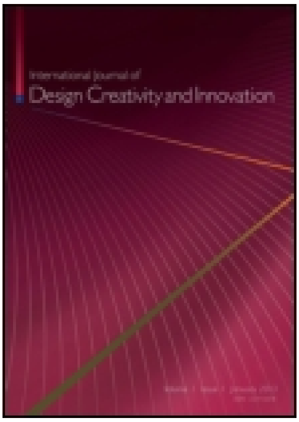

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Developing computational design creativity systems

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INVITED PAPER

Developing computational design creativity systems

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The underlying hypothesis of this paper is that the rigor needed to build computational design creativity systems will produce insights that will increase our understanding of creativity. The paper points to a variety of factors that will need to be studied and understood in detail in order to build such systems. It examines selected technical literature about creativity to determine what key characteristics have been proposed as underlying creative production. In addition, as the existence of creativity is a judgment relative to personal or group norms, it is helpful to understand what factors inform that judgment. Besemer's creative product semantic scale for product assessment provides three dimensions, with nine attributes that can be used for judgments. This paper discusses how creative product assessment scales might provide important clues about how to build computational systems in order to produce creative products.

Keywords: computational; creativity; design

1. Introduction

This paper is concerned with how computer science (CS) can assist with studying design creativity. Although creative design is clearly part of much CS activity, such as system, algorithm, and program design, it is rarely studied from a creativity point of view. However, CS techniques could be used to collect, analyze, and visualize data about creative design in CS or in other areas. CS can also aid in the study of design creativity by building support tools that support collaboration, manage complexity, keep history and rationale, and support exploratory search (Lubert, 2005; Shneiderman, 2007).

An alternative approach involving CS is to try to understand design creativity by "mimicking" it using the computer. As design is a human activity requiring intelligence, its computational study falls within the realm of artificial intelligence (AI). An underlying assumption in AI is that making hypotheses about knowledge and reasoning, and then building systems that embody them, is a good way to investigate intelligent activities. We want these computational models to provide reasonable explanations of design reasoning, and to be consistent with observations. Such models may provide explanations when no others at the same level of detail exist.

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Much of the research in the "AI in Design" area proceeds in this way: for example, modeling routine design, analogical reasoning, or configuration, and then building systems that instantiate those models.

These systems can be used to experiment with the consequences of changing the problem, the knowledge, or the problem solving used. The resulting changes in the designs can be evaluated by experts or compared with existing designs to attempt to "validate" the model.

As creativity is an intelligent activity, AI-based studies of creativity, often called "Computational Creativity," proceed in much the same way.

Designing in general is a complex, opaque activity, and the same is true of creativity. Producing hypotheses about either alone is hard: producing hypotheses about both together is even harder. Computational design creativity (CDC) will need to be studied incrementally, with many hypotheses investigated.

It is extremely important to note that creative designing is, after all, a form of designing, and therefore any computational model of "creative" designing must be firmly based on a strong computational model of "ordinary" designing. The alternative is that creative designing is distinctly different from designing. Most authors do not believe that to be true.

Creativity in design can be detected and assessed by looking at either the designed product or, when possible, the design process. As the existence of creativity is a judgment, relative to personal or group norms (Amabile, 1983; Boden, 1994), it is beneficial to understand what factors inform that judgment.

Clues about what factors might be involved can be obtained from definitions of, and discussions about, creativity, and from existing research in Computational Creativity.

Another place to look at is research that directly concerns how products are judged to be creative. The creative product analysis model (CPAM), with its associated creative product semantic scale (CPSS) for product assessment (Besemer, 2006; Besemer & Treffinger, 1981; O'Quin & Besemer, 1989), provides three dimensions, with nine attributes that can be used for judgments. As expected, "novelty" is one of the dimensions, but its two attributes provide additional subtlety.

A hypothesis of this paper is that the scales used by research in creative product assessment can provide important clues about how CDC systems might be designed in order to produce creative products.

This paper continues by investigating the consequences for CDC systems of several selected pieces of work about creativity. With that foundation established, it moves to an introduction of the CPAM, describing the main factors and their characteristics. The many consequences of that model for CDC systems are described next. The paper ends with a concluding discussion.

2. The technical creativity literature

This section reviews a small selection from the technical literature about creativity, highlighting aspects that might be useful for the construction of CDC systems.

Amabile (1983) argues that a product is creative if appropriate observers independently agree it is creative, assigning "degrees of creativity." A product must be novel, appropriate, useful, correct, or valuable, and the design task should be heuristic and not algorithmic. She lays the groundwork for CDC systems by arguing for a variety of ingredients, most of which suggest computational approaches. One key aspect of her list is the need for several types of meta-level activities, such as ensuring least commitment, detecting functional fixedness, and observing plan/script progress.

Amabile (1983) stresses that ingredients in creativity are education; strong, appropriate, and cognitive skills; and "playful" freedom from constraints. She lists creativity-relevant skills as follows: suspending judgment, seeing relationships between diverse bits of information, accurately remembering large amounts of information, breaking out of well-used scripts, having heuristic knowledge, and productive forgetting. Amabile (1983) argues that having more domain knowledge allows "more response possibilities" and more ability to judge those alternatives.

Boden (1994) states that creative ideas must be new and valuable to be interesting. However, she wants to "distinguish radical novelties from mere 'first-time' newness," as the latter can be generated by a system (perhaps using rules) that "underlies the domain and defines a certain range of possibilities." This "conceptual space" defines what could be produced by a system, resulting in newness that is in some sense expected. However, the space can be changed by "transformations" in order to allow radical originality: by dropping or modifying constraints, for example. "Meta-representation" of constraints would allow their modification. Gero (1994) and Wiggins (2006) provide more detailed accounts of what transformational creativity might be.

Boden (1994) suggests that an understanding of how "novel combinations of old ideas" come about, coupled with a theory of analogical reasoning, would provide a substantial start to a theory of creative reasoning.

As different individuals may vary in their assessment of the newness or value of an idea, the judgment of creativity can also vary. She claims that recognition of creativity by a computer system is necessary if that system is to appear to be creative.

Judging novelty as whether anyone else "has ever done it before" implies comparison to a huge body of recorded knowledge. The variables are the length of the history, and the level of expertise represented. A CDC system needs high values for these variables. We can assume that "experts" know the most about the historical record and about major, creative changes in a product class. Therefore, a large number of experts should provide knowledge for CDC system use.

Eysenck (1994) proposes that that a creative product should have scientific, aesthetic, social, or technical value, plus "appropriateness." Creativity is associated with "loosening of associative thinking," "a quality of over inclusiveness," and "a failure of inhibition that allows less relevant thoughts to intrude into the problem solving process." This allows "ideas and associations" to "become relevant that would not appear to be so for the ordinary person," but "critical assessment" must narrow them to just the most promising. A CDC system needs such abilities.

Eysenck (1994) points out that most creative people are usually highly technically focused with "special knowledge that may take years to acquire." A system that can prune distracting well-known or weaker options will require a lot of specialized knowledge. However, there is tension between having knowledge that allows good decisions, and being constrained by it so much as to reduce creative reasoning.

Clearly, creative processes can lead to creative products, but it is possible for not very creative processes to lead to creative products. So, although creative processes are desirable, they are not necessary.

Eysenck's (1994) ideas suggest that CDCs need to "ask the right questions" as they proceed, producing subgoals that encourage use of those reasoning skills that tend to lead to creativity. Talbot (1997) quotes Ekvall (1995) as writing "unclear goals were contributing to the climate that made radical innovation possible." Given such lack of precision, looser associative reasoning may be needed to take advantage of such subgoals.

Dasgupta (1994, 1996) claims that associative retrieval of "related" knowledge, and the willing ability to "roam freely across the span of knowledge," is vital for creativity. He argues that the "combination or association of apparently unrelated ideas" (bisociations) is an ingredient of creativity. However, "elimination heuristics" must identify any resulting "misfits."

Dasgupta believes that creative designing is knowledge-intensive, opportunistic, and goal-directed, with goals that are "provisional or tentative." Technological knowledge, which is domain knowledge plus operational principles, is important. Operational principles drive creativity, and include heuristics and expectations. Knowledge also includes records of errors made and the failures that resulted from them. Design decisions are affected by the designer's own knowledge, and also understanding of the community's knowledge.

If the design activity is to be exploratory, then ideas generated are going to be provisional. This requires some way of describing the nature and sources of uncertainty about an idea.

Ward, Smith, and Vaid (1997) focus on "'normative' creativity," but acknowledge "the possibility that the mundane and the exotic [forms of creativity] represent endpoints on a continuum of human creativity." This continuum depends on the level of expertise of the designer for the problem or subproblems (Dorst, 2008): i.e., the degree of routineness of the problem for the designer (Brown, 1996). Dorst (2008), referring to Dreyfus and Dreyfus (2002), notes that we need to be specific about what level of design expertise we mean when we write about designing. This raises the possibility of "routine" creativity.

Ward believes that the same sets of conceptual processes underlie all creativity, with sets of processes affected by context, and that a "single overarching theory of creativity" is not very likely. The crucial conceptual processes include conceptual combination, conceptual expansion, analogy, mental models, and knowledge.

The combination of concepts to produce a novel concept involves "comparison, construction, and integration processes," and that the failure to "find a satisfactory coherent interpretation" might lead to a search that results in creativity. Recognizing such mental blocks, and handling them by approaches such re-representation, is key (Smith, Ward, & Finke, 1995).

Expansion occurs when people "construct, stretch, extend, modify, and refine" concepts. It is "driven by the characteristic properties of known concepts," especially recently encountered instances.

For analogy, they distinguish between infrequently occurring, highly creative, "far analogies" across widely separate domains, and "near analogies" within a domain. Mental models, as well as visualization and creative imagery (Ward, Smith, & Finke, 1999), allow complex reasoning and can support discovery.

Ward argues that creative outcomes are "rooted in existing knowledge." This might be especially difficult in the face of the "cognitive inertia" of existing knowledge structures.

Smith (1995) suggests that some creative thinking might be guided by retrieved or constructed plans. In addition, plans might guide the retrieval of appropriate knowledge. Plans represent subgoals, and also contain other subgoals.

Minsky (2006), the most computational in his outlook, quotes Linus Pauling's "The best way to have a good idea is to have lots of ideas." Clearly this is a goal for a CDC system. He suggests that high creativity is due to the unusual combination of strength in common traits, including considerable expertise, persistence, a large variety of ways to think, resistance to irrelevant goals, rejection of "popular myths and beliefs," spending less time on unproductive ideas, and learning more from less experience. Minsky (2006) also suggests that good "mental management" is important, i.e., they "organize and apply what they learn."

Minsky (2006) argues that creative thinkers generate a lot of new, and perhaps novel ideas, they are distinguished by "how effectively they can select which new ideas to further develop," and that they tend to suppress those with "too much novelty." They also need to determine the constraints that indicate "plausible things to try." Minsky (2006), as well as Besemer, mentions "elegance" as a sign of a possible successful candidate, and that evaluation can confirm this, or indicate where it might need repair.

He considers that "negative expertise" (i.e., what not to do) is a very large part of people's knowledge, based mostly on learning from mistakes. Critics are resources that can "recognize some particular kind of potential mistake," either during the process, while planning it, or even before. When being creative, some critics need to be "switched off" so that fewer hypotheses will be rejected. Critics can also "recognize successes and promising opportunities."

Critics can also recognize particular mental conditions, and then activate appropriate selectors that "activate a way to think": e.g., analogy, divide and conquer, re-representation, planning, simplifying, and abstraction. Mappings from types of difficulties (e.g., lack of knowledge) to appropriate ways to think are also needed.

Minsky (2006) argues for a rich, interconnected variety of different types of knowledge representation with multiple versions of the same concept at different levels, allowing different kinds of reasoning for different problems. Each piece of knowledge should be associated with the goals it might help with, the situations for which it might be relevant, what subgoals must be achieved before use, what it has been used for before, what harm or good its use has produced, the cost of use, what methods it works well with, and its common exceptions or bugs.

Differences play a big role in reasoning. Their detection helps us to try to achieve goals and to interpret information, whereas their explicit representation allows us to break out of rigid hierarchical representations.

Minsky (2006) argues that analogical reasoning is "our most usual way to deal with problems," as new situations usually differ from old situations. Differences play a key role in reuse of old methods. Knowing which differences to ignore affects how similar things appear to be, whereas the importance of each difference depends on current intentions and goals.

3. Creative product analysis model

Despite Boden's claim (1994) that "In general, one cannot assess creative ideas by a scalar metric," the CPAM aims to do something similar (Besemer & Treffinger, 1981). It is the basis for a well-validated product creativity assessment instrument called CPSS (Horn & Salvendy, 2006; O'Quin & Besemer, 1989) that is demonstrating its utility in current, practical use. The model has three main dimensions: novelty, resolution, and style. Each has between two and four characteristics that further refine them.

Novelty is "the extent of newness in the product" and refers to the "number and extent" of the new processes, new techniques, and new concepts included in the product. It also refers to "the newness of the product both in and out of the field" (Besemer, 2006). This is what everyone includes when the topic is creativity.

Resolution is "the degree to which the product fits or meets the needs of the problematic situation." This enforces the fact that, for products at least, new but bizarre objects are not seen as creative, as products are usually associated with an intended function, and therefore being "useful" is prized.

Style is "the degree to which the product combines unlike elements into a refined, developed, coherent whole, statement or unit." Besemer (2006) refers to this factor as "how the product presents itself," the "product's personality." It affects how creative the product is perceived to be, and may even impact how novel it seems.

Here are the dimensions with their characteristics.

3.1. Novelty

Surprising: "The product presents unexpected or unanticipated information to the user, listener, or viewer."

Original: "The product is unusual or infrequently seen in the universe of products made by people with similar experience and training."

3.2. Resolution

Logical: "The product or solution follows the acceptable and understood rules for the discipline."

Useful: "The product has clear practical applications."

Valuable: "The product is judged worthy because it fills a financial, physical, social, or psychological need."

Understandable: "The product is presented in a communicative, self-disclosing way, which is 'user-friendly'."

3.3. Style

Organic: "The product has a sense of wholeness or completeness about it. All the parts work well together."

Well-crafted: "The product has been worked and reworked with care to develop it to its highest possible level for this point in time."

Elegant: "The product shows a solution that is expressed in a refined, understated way."

4. Consequences of the CPAM

The various factors included in the CPAM might be used as goals in a CDC system. By driving the system toward these goals, designs that will be evaluated as more creative should be generated. As there are three main dimensions of influence, and a large space of measures in which a design might sit, the system would need to know which parts of the space are the most productive for generating creative products.

What CPSS can provide is a product profile with scores for each of the nine characteristics (Besemer, 2006). The shape of the profile histogram indicates variations in creativity. Products can be "aimed" toward a goal profile shape, depending on which characteristics are more valued (S.P. Besemer, personal communication, 2008). Consequently, a CDC system might be given a goal profile to influence its reasoning, or have one built in.

Besemer (2006) suggests considering the "weakest CPAM facet" of each of the alternative design ideas. A CDC could then improve them by tweaking designs to try to address those weaknesses. Alternatively, as extreme novelty brings doubt to evaluators' minds, it might be avoided by lowering that part of the goal profile.

One proposal is to target particular places in the CDC where actions will affect portions of the resulting creativity profile. This requires an analysis of what "causes" could produce certain positive "effects" in the profile. We hypothesize that it should be possible for the CDC to form the profile. This allows the CDC to evaluate its own creativity. It may also be possible to use the profile to provide evaluations of partial designs, thus shaping the CDC's design process.

Boden (1994, p. 112) argues that creativity "cannot be measured." However, the CPAM does not merely rate products on a linear scale from uncreative to creative, but uses many dimensions. The values do not need to be "correct" if they consistently allow reliable comparisons to be made between products in the same general category.

Colton (2008) argues that art is identified as more creative if, all things being equal, the process is evaluated as being more creative. This raises the issue of whether CPAM can be used to assess the creativity of design processes. Besemer (personal communication, 2008) feels that it should be able to; however, characteristics such as "understandable," "well-crafted," and "elegant" seem very product dependent, although there might be analogous measures for processes.

A major issue is whether the impact of every design decision on every CPAM characteristic can be determined, or even whether it needs to be assessed at every decision point. Where expectations exist (Grecu & Brown, 1999), or where expectation failures have occurred (Brown, 2012; Brown et al., 1992), there may be some appropriate knowledge. In other cases, heuristic relationships may exist. Even if measurements of each characteristic are not possible during designing, it should be possible to positively influence the scores if those causal relationships are known (even partially). A confounding issue is whether each characteristic can be positively influenced without negatively influencing another.

A big problem with having CPAM goals is that it is well known that subproblem solution evaluation is often very difficult, as subsequent decisions may make apparently poor solutions perfectly acceptable in the context of the whole design, and vice versa.

Besemer (personal communication, 2008) reports that the CPAM is very useful for evaluating conceptual designs. Given the significant impact of that phase on the rest of the design process, and the probable impact of conceptual design on creativity (Shai, Reich, & Rubin, 2009), it makes sense to use CPAM characteristics in early design phases. As promoting novelty moves the design problem toward being nonroutine, there will need to be some sort of planning activity, such as gradual problem decomposition, plan fragment execution, or "opportunistic organization" (Visser, 2006).

4.1. Computational novelty

How can a computational design system produce something original? For it to produce something "infrequently seen in the universe of products made by people with similar experience and training," knowledge of existing products of that type is required. This is a comparison between what is (being) produced and knowledge of prior products, judged by considering the whole product. The degree of difference can vary from, for example, a car with five wheels and wings, to a car with just a new paint color. Judging that there is a difference does not seem hard, but estimating the amount on some scale needs to be studied. The nature of the difference must be isolated and characterized, then some sort of conceptual distance needs to be estimated.

To produce the difference at all, a system needs to make design decisions that lead to new concepts, new combinations of concepts, and new values. This could be done by expanding the available choices for decisions, or by selecting a new choice for that context.

To be surprising, the product must present unexpected information to the evaluator. The key problem here is for the system to know what is "usual," and therefore expected.

The system needs strong expectation knowledge for products, with representations that show frequencies, stereotypes, and reasonable variations. Unusual combinations of concepts (e.g., balloons as table legs) need to be produced, perhaps by analogical reasoning, in order to surprise the evaluator.

Many authors have discussed the role of analogy in design and in creativity (Goel, 1997). Several note that analogical reasoning can be done using representations of structure (S), behavior (B), or function (F) (Balazs & Brown, 2001). Engineering and architectural design theorists have separated S, B, and F in their models of designing. Since about 1985, AI researchers have used computational SBF models of devices (Erden et al., 2008; Gero & Kannengiesser, 2007).

Choices intended to be original and/or surprising (Brown, 2012) cannot just be made randomly, as requirements need to be satisfied and the product must still be useful. The more "weird" the choices are, the more the system will need to prune the results of its actions. The system should have some tolerance for the unusual, but also have an accumulated indicator of how unusual the current partial design actually is (novelty stack up), as this represents some sort of risk.

4.2. Computational resolution

How can a computational design system produce something logical? If the product follows the acceptable rules for the discipline, then it is logical. Having and using technological knowledge, explicitly or implicitly as rules, is what computational design systems do well.

To be useful, the product must have clear practical applications. This issue is a little blurred by the question of what the starting situation is for the design process: i.e., where the design activity starts in the conceptual to parametric dimension (Brown, 1996), and how strongly the activity is being driven by a purpose for the product (e.g., it may just be exploratory, intending to discover the limits of the design space). For now, we will consider it useful just to mean that it has some use.

As most products are designed to fill some stated purpose, often with a detailed functional description, being "useful" ought to be easy to satisfy. Some estimate would need to be made, based on the user's typical task history, of how often it could be used.

To be valuable, the product must fill "a financial, physical, social, or psychological need." Function is associated with satisfying needs. So, if the intended function of the product is needed in many situations, by many people, leading to results that are of consequence, then perhaps it is more "valuable."

However, it may be difficult during designing to judge how well it satisfies the functional requirements. The product may need to be simulated (a computational "mental" simulation) in order to assess how well it fits with requirements and intended use. Desired patterns of interaction between the product (and its features) and the environment (often a "user") define the function of the product (Brown & Blessing, 2005; Chandrasekaran & Josephson, 2000).

Besemer (2006) suggests that value estimates result from a cost–benefit analysis. Exactly how these can be assessed by a computational system is unclear, unless the system has considerable knowledge of the potential environments for the product. Products with added functionality (e.g., a knife with blade and bottle opener) may be rated more highly on a cost–benefit scale, but one with a very large number of attachments (e.g., corkscrew, marlinspike, and so on) may have extra weight and size costs.

To be understandable, the product presents itself in a self-disclosing way, which is considered to be "user-friendly." A computational system might assess the product's usability by looking at the patterns of interaction with a user and evaluating the physical and cognitive difficulty of each interaction (Persad, Langdon, Brown, & Clarkson, 2007), or it might use the known affordances of certain features of the product (Brown & Blessing, 2005).

4.3. Computational style

To be organic, the product must have a sense of wholeness or completeness about it, with all the parts working well together. Besemer (2006) refers to this characteristic in terms that are mostly about the product's visible structure and materials. A computational system would need to assess the "flow" of the product's geometry, the snugness of fit, and the "harmonious" relationship between the colors, surface finishes, and materials used. This suggests the needs for some basic ability to make aesthetic judgments (Reich, 1993).

To be well crafted, the product must have been worked and reworked with care to "develop it to its highest possible level for this point in time." This refers mostly to the finish of the product: no rough edges or scratches. As such, it appears to be more about manufacturing than design. However, insomuch as these specifications appear in the design description, this is something that a computational system can assess.

To be elegant, the product must be refined and understated. Besemer (2006) refers to something being simple but powerful, with "little surface decoration" and low visible complexity. Besemer (personal communication, 2008) suggests that elegant is close to "simple" in meaning, but existing work shows that simplicity, or complexity, is a complicated issue (Balazs & Brown, 2001; Summers & Shah, 2003). Although the visible complexity could probably be estimated computationally, the ratio of "power" to simplicity should be included in the measure of this characteristic, where power is some measure of the amount or the complexity of the functionality being delivered.

4.4. Other measures

This paper focuses on Besemer's model, but other research includes measures that might be incorporated in a CDC. Ritchie (2007), building on Wiggins (2006), lists a set of criteria that use measures, ratios, and thresholds, providing 18 possible ways to calculate evidence for creativity. Like Besemer, he also mentions using the evidence in a "profile."

Christiaans (1992) uses seven attributes: creativity; technical quality; attractiveness; interestingness; expressiveness; capacity to integrate form, function, and construction; and degree of prototypicality. Christiaans (1992) found a close relationship between creativity, interestingness, and attractiveness. Designs that were judged as more prototypical were seen as of higher technical quality, but received low creativity ratings.

Shah, Vargas-Hernandez, and Smith (2003) propose four measures for the effectiveness of a designer's idea generation (ideation), novelty, variety, quality, and quantity, noting that they should not be combined into a single measure, so an appropriate mix would need to be determined for CDC systems. Srinivasan and Chakrabarti (2010) provide alternative novelty measures.

5. Summary and discussion

To a certain extent, the main points raised by the creativity literature are not very surprising. There is general agreement that there are degrees of creativity, that its determination requires judgment, and that judgment requires knowledge. Mere novelty is not enough for creativity, and most agree that at least "utility" should also be evaluated.

Most writers stress the need to "break away" from well-known methods and solutions, plus a willingness to be "playful": perhaps by not following "normal" methods, by dropping or relaxing constraints, or by making unusual associations. Such associations would foster analogical reasoning. As these, and other, modes of reasoning will tend to generate more possibilities than is normal, the role of evaluation becomes even more important. Most writers seem to agree that evaluation is highly knowledge based.

In addition to associating concepts, and even blending them, the ability to avoid being tied to existing conceptual organization is important for creativity.

Most of these issues relate to CPAM's "original," "surprising" and "useful" characteristics. The other characteristics raise more subtle and difficult issues. A detailed study of how these characteristics can be affected by actions within a CDC system is a way of pulling the study of CDC systems away from the focus on novelty.

CDC systems are going to be complicated, especially if we wish to study creativity. Although "what" a CDC system can do is much more important than what technology to use, the need for multiple types of knowledge-intensive reasoning at different levels primarily suggests using agent technology with a variety of symbolic knowledge representations.

Agents have been used for design in multi-agent design systems (MADS) (Lander, 1997), but the allocation of functionality to agents and the MADS architecture imposed is going to be critical (Dunskus, Grecu, Brown, & Berker, 1995).

For example, Minsky's (2006) proposal of critics and selectors is similar to the sponsor–selector mechanism explored by Punch, Goel, and Brown (1995), suggesting the use of specialized agents that have restricted functionality and knowledge, and using specialized knowledge structures (Berker & Brown, 1996). In addition, various kinds of capable evaluators will be essential.

We are not advocating collections of agents as models of human design teams, as that adds a layer of coordination and communication to design (Visser, 2006, p. 199) that will "muddy the water" for the study of creativity. However, agents can still have different goals and knowledge, leading to the kind of stimulating conflict that failing conceptual combination might produce, or the kind of memory activation that can be used to look for relevant knowledge or analogies.

The agenda for CDC includes studying fairly fine-grained computational creativity mechanisms, such as detecting possible far analogies, combining mechanisms, adding mechanisms to working computational design systems, observing the changes in behavior and results as systems are changed; and experimentation.

The field of CDC must avoid the trap of assuming that design creativity is a single thing. Some past theories about designing have assumed that there is only one type of designing, and have developed general models from specific examples. Designing by an individual varies depending on where in the conceptual–parametric, routine–nonroutine space the design activity starts. It varies depending on how purpose-directed the design activity is, or how much creativity is being rewarded. On top of these variations, the CPAM defines a multidimensional space for product creativity.

Another trap to avoid is just focusing on obtaining creative results, regardless of how they are obtained, as opposed to making hypotheses about and simulating the underlying processes. Although systems such as those based on genetic programming are able to produce remarkable results (Spector, 2008), it appears unlikely that they will tell us much about creativity. Even the common list of three to five computational "creative processes," such as analogy and mutation, can be seen as too coarse grained, as many authors assume that just having these in a CDC is enough.

We will need some form of explanation facility in the CDC systems, with explanations such as "I was influenced by ...," "I was trying not to ...," "it was analogous to ...," or "I had a goal to ...." Fine-grained systems instrumented to report such things, because the reasoning used supports such explanations, should advance the CDC field. Cross (2006) points out that lack of explanation has been a problem regarding chess-playing programs.

Even if CDC systems are not yet feasible, systems could aid human designers, helping them to be more creative, instead of actually doing the creative designing. However, regardless of whether it provides evaluation, critiquing, or suggestions, the system would still benefit from a full or partial model of the design process in question, as well as a strong sense of the factors that influence product creativity assessment.

The use of CPAM factors and characteristics as goals to influence a CDC system and to evaluate its progress appears to be a promising idea, although it is clearly not without difficulties, and much more investigation needs to be done.

References

Amabile, T. M. (1983). The social psychology of creativity. *Journal of Personality and Social Psychology*, *43*, 997–1013.

Balazs, M. E., & Brown, D. C. (2001). Design simplification by analogical reasoning. In C. Rizzi, U. Cugini & M. Wozny (Eds.), *Knowledge intensive computer aided design* (pp. 29–44). New York: Springer.

Berker, I., & Brown, D. C. (1996). Conflicts and negotiations in single function agent based design systems. *Concurrent Engineering: Research and Applications*, *4*(1), 17–33.

Besemer, S. P. (2006). *Creating products in the age of design*. Stillwater, OK: New Forums Press, Inc.

Besemer, S. P., & Treffinger, D. J. (1981). Analysis of creative products: Review and synthesis. *Journal of Creative Behavior*, *15*, 158–178.

Boden, M. A. (1994). What is creativity? In M. A. Boden (Ed.), *Dimensions of creativity* (pp. 75–117). Cambridge, MA: The MIT Press.

Brown, D. C. (1996). Routineness revisited. In M. Waldron & K. Waldron (Eds.), *Mechanical design: Theory and methodology* (pp. 195–208). New York, NY: Springer-Verlag.

Brown, D. C. (2012). *Creativity, surprise & design: An introduction and investigation*. The 2nd international conference on design creativity (ICDC2012), Glasgow, UK.

Brown, D. C., & Blessing, L. (2005). The relationship between function and affordance. ASME design theory and methodology conference, Long Beach, CA.

Brown, D. C., Horner, R., Kim, M., Large, E., Liu, J., Meehan, E., & Spillane, M. (1992). Experiences with modelling memory and simple learning in routine design problem-solving systems. In M. Green (Ed.), *Knowledge aided design* (pp. 239–257). Waltham, MA, USA: Academic Press.

Chandrasekaran, B., & Josephson, J. R. (2000). Function in device representation. *Engineering with Computers*, *16*, 162–177.

Christiaans, HHCM (1992). *Creativity in design: The role of domain knowledge in designing*. Utrecht: Uitgeverij Lemma BV.

Colton, S. (2008). Creativity versus the perception of creativity in computational systems. *Proceedings of the AAAI spring symposium on creative systems*, The AAAI Press, Menlo Park, California, USA. pp. 14–20.

Cross, N. (2006). *Designerly ways of knowing*. New York: Springer-Verlag.

Dasgupta, S. (1994). *Creativity in invention and design*. Cambridge: Cambridge University Press.

Dasgupta, S. (1996). *Technology and creativity*. New York, NY: Oxford University Press.

Dorst, K. (2008). Design research: A revolution-waiting-to-happen. *Design Studies*, *29*, 4–11.

Dreyfus, H. L., & Dreyfus, S. E. (2002). From socrates to expert systems: The limits and dangers of calculative rationality. Retrieved July 14, 2008, from socrates.berkeley.edu/~hdreyfus/html/paper_socrates.html

Dunskus, B., Grecu, D. L., Brown, D. C., & Berker, I. (1995). Using single function agents to investigate conflicts. *AIEDAM*, *9*, 299–312.

Ekvall, G. (1995). Assessing the climate for creativity and change. *Proceedings of conference on organizational climate for creativity and change*, Center for Studies in Creativity, Buffalo, NY.

Erden, M. S., Komoto, H., van Beek, T. J., D'Amelio, V., Echavarria, E., & Tomiyama, T. (2008). A review of function modeling: Approaches and applications. In A. Goel, R. Davis & J. S. Gero (Eds.), *Special issue on multi-modal design, AIEDAM*, *22*(2), 147–162. New York: Cambridge UP.

Eysenck, H. J. (1994). The measurement of creativity. In M. A. Boden (Ed.), *Dimensions of creativity* (pp. 199–242). Cambridge, MA: MIT Press.

Gero, J. S. (1994). Introduction: Creativity and design. In T. Dartnall (Ed.), *Artificial intelligence and creativity* (pp. 259–267). New York: Kluwer Academic Publishers.

Gero, J. S., & Kannengiesser, U. (2007). Locating creativity in a framework of designing for innovation. In N. Leon-Rovira (Ed.), *Trends in computer aided innovation* (pp. 57–66). New York: Springer.

Goel, A. K. (1997). Design, analogy, and creativity. *IEEE Expert*, *12*, 62–70.

Grecu, D. L., & Brown, D. C. (1999). Guiding agent learning in design. In S. Finger, T. Tomiyama & M. Mantyla (Eds.), *Knowledge intensive computer aided design* (pp. 237–250). New York: Kluwer.

Horn, D., & Salvendy, G. (2006). Consumer-based assessment of product creativity: A review and reappraisal. *Human Factors and Ergonomics in Manufacturing*, *16*, 155–175.

Lander, S. E. (1997). Issues in multiagent design systems. *IEEE Expert*, *12*, 18–26.

Lubert, T. (2005). How can computers be partners in the creative process. *International Journal of Human-Computer Studies*, *63*, 365–369.

Minsky, M. (2006). *The emotion machine: Commonsense thinking, artificial intelligence, and the future of the human mind*. New York, NY: Simon & Schuster.

O'Quin, K., & Besemer, S. P. (1989). Development, reliability, and validity of the revised creative product semantic scale. *Creativity Research Journal*, *2*, 267–278.

Persad, U., Langdon, P., Brown, D. C., & Clarkson, P. J. (2007). Cognitive scales and mental models for inclusive design. In *HCII2007: 12th International conference on human computer interaction* (pp. 776-785). Springer-Verlag.

Punch, W. F., Goel, A. K., & Brown, D. C. (1995). A knowledge-based selection mechanism for strategic control with application in design, assembly, and planning. *International Journal of Artificial Intelligence Tools*, *4*, 323–348.

Reich, Y. (1993). A model of aesthetic judgment in design. *Artificial Intelligence in Engineering*, *8*, 141–153.

Ritchie, G. (2007). Some empirical criteria for attributing creativity to a computer program. *Minds and Machines*, *17*(1), 67–99.

Shah, J. J., Vargas-Hernandez, N., & Smith, S. M. (2003). Metrics for measuring ideation effectiveness. *Design Studies*, *24*, 111–134.

Shai, O., Reich, Y., & Rubin, D. (2009). Creative conceptual design: Extending the scope by infused design. *Computer-Aided Design*, *41*, 117–135.

Shneiderman, B. (2007). Creativity support tools: Accelerating discovery and innovation. *Communications of the ACM*, *50*, 20–32.

Smith, S. M. (1995). Fixation, incubation, and insight in memory and creative thinking. In S. M. Smith, T. B. Ward & R. A. Finke (Eds.), *The creative cognition approach* (pp. 135–156). Cambridge, MA: MIT Press.

Smith, S. M., Ward, T. B., & Finke, R. A. (1995). Principles, paradoxes, and prospects for the future of creative cognition. In S. M. Smith, T. B. Ward & R. A. Finke (Eds.), *The creative cognition approach* (pp. 327–335). Cambridge, MA: MIT Press.

Spector, L. (Ed.). (2008). Genetic programming for human-competitive designs. Special issue, *AIEDAM*, *22*(3), 183–297.

Srinivasan, V., & Chakrabarti, A. (2010). Investigating novelty-outcome relationships in engineering design. *AIEDAM*, *24*, 161–178.

Summers, J., & Shah, J. (2003). Developing measures of complexity for engineering design. *Proceedings of ASME DETC*, paper DTM-48633, Chicago, IL.

Talbot, R. J. (1997). Taking style on board. *Creativity and Innovation Management*, *6*, 177.

Visser, W. (2006). *The cognitive artifacts of designing*. Mahwah, NJ: Lawrence Erlbaum Associates.

Ward, T. B., Smith, S. M., & Finke, R. A. (1999). Creative cognition. In R. J. Sternberg (Ed.), *Handbook of creativity*. Cambridge: Cambridge University Press.

Ward, T. B., Smith, S. M., & Vaid, J. (1997). Conceptual structures and processes in creative thought. In T. B. Ward, S. M. Smith & J. Vaid (Eds.), *Creative thought: An investigation of conceptual structures and processes*. Washington, DC: American Psychological Association.
Wiggins, G. A. (2006). A preliminary framework for description, analysis and comparison of creative systems. *Knowledge-based Systems*, *19*, 449–458.