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Analogical Thinking, Systems Thinking, Visual Thinking and Meta Thinking: Four Fundamental Processes of Design Creativity

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Abstract: In this article, I briefly summarize over two decades of research on design creativity in my Design & Intelligence Laboratory. In particular, I describe our research on four fundamental processes of design creativity: analogical thinking, systems thinking, visual thinking, and meta thinking.

Introduction

One of the core goals of research on design creativity is to understand its fundamental cognitive processes. If we can identify, characterize and specify the fundamental cognitive processes of design creativity, then we can develop pedagogical techniques for enhancing design creativity in formal, informal and everyday educational settings, as well as computational tools for aiding, augmenting and amplifying human creativity in design. For more than two decades now, my colleagues and I at the Design & Intelligence Laboratory have been investigating four fundamental processes of design creativity: analogical thinking, systems thinking, visual thinking, and meta thinking. Below I briefly describe our work on these four processes of design creativity.

I should note explicitly and upfront that it is not my goal to cover related work in this short paper, let alone provide a comprehensive survey of the literature. Instead my goal here is pull together four themes on our research on design creativity. Thus, all citations below refer to papers from the Design & Intelligence Laboratory. The specific papers cited here of course relate our work to similar research.

1. Systems Thinking

The term "system" typically refers to a group of interconnected and interacting components. "Systems thinking" in general refers to not only thinking about systems but also to thinking about the world in terms of systems, in particular, to thinking about the components of the system, the processes through which components interact with one another, and the integration of systems from its components and processes. Design, almost by definition, pertains to systems. Whether in architecture, computing, engineering, fashion, organization, or other domains, we almost always design systems of components and processes; rarely do we design a single, isolated component. We even understand technical, natural and social designs in terms of systems of components and processes, such as the design of biological systems and the design of economic systems.

Systems thinking in general is cognitively challenging because it entails thinking about large number of interacting components and processes, but cognitive resources such as attention, perception and memory are intrinsically limited. The cognitive limitations about systems thinking can adversely impact design and design creativity. Thus, one basic issue in research on design creativity is how do designers think about systems and how can we help them develop more useful systems thinking.

The Design & Intelligence Laboratory has developed a theory of Structure-Behavior-Function (SBF) modeling as a technique for systems thinking (e.g., Goel, Rugaber & Vattam 2009). In brief, SBF modeling uses function as a mental abstraction to decompose a system into subsystems, and to organize knowledge of the processes and components of a subsystem at a given level of abstraction. SBF modeling supports three cognitive processes about systems thinking: (i) it provides a set of concepts for analyzing a system, (ii) it provides a schema for organizing a conceptualization of the system, and (iii) it provides a vocabulary for representing the system conceptualization.

While SBF models provide a system-centric view of a system, ESBF models (Prabhakar & Goel 1998) provide an environment-centric view of a system. BF models capture abstract, generic design patterns that systems embody, and DSSBF models (Yaner & Goel 2008) couple SBF models with diagrammatic representations of the system. In early work, we worked on a technique for acquiring SBF models from natural language texts describing technical systems (Peterson et al. 1996), and in recent work, we have developed a technique for acquiring SBF models from design drawings. In early work, we used SBF modeling to develop a computational model of physicists' creative problem solving (Griffith, Nersessian & Goel 2000), and in recent work, we have developed interactive tools for enabling learning about ecosystems in middle school science (Vattam et al. 2011).

2. Analogical Thinking

Analogy typically refers to transfer of knowledge from a source case to a target problem. Analogies may vary from within domain (or near) analogies, to cross-domain (or far) analogies. If the target problem is very similar to the source case, the analogy may entail identification of modifications to transfer of the solution stored in the source along with transfer of almost the entire solution from the source to the target. If the target problem is less similar to the source case, the analogy may entail transfer of specific relationships from the source to target. Routine design typically pertains to minor modifications to the components in the design solution stored in the source case. Creative design pertains to identification, abstraction and transfer of complex relations from source cases to target design problems.

Analogical thinking in general is cognitively challenging because it engages memory, learning as well as problem-solving processes, because it typically entails re-representation of the source cases and the target problem to find similarity among them, and because if the source cases and the target problem are large, then finding the right modification to make to the source case or the right relationship to transfer to target problem can be complex. Further, analogical thinking in creative design is cognitively challenging also because design is a generative process, because knowledge of the target design problem often can be sparse initially, and because design typically uses multiple analogies from different source cases to generate a design solution.

In early work, my laboratory developed a series of interactive and autonomous case-based design systems. The interactive systems such as Archie (Pearce et al. 1992) and AskJef (Barber et al. 1992) provided access to digital libraries of design cases but left the task of design adaptation to the human designer. The autonomous systems such as Kritik (Goel & Chandrasekaran 1988, 1992) and Kritik2 (Goel, Bhatta & Stroulia 1997) implement theories of case-based design that used SBF models for indexing, retrieving, modifying, evaluating and storing designs cases. Later, we developed an integrated theory of within domain and cross-domain analogies called model-based analogy that is implemented in the Ideal system (Bhatta & Goel 1997; Goel & Bhatta 2004). Given a design problem Ideal first attempts to use the design method of case-based reasoning. If this method fails, then it tries the method of cross-domain analogies based on the transfer of design patterns from source cases to target problems, where a design pattern in Ideal specifies an abstract behavior for achieving a generic function. More recently, we have developed computational theories and techniques for visual (Davies, Goel, Yaner 2008; Davies, Goel & Nersessian 2009) and multimodal analogies (Yaner & Goel 2008).

3. Visual Thinking

Visual reasoning refers to reasoning that uses (only) visuo-spatial knowledge, for example, design sketches, drawings, diagrams, photographs, and graphics. While visuo-spatial knowledge captures elements of the structure of a design, causality in it is at most only implicit. Visual reasoning is a fundamental process of creative design for at least three reasons. Firstly, visual representations such as a diagram enable spatial inferences more efficiently and easily than do verbal representations; this allows easy evaluation of visuo-spatial similarity between two designs. Secondly, since causality is only implicit in visuo-spatial knowledge, visuo-spatial knowledge is ambiguous and thus supports more flexible and malleable inferences. Thirdly, creative design entails aesthetics and affect, and visual representations of form often relate better to aesthetics and affect than do verbal representations.

Cognitive science in general has emphasized and focused on propositional representations, causal knowledge and logical reasoning much more than visual representations, visuo-spatial knowledge and visual reasoning. However, vision enables visual inferences at a very low cost and thus it is cognitively advantageous to use visual reasoning when feasible.

The Design & Intelligence Laboratory has developed a theory of visual analogy that relies solely on visual knowledge and implemented the technique in the Galatea system (Davies, Goel & Yaner 2008). We have also used Galatea to model analogical transfer in creative design (Davies, Goel & Nersessian 2009). Our laboratory has also developed a theory of multimodal analogy for constructing SBF models of technical systems from their drawings, and the technique in the Archytas system (Yaner & Goel 2008). Given an unlabeled 2D target drawing of a mechanical system, Archytas constructs an SBF model of the drawing by analogy to SBF models of similar drawings in its digital library.

4. Meta Thinking

Meta thinking is thinking about thinking. Meta thinking entails processes such as goal spawning, suspension, and abandonment; strategy selection; belief revision; self-explanation; and design, diagnosis and revision of reasoning processes. Creative design often engages not only design processes at the object level, but also the design of the design processes at the meta level. That is, creative design engages both design and meta design.

Meta thinking is cognitive challenging in part because it pertains to thinking about abstract, invisible processes rather physical and visible technical systems. Research on meta-cognition is still in its early stages, and research on meta-design is still sparse.

In early work, the Design & Intelligence Laboratory investigated the use of meta thinking for generating self-explanations of the design process in autonomous design systems (Goel et al. 1996) and modifying the design process when it lead to a failure (Stroulia & Goel 1999). In more recent work, we have developed theories of meta thinking for adapting design processes to new tasks (Murdoch & Goel 2008) as well as diagnosing and repairing domain knowledge when it leads to failures (Jones & Goel 2012). The REM knowledge shell implements the theory of meta design of design processes. Let us consider, for example, a case-based design agent for assembling a system from its components. Now suppose that the agent is given the task of disassembling the system. If the design agent is encoded in REM's knowledge representation language, then REM adapts the agent's reasoning for assembling a system into a strategy for disassembling the system.

Summary

In this article, I have tried to pull together and summarize more than two decades of research in the Design & Intelligence Laboratory on four fundamental processes of design creativity: systems thinking, analogical thinking, visual thinking, and meta-thinking. Before I end, I should note several caveats and qualifications. Firstly, as I mentioned in the introduction, I have focused this short paper solely on research in my laboratory, and have made no attempt to survey or review related work. Secondly, I expect design creativity to entail many more cognitive processes than the four I have described here. Thirdly, I have been silent about the design agent who conducts the four kinds of thinking described here. Insofar as the four kinds of thinking are concerned, the design agent could be a human designer, a team of human designers, or a design team consisting of humans and computers. Fourthly, my description of the four thinking processes has been silent about the tasks and subtasks of design creativity. At least in principle, each of the four thinking processes is applicable to not one but many tasks. For example, analogical thinking can be used not only for generating a solution to a target design problem, but also for understanding the target problem as well as for analyzing, explaining and evaluating the design solution (Vattam, Helms & Goel 2010). Our current work on design creativity in the context of biologically inspired design (e.g., Goel et al. 2011) explores many of these design tasks.

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