our goal here is to find explanations for the observed challenges of online analogy seeking, both for (i) understanding cognition in IAR and (ii) developing a technology for supporting online search for cross-domain analogies. Here we focus on the challenges of findability and recognizability; Vattam (2012) addresses the challenge of understandability of biological cases that requires a different kind of explanation.

Our model builds on two existing theories: *Analogical Retrieval by Constraint Satisfaction (ARCS)* (Thagard *et. al.* 1990), and *Information Foraging Theory (IFT)* (Pirolli 2007). IFT is itself a biologically inspired theory of online information seeking behavior. According to IFT, the online information seeking behavior of people is analogous to how animals forage for food in their natural environments. IFT posits that the human information seekers use *information scent* to navigate from one information region to another in an information environment that is inherently patchy in nature, and from one information patch to another within a region. IFT suggests that the information seekers adapt their behavior to the structure of the information environment in which they operate such that the system as a whole (comprising of the information seeker, the information environment, and the interactions between the two) tries to maximize the ratio of the expected value of the knowledge gained to the total cost of the interaction.

Although several models of analogical retrieval from internal long-term memory informed our work (e.g., Forbus, Gentner, & Law 1995; Kokinov & Petrov 1997; Kolodner 1993; Yaner & Goel 2006), we chose to build specifically on ARCS because it provides a content account of the types of similarity that best explains our observational data. ARCS posits that in order to access sources (represented as schemas in long-term memory) that are analogous to a target (a schema in short-term memory), the access mechanism should simultaneously consider satisfying three kinds of constraints: *semantic similarity* (the overlap in terms of the number of similar concepts between the target and potential sources), *structural similarity* (the overlap in terms of the higher-order relationships between the target and potential sources), and *pragmatic similarity* (the overlap in terms of the pragmatic constraints or goals surrounding the target and potential sources). It is these three pressures acting simultaneously that distinguish analogical retrieval from other kinds of information retrieval.

Thus, on one hand, ARCS explains how source analogues are retrieved from the long-term memory but is silent about analogies situated in external information environments. On the other, IFT explains how people seek information in online information environments in general, but it does not address the pressures of analogical retrieval. Our model specializes IFT to online analogy seeking by introducing the pressures of analogical retrieval from the ARCS model into information foraging. Thus we call our model PRISM (PRessurized Information Scent foraging Model).

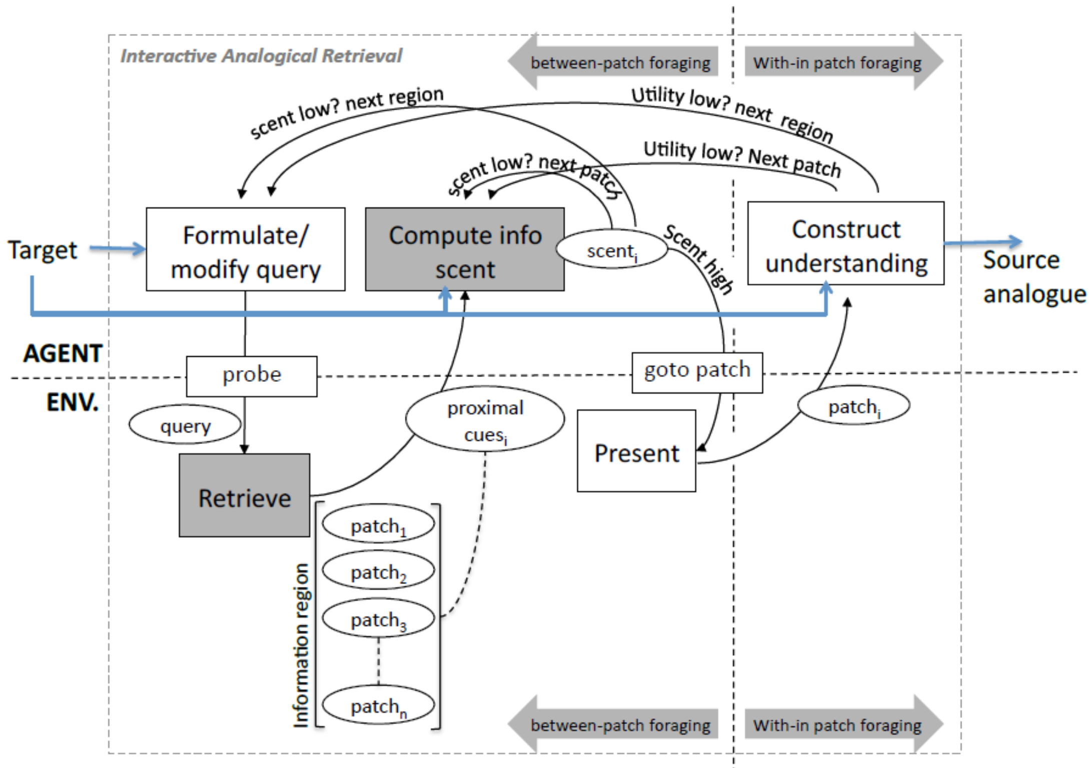

Figure 1. PRISM: An information-processing model of interactive analogical retrieval.

Similar to IFT, as Figure 1 illustrates, in PRISM the task of retrieving a source analogue is accomplished by two iterative processes that constitute the general information seeking behavior: *between-patch* processes (on the left side of the vertical dotted line) and *within-patch* processes (on the right side). Furthermore, the structure of Web-based information environments has evolved to exhibit certain regularities in the distribution of information resources and the navigation mechanisms that lead to those resources. For instance, when an analogy seeker encounters patches in an online environment, the seeker cannot perceive the contents of those patches all at once. Instead, they are presented with snippets of information, called *proximal cues*, which the analogy seeker uses to perceive the *information scent* of the distal information patches. The information scent leads to judgments about the utility of distal information patches and the information seeker can choose to either navigate towards or away from those patches.

Between-patch foraging

Between-patch foraging explains the navigation process where the analogy seeker browses the information environment looking for high-utility information patches to consume. In the context of IAR, high-utility information patches correspond to information resources describing sources cases that are analogous to the target. In this process, numerous information patches (e.g., online articles, etc.) compete for the information seeker's attention. These patches may or may not contain information relevant to the goals of the information seeker. Thus, the analogy seeker expends time and effort navigating from one patch to another until one that can be exploited is found. This is captured by the *Formulate Query–Retrieve–Compute Information Scent* cycle depicted in Figure 1.

Between-patch foraging using information scent in IAR works as follows. Given a target problem or situation:

1. The analogy seeker probes the environment by formulating and issuing a *query*. This query is context-dependent and represents the target problem.
2. In response, the environment retrieves and conveys an information region consisting of a set of information patches $\{(P_1,\{c_{11},c_{12},\ldots\}),(P_2,\{c_{21}, c_{22},\ldots\})\ldots\}$, where P_i is an information patch and c_{ij}'s are the proximal cues associated with the patch P_i.
3. The analogy seeker perceives the information scent of the patches based on the proximal cues; the information scent is an estimation of the analogical relevance of different patches to the target: $\{(P_1, S_1), (P_2, S_2)\ldots\}$, where P_i is an information patch and S_i is the information scent that the analogy seeker associates with the patch P_i.
4. If the information scent of an information patch exceeds a certain threshold, it is considered relevant (high perceived utility). In this case, the information seeker goes to that patch (by acting on the environment like clicking the associated hyperlink), at which point the environment presents the information patch to the forager. This initiates *within-patch foraging*.
5. If the scent does not exceed the threshold, it is considered irrelevant (low perceived utility). In this case, one of two things may happen as depicted in Figure 1: (i) the analogy

seeker may stay within the same information region but loop back to Step 3 for processing the next patch in the region, or (ii) the analogy seeker may abandon the current information region and loop back to Step 1 in order to look for more fruitful regions.

Within-patch foraging

Once the analogy seeker picks up the scent of a potentially useful information patch, the seeker goes to the patch and starts consuming information in it. In the context of biologically inspired design, this involves comprehending the contents of an article and constructing a mental model of the biological system described in the article. In the within-patch foraging process, the analogy seeker is also simultaneously evaluating the actual utility of the patch by comparing/aligning/mapping the emerging mental model of the biological system against the target problem. If the evaluation is successful, the agent has obtained a source analogue. If this evaluation fails, then the between-patch foraging process is again initiated, either within the same information region that led to the current patch or with a search for new information regions as depicted in Figure 1.

Incorporating Pressures of Analogical Retrieval

There are two potential places in our model where the three pressures of semantic, structural and pragmatic similarity might apply: *Retrieve* and *Compute information scent* tasks that are shaded in gray in Figure 1. The *Retrieve* process may use some notion of similarity to access information patches. But in our model, the *Retrieve* process is implemented in the environment (e.g., the Google Scholar search mechanism) and thus is black-boxed here. The *Compute information scent* process computes the perceived utility of an information patch as described below.

Information Scent Perception in PRISM

While IFT explains the scent perception for non-analogy information seeking tasks, it has to be adapted to account for the semantic, structural and pragmatic pressures of analogical retrieval. Hence, as part of PRISM, we developed a different model of information scent perception.

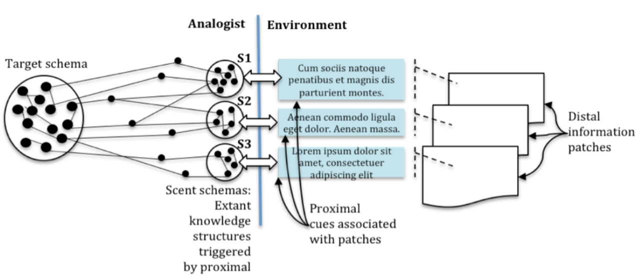

Figure 2. Scent perception in PRISM

Our model of scent perception assumes that the analogy seeker has represented the target problem as a *target schema* as depicted in Figure 2. With a target problem in mind, the analogy seeker forages the information environment for source analogues. Following the between-patch foraging process described above, the analogist encounters a set of information patches with associated proximal cues. When the analogy seeker encounters proximal cues in the environment, she builds corresponding *scent schemas* as indicated in Figure 2**.**

Given the target schema and competing scent schemas, the analogy seeker computes the similarity between the target and scent schemas in four stages similar to ARCS. We illustrate this process with an example. Let us suppose that the conceptual structures representing the dots in Figure 2 consist of predicates. Table 1 illustrates a target schema (P1) consisting of two predicates (P1-1 and P1-2), and two scent schemas (S1 and S2) consisting of two predicates each (S1-1, S1-2, and S2-1 and S2-2, respectively). Let us also suppose that *A* and *M* are semantically similar concepts, and likewise concepts *B* and *N* are semantically similar. For example:

A(a, b) is *Regulate(kidney, potassium_ions)*;
M(m, n) is *Control_Production(pituitary, estrogen)*;
B(b, a) is *Is_Secreted_By(erythropoietin, kidney)*; and
N(n, m) is *Is_Released_By(hypothalmic_hormone, pituitary)*

Let us further suppose that *A(a, b)* is more important than the other predicates as dictated by the pragmatics of the target situation.

Table 1: Example Target and Scent schemas (adapted from Thagard *et al.* (1990), pp. 275).

Target-schema	Scent-schema-1 1	Scent-schema 2
P1	S1	S2
P1-1: A(a, b)	S1-1: M(m, n)	S2-1: M(n, m)
P1-2: B(b, a)	S1-2: N(n, m)	S2-2: R(n, m)

Suppose that predicates *A* and *M* are semantically similar; *B* and *N* are semantically similar; *A(a,b)* is more important (dictated by the pragmatics of the context).

Network Setup: In a manner similar to the original ARCS model, PRISM uses information about the semantic similarity of predicates in the target and scent schemas to create a constraint network. Figure 3 depicts the network corresponding to Table 1: units in the network represent the predicates in the target and scent schemas, and the links between units represent correspondences between the predicates.

The most important units hypothesize that a scent schema is analogous to the target schema. These units have names of the form TARGET=SCENT. ("=" here means "corresponds to," not identity). If the target is P1 and the scent is S1, then the P1=S1 unit represents a correspondence between them. If P1-1 is a proposition in P1 that corresponds to proposition S1-1 in scent S1, then the unit P1-1=S1-1 will have an excitatory link with the unit P1=S1.

Excitatory links are also set up from a special semantic unit to predicate-predicate units based on the degree of semantic similarity of the predicates (in Figure 3, there are excitatory links from the semantic unit to (A=M) and (B=N) because they are semantically similar according to our assumption). Similarly, excitatory links are also set up from a special pragmatic unit to predicate-predicate units that are considered more important than others (in Figure 3, there are excitatory links from pragmatic unit to (A=M) because predicate A was assumed to be more important than others). The activation level of the special semantic and pragmatic units is always kept at the maximum value of 1. Thus, they serve to pump activation to all units that are linked to it.

Inhibitory links are constructed between units representing incompatible hypotheses, for example, between P1=S1 and P1=S2. These make utility calculation competitive, in that choosing one scent will tend to suppress choosing of an alternative.

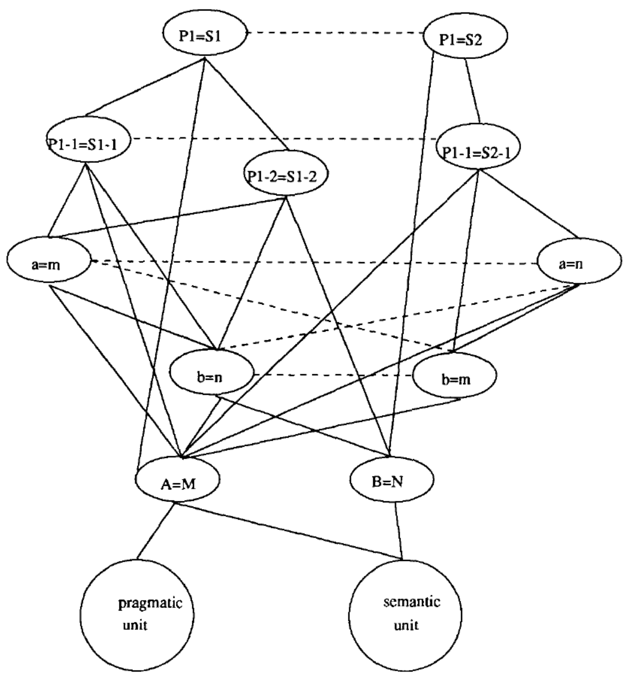

Figure 3. Constraint satisfaction network for computing analogical similarity between target and scent schemas of Table 1 (following Thagard et al. (1990), pp. 275).

Running the Network: The constraint network is run by setting the activation of all units to a minimal initial (random) level, except for the special semantic and pragmatic units for which activation is clamped at 1. Then the activation of each unit is updated by considering the activations of those units to which it has links. Cycles of activation adjustment continue until all units have reached asymptotic activation. As in ARCS, the activation of unit *j* on cycle *t + 1* is given by:

$$a_j(t+1) = a_j(t)(1-d) + enet_j(\max - a_j(t)) + inet_j(a_j(t) - \min)$$

Here *d* is a decay parameter, $enet_j$ is the net excitatory input, and $inet_j$ is the net inhibitory input (a negative number), with minimum activation *min* = -1 and maximum activation *max* = 1. Inputs are determined by the equations:

$$enet_j = \sum_i w_{ij} o_i(t) \text{ for } w_{ij} > 0; \text{ and}$$

$$inet_j = \sum_i w_{ij} o_i(t) \text{ for } w_{ij} < 0.$$

$o_i(t)$ is the output of unit *i* on cycle *t*: $o_i(t) = \max(a_i(t), 0)$.

Updating the constraint network continues until all units have reached asymptote, that is, a cycle is reached at which the activation change of each unit is less than a specified value, typically a low number (e.g., 0.01). (See Thagard et al. (1990) for more details about setting up the activation network, running such a network, computational complexity, etc.)

Scent of a Patch: When the network settles, the similarity between a target schema, *P*, and a particular scent schema, S_i, is equal to the activation value of the unit $P=S_i$ in the constraint network. Higher the activation accumulated by the unit $P=S_i$ the more analogically similar is the scent schema S_i to the target. The scent of a particular patch, IP_i, which is associated with a set of proximal cues, $\{C_{ij}\}$, is equal to the similarity between the scent schema, S_i, obtained from $\{C_{ij}\}$, and the target schema, *P*.

Explaining the Challenges of IAR using PRISM

The findability challenge is attributable to the current keyword-based indexing and access mechanisms in which the *Retrieval* process in Figure 1 supports access to information based on literal similarity (word-for-word matching) while ignoring semantic, structural and pragmatic similarity. As a result, each attempt at access can contain a large number of superficially similar cases as opposed to cases that are truly analogous, which entails a lower average information yield per region. This yield is inversely proportional to the number of times the *Formulate-Retrieve-Compute Information Scent* loop is executed in the PRISM model depicted in Figure 1: a low yield implies more executions of the cycle. Therefore, between-patch foraging time is higher, the period between successive useful finds is longer, and the frequency of encountering useful information resources is lower.

The *recognizability* challenge is attributable to the nature of proximal cues that the information seeker encounters in common online environments – specifically, their lack of affordance for accurately perceiving information scent. Perceiving the scent of an information resource in the context of analogical retrieval requires accurately judging the deeper similarity between that target and the source case as represented by their proximal cues. However, the design of proximal cues typically contains small snippets of information, which is insufficient to construct richer schemas. This likely explains why the designers made many recognition errors in our studies.

Conclusions

In this paper, we identified *interactive analogical retrieval (IAR)* as an important phenomenon in the context of biologically inspired design. We provided a descriptive account of the phenomenon based on our *in situ* studies of designers engaged in online search for biological analogues to their problems. Our descriptive account identified three main challenges associated with IAR: findability, recognizability, and understandability. Although our *in situ* studies were conducted in the context of a classroom environment, we posit that these cognitive challenges are quite general: the same challenges are likely to occur in actual practice of biologically inspired design because although practicing designers are experts in their design domain, they are likely to be novices in biology. We posit further that IAR is a general phenomenon: IAR is not limited to biologically inspired design, but occurs whenever people are searching for cross-domain analogies in external online information environments.

We also developed a causal model of IAR called PRISM combining Pirolli's (2007) information foraging theory (IFT) and Thagard *et al.*'s (1990) ARCS model of analogical retrieval. PRISM extends IFT to account for analogy seeking; it expands ARCS into a model of information scent perception. PRISM provides explanations for the findability and recognizability challenges of IAR we observed in our studies of biologically inspired design.

PRISM could help develop new technology for helping designers find biological analogues more efficiently and easily: the model predicts that the findability and recognizability issues could be addressed, respectively, by changing the indexing and access mechanism and enriching the proximal cues in online environments. Biologue (Vattam & Goel 2011) is an interactive tool for supporting biologically inspired design based on the PRISM model.

In terms of cognitive theory, we view analogy as situated in external information environments. If we take the boundaries of the cognitive system as including online information environments, as seems to be the case in biologically inspired design, then the phenomenon of IAR becomes an important element of understanding the situatedness of analogical reasoning. By folding in interactions with external information environments, PRISM may provide a starting point to think about a general theory of situated analogy.

Acknowledgments

We thank Michael Helms and Bryan Wiltgen for their contributions to this work. We are grateful to the instructors and students of the ME/ISyE/MSE/BME/BIOL 4740 class, especially Professor Jeannette Yen, the prime coordinator of the course. We thank the US National Science Foundation for its support through the CreativeIT Grant (#0855916) Computational Tools for Enhancing Creativity in Biologically Inspired Engineering Design.

References

Benyus, J. (1997) *Biomimicry: Innovation Inspired by Nature*. William Morrow.

Burstein, M., (1986) Concept formation by incremental analogical reasoning and debugging. In R. Michalski, J. Carbonell & T. Mitchell (eds.), *Machine Learning 2,* Los Altos: Morgan Kauffman, pp. 351-370.

Carbonell J. (1986) Derivational analogy: A theory of reconstructive problem solving and expertise acquisition In Michalski, Carbonell & Mitchell (eds.), *Machine Learning 3,* Los Altos: Morgan Kauffman.

Clement, J. (2008). *Creative Model Construction in Scientists and Students: The Role of Imagery, Analogy, and Mental Simulation*. Dordrecht: Springer.

Davies, J., Goel, A., & Nersessian, N. (2009) A Computational Model of Visual Analogies in Design. *Journal of Cognitive Systems Research* 10:204-215.

Dunbar K. (2001) The Analogical Paradox. In Gentner, D, Holyoak, K., & Kokinov, B. (Eds.) *The Analogical Mind: Perspectives from Cognitive Science.* MIT Press. Boston.

Forbus, K., Gentner, D., & Law, K. (1995). MAC/FAC: A model of similarity-based retrieval. *Cognitive Science*, 19(2), 141-205.

Gentner, D. (1983). Structure-mapping: a theoretical framework for analogy. *Cognitive Science*, 23, 155-170.

Gentner, D., & Markman, A. (1997). Structure Mapping in Analogy and Similarity. *American Psychologist,* 52:45-56.

Hofstadter, D.H. (1995). *Fluid concepts and creative analogies*. New York: Basic Books.

Holyoak, K., & Thagard, P. (1989). Analogical mapping by constraint satisfaction. *Cognitive Science*, 13(3), 295-355.

Indurkhya, B. (1992) On the Role of Interpretive Analogy in Learning. *New Generation Computing,* 8(4): 385-402.

Keane M. (1988) *Analogical Problem Solving*. Ellis Horwood. Chichester

Kokinov, B., & Petrov, A. (2001) Integration of Memory and Reasoning in Analogy-Making: The AMBR Model. In Gentner, D., Holyoak, K., Kokinov, B. (editors) The Analogical Mind: Perspectives from Cognitive Science, MIT Press.

Kolodner, J. (1993). *Case-based reasoning*. San Mateo, CA: Morgan Kaufmann Publishers.

Kunda, M., McGreggor, K., & Goel, A. K. (2013). A computational model for solving problems from the Raven's Progressive Matrices intelligence test using iconic visual representations. *Cognitive Systems Research*, *22-23*, 47-66.

Nersessian, N. (2008) *Creating Scientific Concepts*. MIT Press Cambridge.

Pirolli, P. (2007) *Information foraging theory: Adaptive interaction with information*. Oxford: Oxford University Press.

Thagard, P., Holyoak, K. J., Nelson, G., & Gochfeld, D. (1990). Analog retrieval by constraint satisfaction. *Artificial Intelligence*, 46, 259-310.

Vattam, S. (2012) Interactive Analogical Retrieval: Practice, Theory and Technology, Ph.D. Dissertation, Georgia Institute of Technology, December 2012.

Vattam, S., & Goel, A. (2011) Semantic tagging of research articles for interdisciplinary design. In *Proc. 6th International Conference on Knowledge Capture* . Banff, Canada.

Vincent, J. & Man, D. (2002) Systematic Technology Transfer from Biology to Engineering. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 360(1791): 159-173.

Yaner, P., & Goel, A. (2006) Visual Analogy: Viewing Retrieval and Mapping as Constraint Satisfaction. *Journal of Applied Intelligence,* 25(1):91-105.

Yen, J., Weissburg, M., Helms, M., & Goel, A. (2011) Biologically inspired design: a tool for interdisciplinary education. In *Biomimetics: Nature-Based Innovation, Y. Bar-Cohen (editor)*, Taylor & Francis.