Title
Scientific Creativity: Multidisciplinary Perspectives

Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 16(0)

Author
Nersessian, Nancy J.

Publication Date
1994

Peer reviewed

Scientific Creativity: Multidisciplinary Perspectives

Nancy J. Nersessian

School of Literature, Communication & Culture/
School of Psychology/College of Computing
Georgia Institute of Technology
Atlanta, Georgia 30332-0165
nancyn@cc.gatech.edu

Introduction

The long fascination of historians, psychologists, philosophers, and scientists with scientific creativity has produced a wealth of scattered insights about specific individuals and episodes. For the most part these have remained within disciplinary confines. Yet, to advance to a deeper understanding - one that provides a more general theoretical perspective while preserving uniqueness and individuality - presents complex problems that will find resolution only through the combined focus of multiple disciplinary perspectives. Cognitive science provides the venue for such a convergence of disciplinary perspectives on creativity to take place. This symposium brings together perspectives from cognitive psychology, philosophy and history of science, science education, and a.i. The data examined in these investigations comprise historical case studies, protocols of contemporary scientists, and computational models. The questions addressed include: What cognitive mechanisms are employed in generating creative problem solutions? In generating new representations? Are these is any sense "special" to creativity? What function does current knowledge have? What roles do serendipity and "flashes of insight" play? Can automated systems do creative problem-solving? Can they make scientific discoveries? Will understanding creative thinking yield insights for science pedagogy? Although our focus is on science, the kinds of creative processes we discuss are as central to creative thinking in the humanities and arts as they are in the sciences. Seen through the lens of creativity, the gulf between the "two cultures" is not as wide as customarily presumed.

Scientific discovery heuristics: How current day scientists generate new hypotheses and make scientific discoveries

Kevin Dunbar, Department of Psychology,
McGill University
1205, Docteur Penfield Avenue,
Montreal, Quebec, Canada H3A 1B1
dunbar@ego.psych.mcgill.ca

Cognitive scientists have used many approaches to investigate scientific creativity, ranging from conducting experiments, and analyzing diaries of scientists, to computational simulations of the discovery process. These diverse approaches have resulted in many important models and theories of scientific creativity. However, despite the large amount of research conducted, little is known about the cognitive mechanisms underlying creative discoveries that current day scientists make. In this talk, I will present a summary of ongoing research in which I am investigating the cognitive mechanisms used by current-day molecular biologists when reasoning about their research "on-line". Data were collected over a one year period in four leading molecular biology laboratories following all aspects of particular scientific research projects including planning of the research, execution of the experiments, evaluation of experimental results, lab meetings, public talks, and the writing of journal articles. Some projects resulted in scientific discoveries, and some did not. This provides a novel database with which to address fundamental questions concerning the cognitive processes involved in scientific creativity. Using this database, I will discuss three important sets of heuristics that are involved in the generation of new scientific theories: Regional Analogical reasoning, Focusing on unexpected findings, and the use of visual diagrams to both deduce and induce new hypotheses. An overview of these findings can be found in Dunbar (1994).

Analogical reasoning heuristics. By analyzing transcripts of laboratory meetings we have been able to specify how analogical reasoning is involved in hypothesis generation. In particular, we have found that the types of "distant analogies" alluded to in the literature on creativity (e.g., the atom is like the solar system) were not used to make discoveries. Rather scientists used these "long-distance" analogies to help an audience understand a particular phenomenon, or make a point. Instead, we have found that analogies from the same domain --"regional analogies" -- are often used to suggest new hypotheses and theories. For example, an HIV lab drew analogies between the HIV virus and other viruses to formulate new hypotheses regarding the mechanism of specific genes on the virus. Thus, Regional analogies lead to the generation of new hypotheses.

Use of unexpected findings heuristics. We have found that scientists focus on unusual and unexpected findings and that they have developed specific sets of heuristics for deciding which types of findings to focus on. I will specify a number of these heuristics and argue that the main purpose that they serve is one of constraining the generation of a potentially infinite number of novel hypotheses to a much smaller set. (See also Dunbar 1993 & Dunbar and Baker, in press)

Diagrammatic reasoning heuristics. While a number of theorists have argued that visual images are important in scientific discoveries, most data has consisted of retrospective accounts and it has been difficult to propose the way that scientists used images and diagrams. In this data set we have many examples of scientists' "on-line" reasoning using diagrams and images. Thus we can now specify some of the diagrammatic reasoning heuristics that scientists use.

Scientific Creativity: Some Cognitive-historical Reflections

Ryan D. Tweney & Maria F. Ippolito
Department of Psychology
Bowling Green State University
Bowling Green, OH 43403
419-372-2301
tweney@andy.bgsu.edu
mippoli@trapper.bgsu.edu

In an earlier paper (Ippolito & Tweney, in press), we argued that an understanding of creative scientific thought required attention to the presymbolic processes by which perceptual constructs are transformed into derived structures which in turn are used to bridge the gap between the symbolic products of creativity and the environmentally-bound aspects of perception. In the present context, we will briefly sketch an historical case study of Michael Faraday (1791-1867) that served as the illustration for our claim, indicate why attention to presymbolic processes is necessary for an understanding of the case, and extend our argument for the analysis of presymbolic processes in creativity. We thus intend to show that the usual approach to understanding scientific creativity, that is, that it can be understood as resulting from the combinatorial play of symbolic representations, is inadequate. Instead, it is useful to distinguish an intermediate level, which we called the inceptual, to bridge the gap between the perceptual and the symbolic.

Faraday is best known for his discovery of electromagnetic induction in August of 1831. Earlier in that year, however, he engaged in two programmatic researches, one on acoustical vibrations and one on certain optical illusions. Tweney (1992) argued that each served to prepare Faraday for the attention to transient phenomena which was an essential part of the more famous August discovery. Each research program, however, required Faraday to experiment upon the perceptual and cognitive processes of the observer, as well as the physical processes underlying the phenomena. In brief, Faraday was required to formulate cognitive psychological hypotheses as well as physical hypotheses to fully understand the domain of study.

Ippolito & Tweney (in press) argued that much of the recorded experimentation in these two programs could be understood as attempts by Faraday to bridge a gap between purely perceptual phenomena and purely symbolic representations -- mental models of the physical processes. Constructing the appropriate mental models, however, required that he first formulate a quasi- perceptual representation that selectively filtered and transformed aspects of the perceptual phenomena, resulting in intermediate structures that we called inceptions. In contrast to perceptions, these were not isomorphic to a "seen" reality, and, in contrast to the fully-formed mental models that constituted the scientific explanation of the phenomena, they did not have a fixed symbolic character.

In effect, then, we argue for the existence of two separable (and interdependent) activities of construction on the part of the scientist. First, purely perceptual phenomena must be selected and altered in order to open the possibility of constructive "play" not bound by external inputs. Second, the symbolic representations that constitute the mental model itself must be constructed out of these inceptual structures.

Creativity and Conceptual Change

Nancy J. Nersessian

No one would deny that conceptual innovation and change is one of the most creative and extraordinary dimensions of scientific activity. The outcomes, i.e., new representational systems for understanding the world, are customarily perceived to be the works of geniuses - the Newtons, Darwins, or Einsteins of humanity - whose mental capacities and ways of thinking lie far outside of those of ordinary mortals. Philosophers of scientific method have accepted this mythology. Perhaps we can hope to understand the nature of the logical and meaning relationships between the old and new conceptual systems or whether or not the process through which the new systems are adopted is rational, but the processes of their innovation are wholly mysterious.

Previously, I have argued (1984, 1992, 1993) that when one examines the practices of scientists who have created new conceptual structures, a rather different picture emerges. Conceptual change is a problem-solving process whereby scientists articulate speculative intuitions into viable representations, communicate these to their colleagues, and adopt them in lieu of existing representations. Thus, conceptual change is extended in time, dynamic in nature, and embedded in social contexts. This depiction shifts our focus from the products of conceptual change to the processes whereby change comes about. On this interpretation, scientific creativity will best be understood not by focusing on its outcomes, but rather on the methodological practices that constitute the creative processes. Thus, philosophical notions of scientific method need expansion to encompass creative theoretical and experimental practices most of which cannot be reduced to an algorithm, are not always productive of solutions, and can sometimes lead one astray. In conceptual change scientists combine human cognitive resources with the conceptual and analytical resources available to them as members of scientific communities and wider social contexts to create, communicate, and adopt new representations of a domain. To fathom how they do this requires a multidisciplinary approach: one that combines historical research with cognitive investigations of human reasoning and representation. This presentation will focus on an innovative practice that I call "constructive modeling"; specifically as used by James Clerk Maxwell to create a field representation of electromagnetic forces (Nersessian 1992, in press).

Analogical reasoning played a key role in Maxwell's thinking, as did visual representation and thought experimenting. But, these were used in an integrated process that differs from the processes usually discussed in the literature on analogy and on visual reasoning. In constructive modeling the target and source domains interact in a problem-solving process to create hybrid models that become the objects of reasoning. These models are created from multiple sources and informational formats and are entertained as plausible representations of the phenomena under investigation. What is extraordinary about Maxwell's achievement is that by drawing from analogical sources in domains within Newtonian mechanics, he formulated the laws of a non-Newtonian dynamical system.

The Maxwell case furnishes a striking example of a practice that seems also to be employed in scientific reasoning in more ordinary circumstances (e.g.,Clement 1989). In this broader context, I will discuss a unified account of analogical reasoning and mental modeling being developed with James Greeno. Although the historical record provides only traces of cognitive activity, placing these within the framework of cognitive research opens the possibility of going beyond the specific case study to more general conclusions about the nature of cognitive mechanisms implicated in creative problem solving and conceptual change.

Protocol Evidence on Analogy and Model Construction Processes in Science

John Clement
Scientific Reasoning Research Institute
University of Massachusetts
Amherst, MA 01003
clement@srri.umass.edu

Some central issues in discussions of creative processes in science are (1) the mechanism(s) by which hypothesis formation takes place; (2) the sources of new knowledge during hypothesis formation; and (3) the Eureka vs. steady accumulation (accretion) issue concerning the pace of change during hypothesis formation. In our work we have been investigating the question of whether data from transcripts of scientists thinking aloud has the potential to speak to these issues. In such studies one sometimes observes a subject generating a new explanatory model hypothesis--a qualitative picture or description of a hidden process that explains a phenomenon.

Observations from such case studies indicate the following: (1) A new hypothesis can be developed and evaluated by a scientist in the absence of new empirical information via thought experiments and other means that include processes that are neither deduction nor induction by enumeration. (2) In particular, analogies can play a role in the generation of new hypotheses. (3) Analogous cases are not only produced by associations to existing cases in memory, but by transformations which can generate newly invented cases. (4) In some instances "Aha!" episodes are observed which lead to creative insights. It is argued that these can involve fairly sudden reorganizations that break away from previous assumptions but do not necessarily involve extraordinary or unconscious reasoning. (5) Analogies can help trigger such breakthroughs. (6) Using a rough analogy as a starting point, a new explanatory model can be developed via a successive refinement process of hypothesis generation, evaluation, and modification, that goes well beyond simple analogical reasoning.

This suggests a view of hypothesis formation in science that is more complex than can be provided by an inductivist, rationalist, Eurekaist, or accretionist position alone. In one extended case study we found that we could document steps in each of five passes though such a cycle by identifying clauses in transcripts that gave evidence for each step. Thus it appears to be possible to study hypothesis formation processes in think aloud protocols of experts. The analogy plus model construction cycle discussed has educational applications because it provides a description of a process students can use to learn scientific models.

Functional Characteristics of Creativity

Randolph M. Jones
Artificial Intelligence Laboratory, University of Michigan
1101 Beal Avenue, Ann Arbor, MI 48109-2110
{rjones@eecs.umich.edu}

What are the characteristics that an automated agent must possess in order to be considered creative? Naturally, the answer to this question depends in large part on how one defines creativity. Let us first consider three different ways in which humans are said to be creative. In the most literal sense of the term, humans appear to create novel ideas and thoughts based on a synthesis of their experiences. A perhaps more traditional definition for creativity describes the generation of an unusual solution for an important or difficult problem. Finally, if an individual displays a propensity for generating such individual, creative acts, we would describe that individual as creative in general.

We are left with the question of which mechanisms and capabilities would be required for an automated agent to exhibit each of these types of creativity. The basic capability of creating new ideas can be accomplished by an agent that "imagines" or constructs new concepts or behaviors from primitive features and actions that it has experienced. Such an agent must be able to retrieve knowledge and have a mechanism for generalizing and combining knowledge to address the current task. A basic ability of this sort is simple enough to implement, but the space of constructible concepts and behaviors in any realistic domain is immense. The difficult part is controlling generation. For example, the Cobweb system (Fisher, 1987) has a large space of categories it can generate from observed instances. It controls search through this space by creating categories that increase predictive power. AM (Lenat, 1977) creates arithmetic concepts by combining primitive predicates and previously created concepts. Search through the enormous space of combinations is controlled by heuristics that judge mathematical interest. In this manner, the concepts Cobweb, AM, and other machine discovery systems create are a function of their particular control strategies and the background knowledge they possess at any instant in time.

As mentioned above, an individual creative act usually involves the creation of a novel solution to a problem—a solution that would not be created under normal circumstances. Thus, something must be unusual either about the agent's knowledge of the current problem, or the situation in which that knowledge is brought to bear. For example, Eureka (Jones, 1989; Langley & Jones, 1988) explains episodes of creative insight as a fortuitous stimulus causing the retrieval of a stored situation that can be mapped by analogy to create a new solution to a problem. The Gips system (Jones & VanLehn, in press) invents new problem-solving strategies by gathering specific problem-solving experiences and identifying correlated patterns in the features that describe them. At some point, a particular problem can cause a new correlation to be identified, leading to the invention of a new strategy. In other words, individual creative acts arise from the serendipitous combination of the agent's knowledge and its situation. This combination highlights the fact that it is not just important *what* an intelligent agent knows, but also *how* that knowledge is organized, retrieved, and used.

Having discussed the general requirements for generating individual creative acts, we turn to the conditions under which a system might display a propensity to generate such acts. First, such an agent must have sufficient knowledge in the particular domain. This aids the agent both in identifying the problems for which creative solutions might be useful, and in providing a store of information from which to create a novel solution. Second, this knowledge must be indexed in a manner conducive to creative application. Indexing is influenced by the situations and problems the agent experiences (either deliberately or by chance) and the success of various strategies for dealing with those situations and problems. Finally, some event must trigger the retrieval of knowledge that leads to a creative act. Again, this may happen by chance, or because the agent has put itself into a position in which such an event is likely to occur. The "creative" agent will either be one that is very lucky, or it will be an agent that creates situations for itself in which discoveries are likely, and that engineers its experiences to encourage the retrieval of appropriate knowledge when creative solutions are called for. Systems such as Eureka and Gips have the ability to take advantage of their situations to generate creative acts. We will discuss possible extensions to such systems that would lead to the active pursuit of experiences that would encourage creativity.

References

Clement, J. (1981). Analogy generation in scientific problem solving. *Proceedings of the Third Annual Meeting of the Cognitive Science Society*, 3, 137-140.

Clement, J. (1988). Observed methods for generating analogies in scientific problem solving. *Cognitive Science*, 12, 563-586.

Clement, J. (1989). Learning via model construction and criticism: Protocol evidence on sources of creativity in science. In J. Glover, R. Ronning, & C. Reynolds (Eds.), *Handbook of creativity: Assessment, theory and research*. NY: Plenum.

Clement, J. (1991). Non-formal reasoning in experts and science students: The use of analogies, extreme cases, and physical intuition. In J. Voss, D. Perkins, & J. Segal (Eds.), *Informal reasoning and education*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Dunbar, K. (1994). How scientists really reason: Scientific reasoning in real-world Laboratories: In R.J. Sternberg, and J. Davidson Eds. (1993). *Mechanisms of Insight.* Cambridge MA.: MIT Press

Dunbar, K. (1993). Concept discovery in a scientific domain. *Cognitive Science*. 17, 397-434.

Dunbar, K. & Baker, L. (in press). Goals, Analogy, and the social constraints of scientific discovery. (Commentary on M. Boden's "Creativity). *Behavioral and Brain Sciences*.

Fisher, D. H. (1987). Knowledge acquisition via incremental conceptual clustering. *Machine Learning, 2*, 139–172.

Ippolito, M. J. & Tweney, R. D. (in press). The inception of insight. In R. Sternberg & J. E. Davidson (Eds.) The nature of insight. Cambridge, MA: MIT Press.

Jones, R. M. (1989). A model of retrieval in problem solving. Doctoral dissertation, Department of Information and Computer Science, University of California, Irvine.

Jones, R. M., & VanLehn, K. (in press). Acquisition of children's addition strategies: A model of impasse-free, knowledge-level learning. *Machine Learning*.

Langley, P., & Jones, R. (1988). A computational model of scientific insight. In R. Sternberg (Ed.), *The Nature of Creativity*. Cambridge, England: Cambridge University Press.

Lenat, D. B. (1977). Automated theory formation in mathematics. In *Proceedings of the Fifth International Joint Conference on Artificial Intelligence* (pp. 833–842). San Mateo, CA: Morgan Kaufmann.

Nersessian, N.J.(in press): "Abstraction via generic modeling in concept formation in science," in *Idealization in Science*, N. Cartwright & M. Jones, eds. (Amsterdam: Editions Rodophi)

Nersessian, N.J.(1993): "In the theoretician's laboratory: thought experimenting as mental modeling," in *PSA 1992*, Volume 2, D. Hull, M. Forbes, & K. Okruhlik, eds. (East Lansing, MI: PSA), pp. 291-301

Nersessian, N.J.(1992): "How do scientists think? Capturing the dynamics of conceptual change in science," in *Cognitive Models of Science*, R. Giere, ed. (Minneapolis, MN: University of Minnesota Press)

Nersessian, N.J.(1984): *Faraday to Einstein: Constructing Meaning in Scientific Theories* (Dordrecht: Kluwer Academic Publishers, reprinted 1990)

Tweney, R. D. (1992a). Stopping Time: Faraday and the scientific creation of perceptual order. *Physis: Revista Internazionale di Storia Della Scienza*, 29, 149-164.