Scientific Thinking and its Development

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Scientific thinking refers to the thought processes that are used in science, including the cognitive processes involved in theory generation, experiment design, hypothesis testing, data interpretation, and scientific discovery. Many of these aspects of scientific thinking involve cognitive processes that have been investigated in their own right, such as induction, deduction, analogy, expertise, and problem solving. Research on scientific thinking uses many different methodologies such as analyzing historical records, conducting experiments on subjects that are given scientific problems, and building computer programs that make discoveries. Many researchers have noted that, like scientists, children must form theories and test their theories against the world. Research on the development of scientific thinking has been concerned with discovering how children design experiments, the ways that theory and data are linked together by children, and describing children's theories of the natural world and science. There has been a tremendous amount of research on scientific thinking over the past forty years. One way of classifying research in this area is in terms of experimental, computational, and real-world investigations of scientific thinking. Other important areas not covered in this entry are historical and philosophical approaches to scientific thinking (See Nersessian, 1992; Thagard, 1992 for research in these areas).

Experimental Approaches

The hallmark of experimental investigations of scientific thinking has been to take one aspect of scientific thinking that is thought to be important and investigate it in the laboratory. The three aspects of scientific thinking that have been most actively investigated are problem solving, hypothesis testing, and concept acquisition.

Scientific thinking as problem solving. According to this view, scientific thinking can be characterized as a search in various problem spaces (Simon 1977). Simon has investigated a number of scientific discoveries by bringing subjects into the laboratory and getting them to rediscover a scientific concept (Qin and Simon 1990). He has then analyzed the verbal protocols that subjects generate and mapped out the types of problem spaces that the subjects search in (such as a space of possible mathematical functions). In a similar vein, Klahr and Dunbar (1988) characterized scientific thinking as a search in two problem spaces, an hypothesis space and an experiment space. The goal of the researchers using this approach has been to identify the types of search strategies or heuristics that scientists use.

Scientific thinking as hypothesis testing. Many researchers have regarded hypothesis testing as a core attribute of scientific thinking. Much of this work is based on Karl Popper's idea that the best way to test a hypothesis is to attempt to disconfirm the hypothesis. Using this approach, researchers have found that subjects usually try to confirm their hypotheses rather than disconfirm their hypotheses. That is, subjects will conduct an experiment that will generate a result that is predicted by their hypothesis. This is known as confirmation bias. Many researchers have shown that it is very difficult to overcome this type of bias. Mynatt, Doherty, and Tweney (1977) devised a task in which subjects had to conduct experiments in an artificial universe and found that subjects attempt to confirm their hypotheses. Dunbar (1993) has found that while subjects do try to confirm hypotheses, their hypotheses will change in the face of inconsistent findings. Klayman has argued that people possess a positive test bias - people attempt to conduct experiments that will yield a result that is predicted by their current hypothesis, and that under certain circumstances, this is a good strategy to use (Klayman & Ha, 1988). Summaries of work on hypothesis testing can be found in Tweney, Doherty, & Mynatt (1981) and Gorman (1992).

Scientific thinking as concept discovery. Many researchers have noted that an important component of science is the generation of new concepts and modification of existing concepts. Starting with Bruner, Goodnow, and Austin (1956) many researchers focused on the idea that scientists must formulate new concepts and theories. While the Bruner et al. work focused on strategies that are used to generate new concepts, later work focused on the ways that scientific concepts are represented and change with expertise (Chi, Feltovitch, & Glaser 1981). There has also been a considerable amout of work on conceptual change – the radical restructuring of concepts in science (Brewer & Samarapungavan 1996; Carey 1985. This research has shown the types of external events that preceed conceptual change and the ways that scientific concepts change over time.

Experimental approaches to the development of scientific thinking. Many researchers have noted that children are like scientists; they have theories, conduct experiments and revise their theories. Thus, while most researchers agree that scientists and adults have much more complex knowledge structures than children, the developmental question has been whether there are differences between children and adults abilities to formulate theories and test hypotheses. Inhelder and Piaget (1958) demonstrated that children of different ages have different abilities in testing hypotheses and interpreted their results in terms of Piaget's stage theory. While early research focused on different stages in the development of scientific thinking, the idea of stages has largely disappeared from recent theorizing on this issue. Some researchers such as Deanna Kuhn (1989) have demonstrated differences in the ability of children to design experiments at different ages. Other researchers, such as Sodian, Zaitchik, and Carey (1990), have shown that even young children can design good experiments that test hypotheses. Klahr, Fay, & Dunbar (1993) have argued that when a scientific thinking task involves searching in one problem space, few if any developmental differences will be found, but if the task involves use of a number of problem spaces, then there will be developmental differences. More recent research, such as that of Schauble (1996), has tracked children's ability to test hypotheses over extensive periods of time and found that children's experimental design strategies . Research on children's theories of biological mechanisms reveals that pre-schoolers have coherent representations of many biological processes (Wellman and Gelman, 1997). Overall, recent research on the development of scientific reasoning indicates that, once amount of knowledge is held constant, few radical differences between children and adults abilities to test hypotheses and design experiments.

Computational Approaches

Computational approaches provide specific models of the cognitive processes underlying scientific thinking. Early computational work consisted of taking a scientific discovery and building computational models of the reasoning processes involved in the discovery. Langley, Simon, Bradshaw, and Zytkow (1985) built a series of programs that simulated discoveries such as those of Copernicus and Stahl. These programs have various inductive reasoning algorithms built into them and when given the data that the scientists used, were able to propose the same rules. Computational models since the mid 1980's have had more knowledge of scientific domains built in to the programs. For example, Kulkarni and Simon (1988) built a program, with much knowledge of biology and experimental techniques, and simulated Krebs' discovery of the urea cycle. The incorporation of scientific knowledge into the computer programs has resulted in a shift in emphasis from using programs to simulate discoveries to building programs that are used to help scientists make discoveries. A number of these computer programs have made novel discoveries. For example, Valdes-Perez's (1994) has built systems for discoveries in chemistry, and Fajtlowicz has done this in mathematics (Erdos, Fajtlowicz & Staton, 1991). See Darden (1997) for a summary of work on computational models of scientific discovery.

Real-World Investigations of Science

Most psychological research on scientific thinking has been based on implicit assumptions and preconceptions about what is important in scientific thinking. Other than historical records and scientists' recollections, little is known about what scientists really do in their research. Thus we do not know how relevant the cognitive processes investigated by cognitive scientists are to real-world science. Using techniques from verbal protocol analysis, Dunbar (1995, 1997) has analyzed the “on-line” thinking of molecular biologists and immunologists as they work in their laboratories. These data include a number of important scientific discoveries that occurred "on-line." He has found that much of the scientists’ reasoning is concerned with interpreting unexpected findings. In fact over 50% of the findings that the scientists obtained were unexpected. As a consequence, scientists have developed specific strategies for dealing with unexpected findings that are very different from the strategies seen in the hypothesis testing literature. Dunbar has also found that scientists use analogies from similar – rather than dissimilar- domains in proposing new hypotheses . Furthermore the scientists distribute reasoning among members of a laboratory. For example, one scientsist may add one fact to an induction, another scientist add another fact, and yet a third scientist might make a generalization over the two facts. This type of research on real-world science is now making it possible to see what aspects of scientific thinking are important. By fusing together findings from real-world science with the results of the more standard experimental methods, it should be possible to build detailed models of scientific thinking that, when implemented, can be used by scientists to help make discoveries.

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