Symposium on Computational Approaches to Creativity in Science

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The Symposium on Computational Approaches to Creativity in Science was held at Stanford University on March 29 and 30, 2008. Over 30 researchers from academia, government, and industry attended the meeting, of which 14 participants, all known for their work in this area, presented talks on their recent results. The symposium fostered discussion among researchers working on scientific creativity in the cognitive, computational, and mathematical sciences and provided a forum where they could meet to share their experiences and approaches. The computational metaphor of scientific discovery, which stresses the role of heuristic search through a problem space, set the central theme of the meeting. Speakers discussed a variety of issues, including collaborative communication, abductive reasoning, imagination and analogy, and the role of constraints.

We organized the symposium into talks and discussions over two consecutive days. Below we summarize the contents for each speaker's presentation in the order given. This information, together with slides and references to what each author judged to be his or her most relevant paper, is available at `http://cll.stanford.edu/symposia/creativity/`, the symposium Web site.

1. Uncovering the Creative Processes in Chemistry: Implications for Discovery System Design. *Catherine Blake* (University of North Carolina, Chapel Hill) reported on her efforts to better understand the activities of "normal" science and to identify aspects of those activities that informatics tools could support. To this end, she investigated the ways that seasoned chemical engineers and chemists define "discovery," generate research questions, and transform their ideas into final publications. Interviews with this group indicated that they value an idea's novelty, its relationship to existing work, and its utilitarian value. Blake also found that research questions often arose from informal and formal social interaction. For instance, many of the engineers and scientists valued highly their discussions with researchers who work on other projects or in other disciplines, considering those interactions fruitful sources of new ideas. She concluded with an approach for eliciting workflows that characterize the activities common to publishing a scientific paper.
2. Imagination and Scientific Visualizations. *Greg Trafton* (Naval Research Lab) presented his studies of how scientists and meteorologists use imagination to analyze uncertain or anomalous data. To frame the results, he distinguished among three types of imagination-driven behavior. The first, *pure spatial transformations*, occurs when one imagines movement, rotations, and other spatial alterations of given data. The second, *comparison spatial transformation*, involves the projection of an imagined situation onto existing data, emphasizing differences and similarities between the two. The third

type, *conceptual simulation*, emphasizes counterfactuals and may involve the creation of a new representational space to compare the what-if scenarios to observed phenomena. Experiments suggest that the prevalence of each activity differed based upon expertise and scientific focus (e.g., scientists are more likely to engage in conceptual simulations than meteorologists). These results informed the design of an informatics tool for meteorological analysis.

3. Re-Conceptualizing Literature-Based Discovery. *Neil Smalheiser* (University of Illinois at Chicago) examined the idea of creativity through synthesis as expressed in tools for literature-based discovery. This field of research is concerned with automatically identifying deep relationships between two bodies of scientific literature. A common approach involves the extraction of search terms from a set of source articles, the identification of articles from a target research area that contain those terms, and the ranking of target articles based on the novelty, relevance, and other aspects of the search terms that they contain. Smalheiser suggested extending this method with a richer set of interestingness measures that consider factors external to the search terms.
4. Mathematical Modeling and Computational Creativity. *Ljupco Todorovski* (University of Ljubljana) reported on a computational approach for exploring the space of potential mathematical models of dynamic systems. The Lagramge program seeks out systems of differential equations that characterize multivariate time-series data. Todorovski stressed those aspects of Lagramge that constrained its search to plausible solutions. Ultimately, he argued that computational approaches like the one he described are not creative artifacts, which raised the question of how discovery and creativity differ.
5. A Framework for Studying and Facilitating Collaboration in Science and Technology. *Michael Gorman* (University of Virginia) highlighted the potential for interdisciplinary collaboration to spur scientific creativity. In response, he presented the idea of trading zones as the conceptual space where participants who operate in different scientific fields meet. Such trading zones are characterized by a shared interlanguage, a jargon or creole that helps build links between world views, and the idea of a moral imagination, the realization that one's reality is a mental model. Gorman claimed that Arizona State University's Decision Theater and the game Second Life can provide computational support for trading zones and called for further solutions that specifically address the problems associated with interdisciplinary work.
6. Supporting Creativity in Science: Cooperative Knowledge Acquisition and Knowledge Refinement Systems. *Derek Sleeman* (University of Aberdeen) focused on the development and use of knowledge-based systems in science. He presented case studies of systems that assist users as they revise encoded knowledge. For example, the RETAX+ system identifies inconsistencies in ontologies and suggests effective repairs. Sleeman argued that these systems support creativity both by assisting experts in codifying their knowledge, a creative process that emphasizes communication and clarity, and by helping them question their assumptions when inconsistencies arise.
7. A Computer Program for Mathematical Discovery. *Ermelinda DeLaVina* (University of Houston) presented research on Graffiti.pc, a computer program that poses and evaluates conjectures in graph theory. Specifically, the system searches for mathematically interesting conjectures by employing a generate-and-test strategy. The test stage estimates novelty and prunes redundant or uninteresting candidates. DeLaV-

ina discussed several conjectures posed by the system, many of which were both novel and ultimately proven. Notably, Graffiti.pc emphasizes creativity during problem generation as opposed to solution generation.

8. Combining Reasoning Systems for Mathematical Discovery. *Simon Colton* (Imperial College London) reviewed several discovery systems that were built by integrating existing reasoning components. These systems identify interesting mathematical conjectures, classify algebraic structures, and revise nontheorems to create related but provable conjectures. As with Graffiti.pc, research in this area has led to findings that were publishable in the mathematical literature.

9. On Modeling Scientific Creativity: An Historical Case Study of Watson and Crick's Creation of the Double Helix. *Robert Weisberg* (Temple University) compared artistic and scientific creativity, focusing on the aspects of each that are objective and subjective. Specifically, he asserted that objective creativity stems from those facts or experiences readily available to anyone and that subjective creativity evolves from a specific individual's experiences and efforts. Weisberg then argued that artistic and scientific achievements result from a mixture of these two qualities. For instance, the structure of DNA exists as an objective fact that others would have uncovered in the absence of Watson and Crick, but subjective experience acutely tuned these investigators to and informed their presentation of this discovery. The implication is that computational models of scientific creativity should include explicit mechanisms for guiding the focus of attention.

10. Analogies Between Science and Design: What Models of Science Can Learn from Models of Design. *Christian Schunn* (University of Pittsburgh) focused on building a bridge between research on scientific discovery and engineering design. He began by mapping concepts between the domains (e.g., relating confirmation bias in science to design fixation in engineering). Schunn then reported on the role of analogies in the design process, noting that those linking two disparate domains (between-domain) appeared more often in this process than during scientific investigation. He concluded by suggesting that the knowledge of the roles of analogy and other concepts in design could inform computational models of science.

11. Creativity with Restraint. *Will Bridewell* (ISLE and Stanford University) presented research on the role of explicit, structural constraints in scientific modeling. To illustrate these ideas, he described SC-IPM, a modeling system that uses this kind of knowledge to restrict the models it considers to only plausible candidate structures. He then introduced a system that could induce such constraints from previous modeling experiences. Bridewell claimed that moving from a discovery system to a creative system involves both this ability to learn new constraints from experience and the ability to violate constraints when a solution is evasive.

12. Integrating Explanation-based and Generalisation-based Reasoning for Scientific Discovery. *Oliver Ray* (University of Bristol) presented research on abduction and induction from the perspective of the philosopher Charles Peirce. Whereas induction leads to generalizations from multiple observations, abduction stresses the explanation of one or more events. Ray integrated these ideas in the framework of computational logic and illustrated their use on discovery problems from the discipline of biology.

13. Discovery and Neural Computation. *Paul Thagard* (University of Waterloo) outlined a neurocomputational model of scientific creativity. This model was unique among the presentations in its emphasis on explaining creative cognition in an emotional context. Thagard discussed how a connectionist model could support abductive inference and stressed a general need for computational models of creativity that possess a deep understanding of causality.

14. Computational Imagination and Scientific Creativity. *Ashok Goel* (Georgia Institute of Technology) argued that analogy plays a central role in imagination and creativity. He first presented TORQUE, a computer program that uses analogical reasoning to make abductive leaps in problem solving. Goel then reported on the extensive use of analogical mapping by teams of students during a course project in bioengineering. Importantly, participants used analogies at multiple levels of abstraction and relied heavily on drawings and other figures to communicate across disciplinary boundaries.

The presentations covered a wide variety of topics related to creativity in science and highlighted research that took the form of theoretical analyses, computational models, and empirical observations of creativity (sometimes in a single talk). Although divisions occasionally surfaced between researchers who espoused a descriptive approach to the topic based on empirical findings and those who argued for a normative approach based upon theoretical frameworks, these were relatively uncommon. In large part, we attribute this to the participants' wide interdisciplinary experience and their avid appreciation of extending the common ground.

Through formal and informal discussions, the participants discovered joint interests. For example, a common theme centered on the extent to which the products of creativity research meet the needs of the scientific community. One opinion held that many systems automate the simple or even pleasurable aspects of scientific enquiry while leaving the drudgery to the humans. Another opinion stressed the need to analyze laboratory tasks and to develop tools that address workflow inefficiencies that go undetected by the scientists. In general the focus of discussion was directed toward new and existing problems that centered on the human side of human–computer systems.

In summary, the Symposium on Computational Approaches to Creativity in Science provided researchers who normally move in different academic circles with the opportunity to exchange ideas about their most recent findings. The talks were broad in scope but touched on similar themes, which provided a common ground for discussions. The interactions revolved around the relevance and acceptance of creative systems that support the scientific enterprise. In all, the participants expressed enthusiasm for the symposium and showed interest in holding similar meetings in the future.