Creating Scientific Concepts

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Preface

There are moments of profound insight in science, when, in what seems a blinding flash of conceptual change, the very way we think about the natural world is altered. How do such conceptual innovations arise—what cognitive mechanisms underlie such innovations? This book will argue that, contrary to the popular image of science, such novel concepts do not emerge from the minds of their originators as Athena from the head of Zeus—fully developed and ready to do their intellectual work. Rather, such conceptual innovation, like perfect orchids and flavorful grapes, emerges from lengthy, organic processes, and requires a combination of inherited and environmental conditions to bud and bloom and reach full development.

Very little is understood about the creative thinking that leads to conceptual innovation, and how it achieves its novel outcomes. These creative processes are often thought to be mysterious and unfathomable. Those who study the records of such creations, however, offer a different characterization. Novel concepts arise from attempts to solve specific problems, using the conceptual, analytical, and material resources provided by the cognitive-social-cultural context in which they are created. They are located within "problem situations." So, to understand creativity, it must be located not in the act but in these problem-solving processes. Focusing on the creative act, instead of the process, would be like trying to understand the rainbow by looking carefully at what goes on in a drop of water:

> It is not that rainbows aren't made of drops of water, but simply that rainbows don't exist inside drops—they exist only when one takes into account other aspects of the environment of the drop: the direction of a light source, the position of other drops of water, and the position of observers. (Edwin B. Holt, quoted in Reed 1996)

In this spirit, my earlier investigation of conceptual change examined the field concept from Faraday to Einstein, and described the processes leading to the four major field concepts of that period, including also those of Maxwell and Lorentz. This analysis showed in detail how each concept came about through attempts to solve specific problems, and located each scientist within his problem situation. The focus of that research was the so-called *problem of incommensurability*, and its associated problem of the rationality of scientific change. I argued that these philosophical problems are artifacts of the framing of change, in a way that just compared the endpoints of a long process, and did not take into account the fine structure in between. For instance, the passage from the Newtonian concepts to those of relativity theory involved, among others, numerous developments in electromagnetic theory. Many philosophical problems dissolve when one examines the fine structure of the transitions between theories, where the various conceptual developments can be seen to be reasoned responses to particular problem situations.

My investigation of the processes leading up to the field concept highlighted another aspect of the creative process—that, in problem solving leading to conceptual change, the use of analogies, imagistic representations, and thought experiments work hand in hand, first with experimental investigations and then with mathematical analyses. By way of conclusion—and bolstered by a number of case studies across the sciences in which these practices are implicated—I hypothesized that rather than mere aids to thinking, these were powerful forms of reasoning, "model-based reasoning," and I posed the question of how they accomplish this intellectual work. That is, how do they generate novel conceptual representations?

There are many thick descriptions of periods of conceptual change, and they establish the prevalence of model-based reasoning in such periods. To borrow a concept from ethnographic analysis, model-based reasoning transfers across numerous cases from numerous domains. More case studies will not provide an answer to the question. What is needed instead is an investigation into the kinds of reasoning that underlie conceptual innovation. That is what I seek to provide in this book.

The nature of creative thought in science has been addressed in history, philosophy, and the cognitive sciences. Although each of these fields brings indispensable insights and methods to bear on how the creative mind works, the fine structure of creative processes is multidimensional, and explanation requires an interdisciplinary approach, one that uses methods, analytical tools, concepts, and theories from all these areas. Historical records provide the means to examine the processes and developments of authentic practices, as do ethnographic observations. They record the development of investigative practices, and provide significant clues as to how novel conceptual developments have come about. Cognitive science investigations aid in aligning these practices with those that non-scientists use to solve problems and make sense of the world, as scientists are not the only ones to solve problems using reasoning strategies such as analogy, imagery, and mental simulation. People involved in mundane problem solving resort to them as well, though not as part of an explicit, well-articulated, and reflective methodology ("metacognitive awareness"). Scientists' use has developed out of these ordinary human cognitive capabilities ("continuum hypothesis"), and thus research into these problem-solving heuristics by the cognitive sciences provides resources to tackle the more elaborate and consciously refined usage by scientists.

The method used in my analysis is thus "cognitive-historical," drawing on cognitive science research to understand the basis of the scientific practices, and reflecting back into cognitive science many considerations that arise in analyzing scientific problem solving. Cognitive science, however, does not provide interpretations and theories that can simply be adopted to explain the scientific practices. By and large it does not study problem solving of the complexity, sophistication, and reflectiveness seen in scientific thinking; thus science provides a novel window on the mind. Further, cognitive processes are most often studied in isolation from one another, such that the research on analogy, imagery, mental modeling, conceptual change, and so forth, are not treated in an integrated fashion. In scientific problem solving, though, these processes are interwoven, making an integrative account imperative. To carry out this investigation of creativity in conceptual change has, thus, required my undertaking an integration of a cross-section of the pertinent research and analysis of foundational issues, as well as advancing new cognitive hypotheses. In achieving all this, the book contributes equally to cognitive science and philosophy of science.

Throughout the analysis offered here I use two problem-solving episodes—one historical (Maxwell) and one think-aloud protocol (S2)—as exemplars of the kinds of reasoning under investigation. For readers familiar with scientific practices in other areas, exemplars from those areas will readily come to mind. Thus, this investigation is not about Maxwell or "S2" per se, but about the kinds of creative reasoning the two cases exemplify. The goal is to understand the dynamic processes of model construction and manipulation as genuine reasoning and as leading up to conceptual innovation. This goal has required shifting the balance of the presentation toward foregrounding the fine structure of the creative modeling processes.

Establishing a cognitive basis for scientific practices, in a way continuous with everyday reasoning practices, does not explain the history of how and why the scientific practices were developed; nor does it explain away the philosophical problems about how they create knowledge. To the contrary, it sheds light on these, and opens new avenues of exploration. Notably, it makes us entertain seriously the possibility that the modeling practices of scientists are not "mere aids," but are in themselves ways of reasoning and understanding that are exploited both in creating and using theories—a core thesis of this book. This project, investigating how models figure in reasoning and facilitate reasoning about phenomena, adds a significant dimension to the growing philosophical literature on models, which largely focuses on the static, representational relations between models and targets.

The objective of the book is to develop a framework for understanding model-based reasoning in conceptual innovation, but the implications of the analysis extend beyond that specific topic. Conceptual innovation is a representational problem—how to represent the known information so as to enable satisfactory inferences that go beyond the target information at hand and lead to novel hypotheses for further investigation. Features of model-based reasoning, as will be shown in the following pages, prove particularly well suited to solving such representational problems.

A growing body of research shows model-based reasoning to be a signature practice of the sciences, and the analysis offered here sheds light on its wider usages within science. For my own research, it stands as a further step in a larger project of investigating how scientists create insights and understandings of nature through modeling—conceptual, physical, computational—and how cognitive, social, and cultural facets of these practices are fused together in scientific knowledge.