

Scientific Creativity
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I. Overview

II. Historical approach

III Scientific Creativity "InVivo"

IV Experimental work on Scientific Creativity

V. Beyond the Lone Scientist

VI Where is research on scientific creativity headed?

I Overview

Scientific Creativity has been of central concern to all who work on creativity and is a topic that has been tackled by almost every major area in psychology ranging from Psychoanalytic accounts of creativity (Freud 1932), to Gestalt (Wertheimer 1945), Social (Amabile 1983), Cognitive (Simon 1977), and Psychometric approaches (Roe 1952). Why this great interest in the creativity of scientists? One part of the reason is that scientists speak of their research and discoveries in the same terms that are used by other creative thinkers such as poets and artists. We hear of sudden flashes of insight, accidental discoveries, lone scientists striving against their peers and so forth. Like most creative processes scientific creativity is shrouded in mystery. The other part of the reason for the vast interest in scientific creativity is that science is highly regarded in our society and by discovering the key components of scientific creativity it should be possible to foster scientific discovery. One political event that generated much research on scientific creativity was the race between the United States and the former Soviet Union to put a man in space. The politicians turned towards psychologists and asked them to devise ways of identifying and fostering scientific creativity that could help the United States be first in the Space race. This resulted in a renaissance in the psychometric approach to creativity. More recently, the cognitive approach to creativity has uncovered many of the important components of scientific thinking and creativity through experimentation, historical analyses, and "InVivo" investigations of live scientists.

Most researchers see scientific creativity as being composed of the same mental processes that guide all other forms of creativity. What makes science different is that there is a vast theoretical, technical and experimental knowledge that creative scientific ideas must either extend or more rarely supplant. Furthermore there are sets of norms and scientific practices that any new scientific discovery must abide by before it is accepted by other scientists as being a discovery. Roughly speaking, contemporary research on scientific creativity falls under the four following headings; Historical analyses of great discoveries, "InVivo" analyses of scientists as they reason in their laboratories, cognitive analysis of people performing scientifically challenging tasks, and creative reasoning of groups of scientists. These different types of approaches are a microcosm of the different ways that creativity in general is investigated.

II Historical investigations of the creative scientist

One of the most common ways of investigating scientific creativity has been to analyze either the life of a creative scientist or how a scientist made an important scientific discovery. The goal of the analyses is to determine the mental processes that a particular scientist used to make a discovery or discoveries. Researchers use autobiographies, lab notebooks, and interviews with scientists and attempt to determine the strategies that the scientist used to make a discovery. For example, many researchers on scientific creativity have used James Watson's autobiographical "Double Helix" to build an account of scientific creativity. See Weisberg 1993 for an interesting analysis of the discovery of the structure of DNA. Another common figure used in research on scientific creativity has been Albert Einstein. Early work using this approach was initiated by Gestalt psychologists such as Max Wertheimer. In his studies of Einstein,

Wertheimer (1945) concluded that the way Einstein restructured the problems in physics were critical to his discoveries. While this approach was innovative, one of its main problems was that Gestalt psychologists did not have a detailed theory of how knowledge is represented in the mind or an account of the specific mechanisms by which knowledge changes over time. The more recent cognitive approach to scientific creativity made it possible to propose specific models of both the conscious and unconscious components of knowledge representation that form the basis of contemporary accounts of thinking and reasoning. Nersessian 1993, and Thagard 1992 provide historical accounts of scientific discoveries that give detailed models of how creative scientists represented and changed their knowledge while making a discovery.

Nersessian has conducted extensive analyses of Faraday's notebooks and has argued that the key to understanding his discoveries is in terms of his use of mental models. These mental models are mental representations that have spatial and temporal relationships to objects and processes in the real world. By mapping out the types of mental models that Faraday used and showing how these types of models shaped the discoveries that Faraday made, it is possible to give a precise account of the mental processes that underlie scientific creativity. Other researchers such as Ryan Tweney, Mike Gorman, David Gooding, and Arthur Miller have used this approach to analyze the discoveries of many eminent scientists and have provided a detailed account of the cognitive processes underlying the creative scientific mind. Tweney & Chitwood 1995 provide a good summary of this work.

One influential theory of scientific creativity that is based on an analysis of historical figures in science is Simonton's (1988) "chance-configuration" theory in which he argues that scientific creativity begins with the chance permutation of mental elements. He argues that from time to time these chance permutations coalesce to produce a configuration that is a new scientific idea, hypothesis, explanation, or experiment. This can then lead to a scientific discovery. The idea that a core mental process underlying scientific creativity is the random permutation of ideas is at the root of many theories of scientific creativity and was used by Donald Campbell in his evolutionary model of creative thought and has also been used by Kantrovitch, Martindale, & Perkins in their models of creativity.

Another approach to historical analyses of the scientific is exemplified by the work of Herbert Simon and his colleagues. What they have done is to use historical records, such as diaries and notebooks to identify the creative strategies that the scientists used in making a discovery. Having identified the creative thinking strategies that the scientists used, Simon has built computer programs that use these strategies and then conducted simulations to determine whether the program could make the discovery. For example, in Kulkarni & Simon (1988) they focused on the scientist Krebs and identified the strategies that Krebs used to discover the Urea cycle. One strategy that they built into the program that was crucial for making the discovery was to focus on unexpected findings.

Yet another way of using historical data to test hypotheses regarding scientific creativity is to take a real scientific discovery and bring subjects into the psychological laboratory, provide them with information, and let them conduct simulated experiments similar to what the original scientists discovered. Using this approach, Dunbar (1993) took Monod and Jacob's Nobel prize winning discovery of the inhibitory mechanism of genetic control into the psychological laboratory. He found that one of the key aspects to making a discovery is to switch goals from testing a favored hypothesis to a goal of accounting for unexpected findings. Again, being able to focus on and use unexpected findings is a key component of scientific discovery.

III Scientific Creativity InVivo

While much has been learned about scientific creativity using detailed historical analyses of scientists' lives, much of what scientists really do and how creative scientists really think is difficult to determine from notebooks and interviews. Recently, Dunbar (1995, 1997) has proposed that to gain a fuller insight into scientific creativity it is necessary to collect data on scientists as they think and reason in their laboratories as they are working and use this type of data to formulate theories and models of scientific creativity. It is necessary to investigate "live" scientists, as many of the important thought processes that the scientists use are forgotten by the scientists and do not make it into their lab books or notes. Dunbar has argued that it is possible to use this "InVivo" data to build models of the ways that creative scientists think and reason. Models built using the "InVivo" method be tested and further elaborated by conducting controlled experiments in the psychological laboratory - "InVitro" research. Thus, he has proposed a general methodology of going from real-world "InVivo" data collection back to "InVitro" research in the psychological laboratory. Using this approach, Dunbar has identified Analogy, Distributed reasoning, and focussing on the unexpected as key components of scientific creativity. The findings on Analogy and Distributed reasoning will be discussed in other sections of this entry. Here, I will focus on unexpected findings.

One of the most frequently mentioned aspects of scientific discovery is that a finding was due to chance or was unexpected. The recent discoveries of Naked DNA and Buckey balls are among the many significant discoveries that have been attributed to unexpected findings. Given that claims of unexpected findings are such a frequent component of scientists' autobiographies and interviews in the media, Dunbar (1995, 1997, 1999) decided to investigate the ways that scientists deal with unexpected findings. He spent one year in three molecular biology laboratories and one immunology laboratory at a prestigious U.S. university. He used the weekly laboratory meeting as a his source of data on scientific creativity as a number of discoveries and much creative thinking occurred at the meetings. When he looked at the types of findings that the scientists made, he found that over 50% of the findings were unexpected and that these creative scientists had evolved a number of important strategies for dealing with such findings. Thus, what Dunbar found is that rather than the unexpected being a rare event scientists must deal with unexpected findings virtually all the time. One of the most important places that they anticipate the unexpected is in designing experiments. They build many conditions and controls into their experiments. These multiple conditions

allow unknown mechanisms to manifest themselves. Thus, rather than being the victims of the unexpected, they create opportunities for unexpected events to occur, and once these events do occur, they have specific reasoning strategies for determining which of these events will be a clue to a new discovery. They focus on the method, using analogies to very similar experiments on the same types of organisms, and only after repeated demonstration of the unexpected event, will they switch to the use of new theoretical explanations using more distant analogies and generalizations. Creative Scientists are not passive recipients of the unexpected, but actively create the conditions for discovering the unexpected and have a robust mental toolkit that makes discovery possible.

IV Experimental work on scientific Creativity

Experimental Cognitive research on scientific creativity has tended to fall into two broad classes of investigations. The first class is concerned with the types of reasoning that lead scientists astray and blocks scientific creativity. A large amount of research has been conducted on the potentially faulty reasoning strategies that scientists use such as considering only one hypothesis at a time and how this prevents the scientists from making discoveries. The second class is concerned with uncovering the mental processes underlying the generation of new scientific hypotheses and concepts. This research has tended to focus on the use of analogy and imagery in science as well as the use of specific types of problem solving heuristics.

Turning first to investigations of what diminishes scientific creativity, philosophers, historians, and experimental psychologists have devoted a considerable amount of research to a type of creativity block known as "Confirmation Bias." This is where scientists only consider one hypothesis and ignore other hypotheses. This important phenomenon can distort the design of experiments, formulation of theories and interpretation of data. What psychologists have repeatedly shown is that when subjects are asked to design an experiment to test an hypothesis they will design experiments that they think will yield results consistent with the hypothesis. This confirmation bias is very difficult to overcome. Even when subjects are asked to consider alternate hypotheses they will not conduct experiments that could potentially disconfirm their hypothesis. Tweney and his colleagues provide an excellent overview of this phenomenon in their classic monograph "On Scientific Thinking" (1982). The precise reasons for this type of creativity block are still widely debated. Researchers such as Michael Doherty at Bowling Green University have argued that working memory limitations make it difficult for people to consider more than one hypothesis. Consistent with this view, Dunbar & Sussman (1995) have shown that when subjects are asked to hold irrelevant items in working memory while testing hypotheses, the subjects will be unable to switch hypotheses in the face of inconsistent evidence. While working memory limitations are involved in the phenomenon of confirmation bias, even groups of scientists can also display confirmation bias. For example the recent controversies over cold fusion and whether a meteorite that landed on earth shows signs of life having existed on Mars are examples of confirmation bias. In both these cases, large groups of scientists had other hypotheses available to explain their data, yet maintained their hypotheses in the face of other more standard hypotheses. Clearly, factors such as motivation and commitment to hypotheses are at work here. Mitroff (1977) provides some interesting examples of

NASA scientists demonstrating confirmation bias that highlights the roles of commitment and motivation in confirmation bias.

Turning now to processes that have been claimed to enhance scientific creativity of the most widely mentioned psychological processes is analogy. Many scientists have claimed that the making of certain analogies was instrumental in their making a scientific discovery and almost all scientific autobiographies and biographies feature an important analogy that is discussed in depth. Coupled with the fact that there has been an enormous research program on analogical thinking and reasoning, we now have a number of sophisticated models and theories of analogical reasoning that show exactly how analogy can play a role in scientific discovery. Boden (1993) provides an excellent summary of different theories of analogical reasoning and how they can be applied to different scientific discoveries. Furthermore, Holyoak & Thagard (1995) have an interesting chapter entitled the Analogical scientist which gives a history of the use of analogy in scientific discovery. Accounts of analogy distinguish between two components of an analogy; the target and the source. The target is the concept or problem that the scientist is attempting to solve or explain. The source is another piece of knowledge that the scientist uses to understand the target, or explain the target to others. What the scientist does when he or she makes an analogy is to map features of the source onto features of the target. By mapping the features of the source onto the target new features of the target may be discovered, or the features of the target can be rearranged so that a new concept is invented and a scientific discovery is made. One frequently mentioned analogy in the history of science is Rutherford's analogy of the structure of the solar system and the structure of the atom. In this case, the target was the atom and the source was the solar system. Rutherford ostensibly mapped the idea that the planets revolve around the sun onto the atom and argued that the electrons revolve around the nucleus. Thus, a number of historians have argued that by drawing an analogy to the solar system, Rutherford was able to propose a new account of the structure of the atom. By mapping the feature of the planets revolving around the sun, Rutherford was able to align his data with those predicted by a solar analogy. According to this view, the analogy resulted in a major restructuring of his knowledge and a scientific discovery was made.

The process of making an analogy involves a number of key steps (1) retrieval of a source from memory, (2) aligning the features of the source with those of the target, and (3) mapping features of the source onto those of the target. Scientific discoveries are made when the source highlights a hitherto unknown feature of the target or restructures the target into a new set of relations. Interestingly research on analogy has shown that subjects in psychology experiments do not easily use analogy (see Gentner et al. 1996, Holyoak & Thagard 1995). Subjects tend to focus on the sharing of superficial features between the source and the target, rather than the deep structural features, such as the feature of "revolving around" in the Rutherford analogy. The difference between the scientists and the subjects in experiments is that the scientists have deep structural knowledge of the processes that they are investigating and can hence use this structural knowledge to make analogies. Subjects in psychology experiments rarely have the structural knowledge and instead focus on superficial features of problems.

Most accounts of the use of analogy in science have focussed on situations where the source and the target are from radically different domains. However using the "InVivo" approach outlined above, Dunbar (1995, 1997) has found that most analogies that scientists use, even when they are making an important discovery, are from related domains, rather than widely different domains. Dunbar found that few analogies were made to radically different domains. This data shows that analogy is indeed important, but that the ways that analogies are used vary, both as a function of the goals of the scientist and their current state of knowledge. Dunbar found that when scientists are formulating hypotheses, they tend to make analogies to related domains, However, when they initially attempt to account for unexpected findings, they use analogies to highly similar experiments. Their use of analogy changes when they receive patterns of unexpected findings. Here they draw analogies to related domains. Dunbar also found that many different analogies are involved in a scientific discovery. Thus, rather than one analogy restructuring the scientists' knowledge a whole series of analogies could be used. A further aspect of analogy was that the scientists usually forgot the analogies that they had made, even when these analogies resulted in a scientific discovery. In fact, in post lab meeting interviews the scientists rarely remembered the analogies that were generated during the meeting. Thus, analogies are often used as a scaffolding that the scientists use in the construction of new theories and methodologies. Once the new concepts and methods have been advanced the analogy can be discarded.

One important goal for accounts of scientific creativity has been to provide an overarching framework. One framework that has had a great influence in Cognitive Science is that Scientific thinking and discovery can be conceived as a form of problem solving. Simon (1977) argued that both scientific thinking in general and problem solving in particular can be thought of as a search in a problem space. A problem space consists of all the possible states of a problem and all the operations that a problem solver can use to get from one state to the next. According to this view, by characterizing the types of representations and procedures that people use to get from one state to another it is possible to understand scientific creativity. Thus, scientific creativity can be characterized as a search in various problem spaces (Simon 1977). As discussed above Simon has used this approach to describe the ways that Krebs discovered the Urea cycle. Klahr and Dunbar (1988) extended this approach and proposed that scientific thinking can be thought of as a search in both an hypothesis and an Experiment space. In a similar vein other researchers have argued that another important problem space that scientist must reason in is a data space. Each problem space that a scientist uses will have its own types of representations and operators used to change the representations. The contribution to creativity research that this approach has made is to identify the strategies or heuristics that are used to generate new theories, models and explanations.

V. Beyond the Lone Scientist

The classic image of science is one lone, balding white male peering into a test tube. Scientists often pose for photographs alone, and their biographies usually stress their individual contributions to a scientific discovery; the contributions of other collaborators take a secondary role. Along with other areas of creativity, this type of story of the lone

genius is now being called into question. Thus, just as in other areas of creativity (see Amabile 1983, Csikszentmihalyi & Sawyer 1995), the scientist is now seen as part of a social group that has a very important role in the creative process. In his "InVivo" investigations of groups of scientists reasoning at lab meetings, Dunbar (1995, 1997, 1999) has found that much of the creative aspects of science such as the generation of new concepts and theories takes place in groups and that the reasoning in these creative moments is distributed over individuals rather than residing in one individual. One way distributed reasoning works is for one scientist to perform one type of cognitive process such as an induction and another scientist perform another cognitive operation such as a deduction to build a new theory or model. Sometimes one scientist will add one fact to an induction and another scientist will add another fact, and a yet a third scientist may make a generalization from the two facts. This type of distributed reasoning frequently occurs when a series of unexpected findings is obtained and can be key to many creative moments in contemporary science. Dunbar has found that the composition of the group can have radical effects on distributed reasoning. When all members of a group are from the same background, the group is little better than the lone scientist. What happens in distributed scientific reasoning is that many different representations of an issue are generated, allowing the scientists to look at problems from multiple perspectives. This helps ameliorate one of the major problems that lone scientist suffer from - generating alternate hypotheses and models to the ones that they currently have

VI. Where is research on Scientific Creativity headed?

While much is known on certain components of scientific creativity, much remains to be discovered. In particular, there has been little contact between cognitive, social, personality, and motivational accounts of scientific creativity. Clearly these different aspects of the creative process need to be combined to produce a truly comprehensive picture of the creative scientist. One way that a comprehensive account of the creative scientist can be achieved is by using the InVivo/InVitro method outlined above. Yet another way of achieving more comprehensive models of scientific creativity is through cognitive neuroscience investigations of creative scientists. The emergence of the field of cognitive neuroscience is already having an impact on creativity research with there being a number of studies of brain activation of creative pianists and conductors using brain scanning techniques such as PET, fMRI, and ERP. Similar studies of the important components of scientific creativity such as the use of analogy, hypothesis testing and deductive reasoning are currently taking place. Rather than being the latest attempt in reducing creativity into a physiological process, these new techniques may make it possible to understand how cognitive, motivational, personality, and even social processes combine in the living brain to produce scientific discoveries. This new synthesis has the potential to not only give a more complete picture of scientific creativity, but can make it possible to educate future scientists in ways of making scientific discoveries.

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Glossary

InVitro/InVivo Cognition

InVivo refers to investigating scientists as they think and reason in naturalistic settings such as lab meetings. In Vitro refers to investigating scientific thinking abilities of subjects in controlled experiments. The InVivo InVitro distinction is borrowed from biology. In biology, InVivo usually refers to investigating a biological process in the live organism, whereas InVitro refers to investigating some aspect of the organism, often in a test tube or petri dish.

Confirmation bias

Confirmation bias is the tendency that people have to seek evidence that confirms their hypothesis rather than seek evidence that could disconfirm their hypothesis.

Problem Space

A problem space is all the possible states that a problem could have as well as all the operations that can be applied to get from one state in the problem space to another state.

Distributed Reasoning

Distributed reasoning is when different components of a reasoning episode are conducted by different people rather than being conducted by one person.