

Annotated Table Of Contents

Creative Model Construction in Scientists and Students: The Role of Imagery, Analogy, and Mental Simulation

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Fig. 15.4 Extreme case for imagery enhancement generated by subject: “It just seems to me as though it [a longer rod] would twist more...And again, now I'm confirming that.. As I bring my hand up closer and closer to the original place where I hold it, I-I realize very clearly that it will get harder and harder to twist.”

PART ONE: ANALOGIES, MODELS AND CREATIVE LEARNING IN EXPERTS AND STUDENTS

Chapter 1: Introduction: A Hidden World of Nonformal Expert Reasoning

This chapter motivates the study of nonformal methods experts use during the process of creative theory formation rather than those they display in polished articles after the fact, and describes the method of video taped think aloud protocols used in this study. The tapes capture scientifically trained experts in the act of: mentally performing imaginative spatial transformations such as deforming, cutting, and reassembling objects in novel ways; and generating creative analogies, extreme cases, explanatory models, and thought experiments. The book aims to document the fact that such methods are actually used in scientific thinking.

Section I: Expert Reasoning and Learning via Analogy

Later sections of the book argue that analogical reasoning can be centrally important in scientific insights and other processes involved in scientific model construction, so individual analogies are the main topic of the first section of the book. Case studies are presented showing experts generating analogies that help them understand a poorly understood system.

Chapter 2: Major Subprocesses Involved in Spontaneous Analogical Reasoning:

Most previous studies of analogy focus on cases where part of the analogy is provided and the subject is left to complete or utilize the analogy. This study documents the use of spontaneous analogies, where all parts of the analogy are formed by the subject spontaneously in response to a target problem. Four major subprocesses are identified in examples from protocols: generating the analogy, understanding the analogous case, gauging the validity of the analogy relation, and applying findings from the analogy.

Chapter 3: Methods Experts use to Generate Analogies

Protocols from ten experts solving an unfamiliar problem are examined and a large variety of spontaneous analogies (31) are identified in the solutions. *Associative access* is the standard method for analogy generation in most models of analogical reasoning. In contrast, in the present study the method of using a *transformation* of the target case was more common than generation via association. Some of the cases generated via transformations are of special interest as novel cases that are invented by the subject rather than recalled from memory.

Chapter 4: Methods Experts use to Evaluate an Analogy Relation

Once one generates an analogous case for a situation, how does one know whether the analogy is valid? The standard method of evaluating analogy relationships in previous studies is to use a mapping of discrete symbolic

elements between the base and the target of the analogy. This chapter identifies an additional "bridging" strategy, involving generating a second intermediate analogy. These appear in both science and mathematics solutions and may or may not depend on mapping as the only underlying process. The chapter also examines how these techniques were applied by Newton and a predecessor of Galileo. Ordinarily we associate creativity with hypothesis and analogy *generation*, but these bridging cases demonstrate that analogy *evaluation* can also be a very creative process.

Chapter 5: Expert Methods for Developing an Understanding of an Analogous Case and Applying Findings

In some cases one's understanding of the base of an analogy is insufficient and must be developed. This chapter discusses subprocesses involved in understanding the analogous case, and applying findings. It describes several possible ways of completing each of these processes.

Section II: Expert Model Construction and Scientific Insight

This section examines expert subjects in the act of model construction. The finding that analogies are a means by which key prior knowledge schemas can play a role in model construction provides an answer to the question of why expert subjects go to the trouble of using analogies when the effort is high and the payoff uncertain.

Chapter 6: Case Study of Model Construction and Criticism in Expert Reasoning

The extended case study in this chapter concerns a subject who goes through a significant conceptual change in modeling an unfamiliar system. It documents a central method for doing this: a model construction cycle of model generation, evaluation, and modification which is closely related to the hypothesis formation, criticism, and revision cycle sometimes referred to as "scientific method." Because subjects had virtually no access to new empirical information, these model evolution processes are largely non-empirical, in contrast to the empirical testing usually associated with scientific method.

Chapter 7: Creativity and Scientific Insight in the Case Study for S2

A powerful "Aha" episode is examined in order to judge whether to describe it as a "Eureka" event of extraordinary reasoning, or some more ordinary form of scientific thinking. This chapter provides an initial discussion of the role of insight and creativity in scientific thinking. The persistence of the subject's initial model and the observed tension between it and a perceived anomaly may be partially analogous to the persistence of a paradigm in the face of anomalies in science. An important function of the strategy of searching for analogous cases is that it may help the subject break away from such a persistent, but inadequate, model during an insight episode. Such a "mini-revolution" can occasionally complement the *evolution* cycle described in Chapter 6.

Section III: Nonformal Reasoning in Students and Implications for Instruction

Previous reports have emphasized differences between experts and novices with little attention given to processes they use in common. Evidence is presented which documents novice students spontaneously using some of the same reasoning and learning strategies as experts. Thus there are important similarities between experts and novices. Case studies of tutoring sessions are also presented where these processes are used to help students deal with deep-seated preconceptions.

Chapter 8: Spontaneous Analogies Generated by Students Solving Science Problems

Thirty-seven analogies produced spontaneously by a sample of 15 college freshmen while solving problems are analyzed. Several types of analogies are identified, including personal vs. physical analogies, and invented thought experiments vs. analogies based on authority or observation. Reasoning by analogy appears to be a natural form of reasoning for many beginning college students of the kind we interviewed. This suggests that analogies could be utilized in instruction to a greater extent than is currently done.

Chapter 9: Case Study of a Student Who Counters And Improves His Own Misconception by Generating a Chain of Analogies

This chapter analyzes a protocol from a college freshman who is able to spontaneously correct a difficult misconception on his own. He does this by generating a remarkable series of analogous thought experiments and extreme cases which argue for the correct view on the basis of other physical intuitions. In doing this, he

exhibits many of the same creative reasoning patterns as those that were documented in experts in the previous sections above. The richness of the issues surrounding this protocol suggests that rather than starting instruction with operational definitions and equations, it may be advantageous to raise a specific problem and consider analogies and intuitive arguments at a qualitative level first.

Chapter 10: Using Analogies and Models in Instruction to Deal with Students' Preconceptions (by John Clement and David Brown)

This chapter presents case study evidence that some of the strategies experts use to overcome conceptual difficulties in problem solving can be used in instruction to overcome the conceptual difficulties of students. It presents an analysis of two taped tutoring sessions with students who are able to overcome misconceptions in physics by considering and evaluating analogies and models suggested by the instructor.

PART TWO: ADVANCED USES OF IMAGERY AND INVESTIGATION METHODS IN SCIENCE AND MATHEMATICS

Section IV: Transformations, Imagery And Physical Intuition In Experts And Students

This section lays groundwork for the rest of the book by examining evidence for the use of spatial transformations, imagery, physical intuitions, and imagistic simulations in protocols.

Chapter 11: Analogy, Extreme Cases and Spatial Transformations in Mathematical Problem Solving by Experts

This chapter extends several of the findings of the previous chapters from the physical domain to the mathematical/geometric domain. Special attention is given to creative spatial transformations (such as deforming, cutting, and reassembling) used by experts to transform a difficult problem into an analogous, familiar problem or to reduce the problem to much simpler cases.

Chapter 12: Depictive Gestures and Other Case Study Evidence for the Use of Imagery in Scientists and Students

This chapter attempts to identify new types of evidence for imagery use from think-aloud protocols. An initial set of imagery indicators that also includes certain types of (depictive) gestures, is developed (see Fig. 15.4 above). Protocols are analyzed which provide evidence for the use of imagery and dynamic imagery, as well as for the importance of such processes to the solutions.

Chapter 13: Physical Intuition, Imagistic Simulation, and Implicit Knowledge

This chapter provides more evidence on the "presence and importance of imagery" question but also attempts to go beyond it by asking what generates the imagery. In contrast to some views of physics expertise, transcripts indicate that part of the knowledge used by expert problem solvers consists of concrete intuitions rather than abstract verbal principles or equations. They also suggest that such self-evaluated physical intuitions are based on perceptual motor schemas and that these intuition schemas can be used to generate predictive imagistic simulations, as a type of embodied knowledge. In some cases, implicit knowledge in an intuition schema can be tapped as previously undescribed expectations in the schema generate images that can be interrogated and described, thereby being converted to explicit knowledge. This analysis provides an initial foundation to address the fundamental question of how people can gain new knowledge by running a mental simulation.

Section V: Advanced Uses Of Imagery In Analogies, Thought Experiments, And Models

This section uses the findings from the previous section on imagery to analyze more deeply the more complex processes of analogy and scientific model construction. Components discussed include the use of imagistic simulation, spatial reasoning, imagistic transformations, thought experiments, and symmetry arguments.

Chapter 14: The Use of Analogies, Imagery, and Thought Experiments in Both Qualitative and Mathematical Model Construction by Experts

This chapter presents a composite dialogue of transcript excerpts that displays a surprisingly rich variety of qualitative and quantitative reasoning patterns used by experts to form progressively deeper understandings of a physical system. The dialogue illustrates the power of nonformal reasoning processes to gradually expand the modeling of the problem situation in five stages from initial tentative analogies and dilemmas to roughly explanatory models, then fully connected models, then geometric, and quantitative models. The methods include creative spatial transformations in highly focused and creative thought experiments that help discount

original models and develop the final model causally, geometrically, and finally quantitatively.

Chapter 15: Thought Experiments and Imagistic Simulation in Plausible Reasoning

Mechanisms for thought experiments are discussed in an attempt to explain the paradoxical ability to conduct such experiments in the head with conviction, as if they were real experiments. Previous historical work on thought experiments has hypothesized that they may play an important role in scientific discovery and evaluation. What has not been previously examined systematically are the underlying cognitive processes and the specific roles that thought experiments can play on the basis of analyses of expert think aloud protocols. In addition, the question of how thought experiments may utilize imagery, mental simulations, or mental schemas has not been sorted out. This chapter provides initial empirical grounding for a set of distinctive meanings for the concepts of 'untested thought experiment', 'evaluative Gedanken experiment', 'analogy', and 'explanatory model', and an analysis of how they each depend in different ways on imagistic simulation. The theory offers a description of several sources of conviction in such experiments that addresses the thought experiment paradox mentioned above (See Fig. 15.3 below). Several aspects of this imagery based theory receive further support from the phenomenon of *imagery enhancement* – in transcripts where experts actually create special cases in order to enhance their imagery.

Chapter 16: A Punctuated Evolution Model of Investigation and Model Construction Processes

Progressive layers of expert model construction in the composite protocol in Chapter 14 are explained by a larger three-part model of the scientific investigation process. The process can produce the five stages identified in Chapter 14 by coordinating the use of analogies, imagistic simulations, and Gedanken experiments. The process is described as an abductive and primarily evolutionary one rather than as simply inductive or deductive. A new stage, imagistic alignment for a fully connected mechanistic model, is analyzed that provides a bridge between qualitative and geometric modeling. Other passages show that many of the analogical, imagistic, modeling cycle, and thought experiment techniques used in qualitative modeling can have parallel counterparts in mathematical modeling. The investigation strategy also relies on a partially decentralized control process with modulated divergence that can account for occasional sudden insights (punctuated evolution).

Chapter 17: Imagistic Processes in Analogical Reasoning: Transformations and Dual Simulations

Using examples from expert protocols, this chapter describes the role of conserving transformations and dual imagistic simulations in the evaluation of analogies-- as possible alternatives to the classical mapping-based view of analogical reasoning. This includes evidence for "overlay simulations" in which the behaviors of two dynamic images are compared by overlaying one on the other. The use of imagistic transformations in generating and modifying analogies and models is also examined.

Chapter 18: How Grounding in Runnable Schemas Contributes to the Production of Flexible Scientific Models in Experts and Students

Integrating many of the previous findings in the book, the following hypothesis is proposed: a major reason that expert subjects put time and effort into risky analogical reasoning processes is to attempt to make their models runnable (dynamically imageable). Both expert and student transcripts are examined showing subjects grounding a model in more primitive schemata or source analogues that are already runnable. They appear to transfer dynamically imageable schema elements from a source analogue to a more general model, a process termed "transfer of runnability" that contrasts with discrete symbolic inference. It is suggested that dynamically imageable models lead to a number of important cognitive and scientific benefits, and that this provides reasons to see them as central to conceptual understanding in science for both experts and students.

Section VI: Conclusions

This section summarizes findings on expert nonformal reasoning that can lead to scientific discoveries. It also discusses the extent to which there are similar processes in students, and implications for education.

Chapter 19: Summary Of Findings On Plausible Reasoning And Learning In Experts I: Basic Findings

The largest questions addressed by this book are: How do experts form new theoretical models? How do creative insights occur? Basic findings from sections 1, 2, and 4 of the book in three areas that lay a foundation for answering these questions are summarized in this chapter. Experts exhibit the use of spontaneously generated analogies that can be novel and provocative; they can also exhibit more complex model construction cycles of generation, criticism, and revision that can produce both sudden insights and smoother evolutionary

periods (see Fig. 21.1 below). Five different functions of analogy are identified indicating that the relationship between analogy and explanatory model construction is more complex than commonly realized. Scientific insights are real and can be documented, but major aspects of them can be explained cognitively; for example the “evolution cycle” can break down when an expert gets “stuck” in an unproductive model but an analogy or visual transformation can help them break out of such a rut suddenly; this kind of pattern can be seen as “punctuated evolution”. This hidden world of qualitative and nonformal, but powerful reasoning processes contrasts with the image of scientists as abstract thinkers who use only formal logic and mathematics.

Chapter 20: Summary Of Findings On Plausible Reasoning And Learning In Experts II: Advanced Topics

This chapter summarizes findings on how the above reasoning processes can interact with imagistic representations to actually construct a new theory. Processes where imagery indicators were observed are described at several hierarchical levels: 1) individual imagistic simulations; 2) nonformal reasoning operations, such as analogy, that can utilize imagistic simulation; 3) larger model construction processes that utilize the nonformal reasoning operations. The chapter builds on these findings to propose possible advantages of imagistic representations for scientific theory construction. To name just a few: images have the ability to represent multiple spatial constraints simultaneously; grounding in imagistic simulation processes at the lowest level can percolate up to provide many advantages for the expert at the higher levels of scientific model construction and application; and once higher level models become grounded in this way, they in turn can become runnable building blocks for grounding and assembling even more sophisticated theories. The chapter proposes the hypothesis that the ability to generate mental simulations is what gives qualitative scientific models their power of flexibility in application and future growth as a form of adaptive expertise.

Chapter 21: Creativity In Experts, Nonformal Reasoning, And Educational Applications

The larger question of how experts used creativity effectively is discussed. Although nonformal reasoning modes are individually weak in the sense that they, unlike deductions, are not guaranteed to work or produce valid inferences from givens, they can combine in powerful ways to meet the challenge of fostering both creativity and validity at the same time during model construction. Diagrams illustrating the present view of creative model construction provide an image of a considerable number of nonformal processes that must work together in order for this to succeed (e.g. Fig. 21.1, 21.2 below). This system can be beautifully balanced and modulated in experts, so as to provide varying proportions of divergence—volatile divergence at an early stage or focused convergence in a later stage of a solution. The analysis of expert protocols leads to an expanded model of conceptual change processes in science. Similarities between novice and expert reasoning processes summarized along with other evidence indicating that these processes can be utilized in the classroom. Major implications include: using mental simulation, and imagistic forms of analogy, abduction, and model based reasoning to foster conceptual change and sense-making; and using model construction cycles as central to the development of students’ scientific inquiry skills. Finally, the data in this book reveal some expert processes one would not expect to see in laymen, but they do not point to processes that are unexplainable. Creative theory construction in talented experts is described as lying between the ordinary and the extraordinary; in some cases it is sophisticated and remarkable, even though it can be seen as a developed skill that had its origins in natural reasoning.

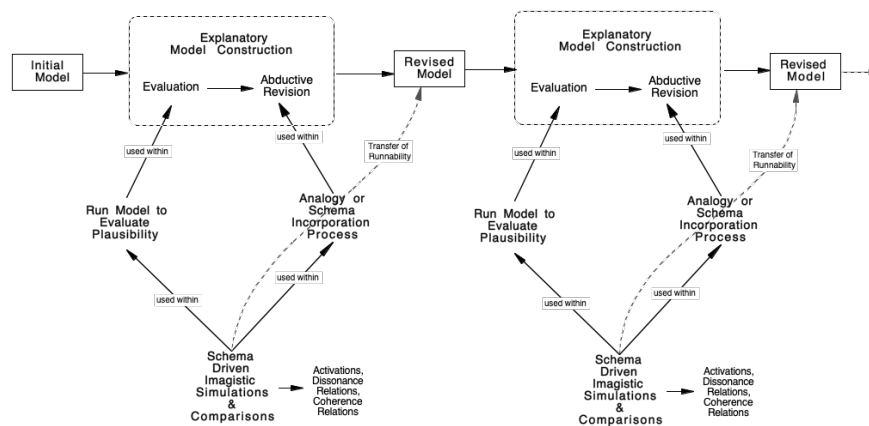


Fig. 21.1 Some major non-empirical subprocesses involved in explanatory model construction

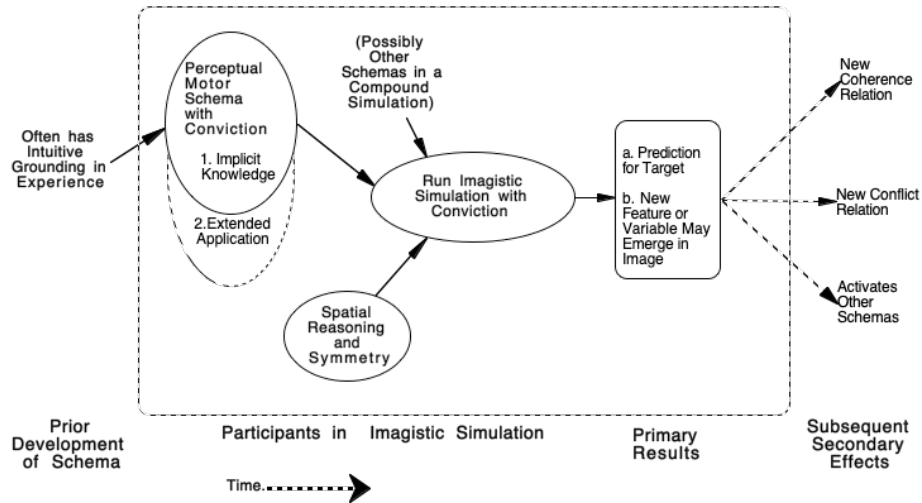


Fig. 15.3 Imagistic simulation process with possible benefits on the right and four origins of conviction on the left

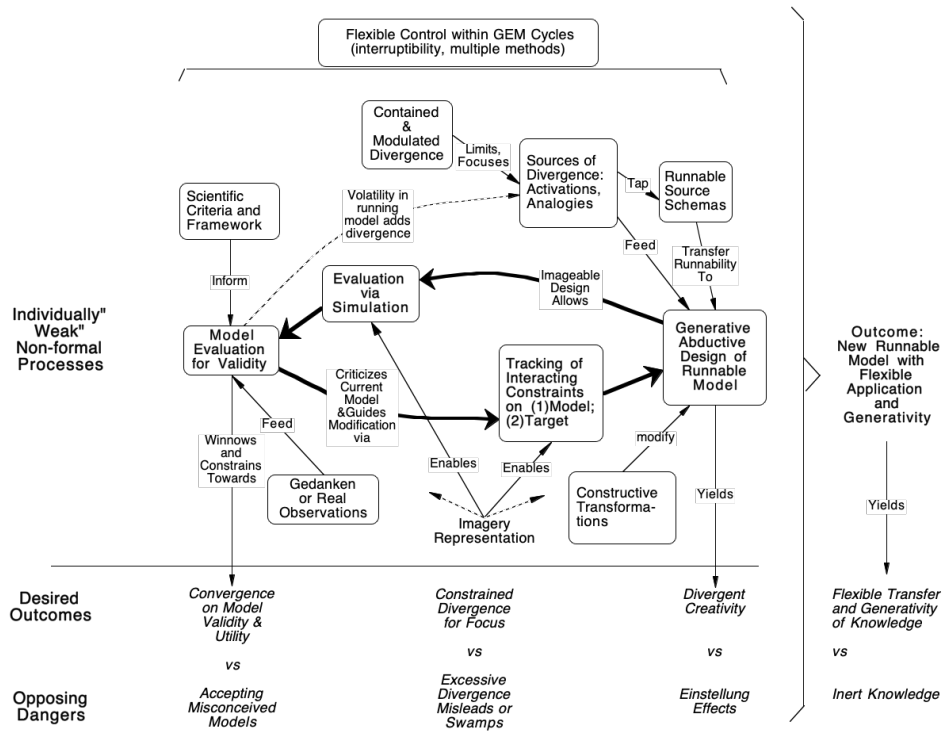


Fig. 21.2 A balanced system for productive creativity: how a coalition of seemingly "weak" non-formal methods can overcome the dilemma of fostering both creativity and validity during model construction