COGNITIVE MODELS AND ARCHITECTURES

In Order to Learn

HOW THE SEQUENCE OF TOPICS INFLUENCES LEARNING

EDITED BY

Frank E. Ritter
Josef Nerb
Erno Lehtinen
Tim O'Shea

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OXFORD SERIES ON COGNITIVE MODELS AND ARCHITECTURES

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To our families, who help us learn

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Foreword

David Wood

How can we explain our species' remarkable capacity to disseminate and propagate intellectual discoveries through generations and over time? For me, this is the most fundamental theoretical question that underpins and integrates the chapters offered in this volume. Deep divisions separate those theorists who have sought explanations in a selective, self-constructive, and self-evaluative learning process from theoretical positions that look to processes of spontaneous or intentional teaching as mediators of learning and rediscovery. Each of the two general positions is occupied by competing, special theories. These theories, in company with yet other approaches—ones that seek more integrated explanatory accounts of interactions between processes of learning and teaching—make for the complex conceptual and methodological landscape that this book explores.

The book's focus on the study of order effects in learning continues and advances a major methodological strategy for exploring this fundamental issue. Crudely, to the extent that the order and sequence of experience is crucial for learning and rediscovery (and to the extent that learners are unable to impose such ordering on their own learning environment), one is tempted to seek explanations in terms of an implicit or explicit pedagogy. Conversely, where order is irrelevant or of little account (or where learners are able to structure and evaluate their own environment to help optimize the learning process), one might take more seriously those theories that stress self-construction and autodidactics. Alternatively, of course, one might prefer to turn to learning theories that explain why sequential order is unimportant in the first place.

Added to the theoretical promise of research into order effects are potential educational applications afforded by a deeper understanding of sequential constraints on curriculum design. The book also contributes to this tradition with, for example, critical evaluations of and challenges to supposed "principles" of curricula organization found in contemporary educational settings.

Many chapters, the editors warn us, raise more questions than they answer. Some also generate empirical findings that either are less decisive or clear-cut than expected or seem impossible to reconcile with the hypotheses tested and theories advanced. Others generate unambiguous but intriguing and even counterintuitive outcomes that are worthy of future replication and extension into new learning contexts.

To give a flavor of these latter cases, I was struck by findings that, for me, gave rise to the following questions:

- How, when, and under what conditions is it possible for learners to learn from their own errors when they seem to lack the knowledge about how to be right?
- How can we explain a finding that implies that learning improves when learners impose their own order on the tasks to be learned—even when they change the order away from one found to benefit learning?
- How, why, and under what conditions can feedback to a learner that is actually based on a misconceived explanation of the phenomena they are attempting to understand enhance their learning more so than feedback based on a robust understanding of the phenomena?
- How should we conceptualize the nature of the relations between the processes underpinning original acts of discovery (such as the construction of a new and powerful theory) and those involved in subsequent learning (rediscovery?) by others about what has been discovered?
- Instructional support often seems to enhance learning best when it is contingent on learner problem solving, minimalist in content and offered in response to learner error or help request. This seems to apply not only to learning specific skills but also to learning strategies for regulating one's own learning. What kind of theory of learning can explain why learning should be enhanced by such attributes of instructional support?
- The idea that order effects might be optimized by sequences of tasks or assignments that become progressively harder has intuitive appeal. Under what conditions of learning might the idea prove false . . . and why?
- Why might the timing and spacing of learning activity that optimizes rapid learning be far from optimum in promoting the most enduring memorization of what has been learned?

I have drawn these questions from findings reported in this volume. These findings, when taken in company with other highlights found in the chapters that follow, do not exactly lend support to any one major theoretical position: In this sense, as the editors caution us, they spawn more questions than answers.

One has to ask whether and where the everyday connotations of natural language might mislead us to expect theoretical coherence across contexts that, though bound together under everyday uses of the verb "to learn" or "to discover," rest on quite different psychological processes, processes that might best be investigated using different empirical approaches. This book addresses such issues as an explicit part of its agenda and its rationale. The editors tell us that the volume has a self-conscious tutorial function. The inclusion of

- chapters that guide readers through the theoretical and empirical landscape
- efforts by the authors of each chapter to articulate questions, projects, or issues designed to support further thought and learning
- cross-referencing across chapters on key points

offer evidence of the authors' efforts toward these objectives. The result is a book that manages to explore the state of the art without trivializing the complexity of the challenges involved, one that also offers support to its intended readers as they try to meet the demands of such challenges.

Preface

The order that material, for acquiring both facts and skills, is presented or explored by a learner can strongly influence what is learned, how fast performance increases, and sometimes even whether the material is learned at all. This book proposes that these effects are more pervasive and important than we have previously believed. The chapters explore the foundational topics in this area at the intersection of psychology, of machine learning, of AI and cognitive modeling, and of instructional design. We inclued some case studies and numerous questions that should lead to further research projects and provide stimulation and encouragement for professionals working in areas such as education. In some ways, the chapters raise more questions than they answer.

This book will interest experimental psychology types, educational design folks, and machine learning aficionados, as well as cognitive scientists in general. The audience also inclueds graduates and practitioners of computer science (particularly AI and machine learning), psychology and cognitive science, and educational technology who are interested in order and learning. Readers may be potential researchers or informed consumers of future computing or instructional design products that support human learning or deploy machine learning techniques. This book is intended for those who are seriously interested in these issues and have some training or a strong interest in one of these fields.

Each chapter is self-contained and relatively short. They are directly accessible to at least one of the three types of readers that the book is designed for and should be useful for the others. We worked with the authors to help the book chapters integrate more like a textbook and to appear less like an edited conference collection. Many argue a surprising point of view on the importance or irrelevance of ordering or sequencing for instructional design domains and about human skill or machine learning mechanisms. Each chapter ends with clear conclusions, including generalizations, suggestions for action, and projects of various sizes. The book is also designed to be a source book for people at the early stages of their PhD. It has started to be used in this way.

HISTORY OF THE BOOK

This book arose out of a task force created as part of the Learning in Humans and Machines (LHM) project. Hans Spada was the leader of this European Science Foundation (ESF) initiative.

The research program was organized by means of five task forces on the following themes:

- representation changes in learning (Task Force 1, Kayser)
- learning with multiple goals and representations (Task Force 2, van Someren)
- learning strategies to cope with sequencing effects (Task Force 3, O'Shea and then Lehtinen)
- situated learning and transfer (Task Force 4, Bliss)
- collaborative learning (Task Force 5, Dillenbourg)

This book was discussed at several general meetings of the task force, including the first one in Milton Keynes, where Tim O'Shea put forward the idea of a highly edited, accessible book to serve as an introduction to order effects in learning. Over time, chapters were added by members of other task forces and by other prominent thinkers on learning. Thus, this book joins the other books produced by the other LHM task forces, including:

Learning in humans and machines: Towards an interdisciplinary learning science. Edited by P. Reimann and H. Spada. 1996. New York: Pergamon.

Modelling changes in understanding. Edited by D. Kayser and S. Vosniadou. 1999. New York: Pergamon.

Learning with multiple representations. Edited by M. W. van Someren, P. Reimann, H. P. A. Boshuizen, and T. de Jong. 1998. New York: Pergamon.

Learning sites: Social and technological resources for learning. Edited by J. Bliss, R. Sãljõ, and P. Light. 1999. New York: Pergamon.

Collaborative learning: Cognitive and computational approaches. Edited by P. Dillenbourg. 1998. New York: Pergamon.

PROGRAM STRUCTURE: THE TASK FORCES

Authors

The initial set of chapter authors were selected by the steering committee of the LHM special program to be members of a task force on the effects of task order on learning in humans and machines. Our task force's charge was to explore how the order in which learning tasks are performed affects the final outcome of learning. We were also to determine how each of the three areas of (a) psychology, (b) machine learning and cognitive modeling, and (c) instructional design can be fruitfully combined to understand and use order effects in learning tasks. Thus, cross-disciplinary results are common in the chapters. We invited members of other ESF task forces and other authors as appropriate who have a strong point of view on ordering and learning.

Other Acknowledgments

We would like to thank the members of the initial task force who were not able to contribute chapters but who contributed to our thinking and the design of the book: Eileen Scanlon, Nicolas Szilas, and Teresa del Soldato. Kurt VanLehn, Stellen Ohlsson, and Pat Langley supplied invaluable council on editing books, and Wally Feurzeig and Oliver Selfridge provided crucial support at the end of this process. Katharina Scheiter nudged us when we needed encouragement. Ying Guo offered valuable editorial assistance. We would also like to thank our senior editors, Tim O'Shea and Erno Lehtinen, for the guidance they gave us, as well as our editor at Oxford, Catharine Carlin, who was very supportive as we pulled this project together. We recommend her highly. Anonymous reviewers provided useful feedback on our book at the proposal stage, and Carlin helped us interpret and incorporate their suggestions. The graduate students in an advanced seminar on learning at Penn State (Mark Cohen, Joshua Gross, Sue Kase, Jong Kim, Andrew Reifers, and Bill Stevenson) made numerous useful suggestions on the first reading of the book as a whole. Final preparation of this book was performed with help from kind colleagues at TU/Chemnitz and Tufts when Ritter was on a gratefully received sabbatical from Penn State. Finally, thanks to our families and friends who supported us in this endeavor. In particular, we would like to thank Josef Krems and Pat Langley for advice and comments and Nicole, Colleen, Robert, Paul, and David. Finally, *Alles in Ordnung!*

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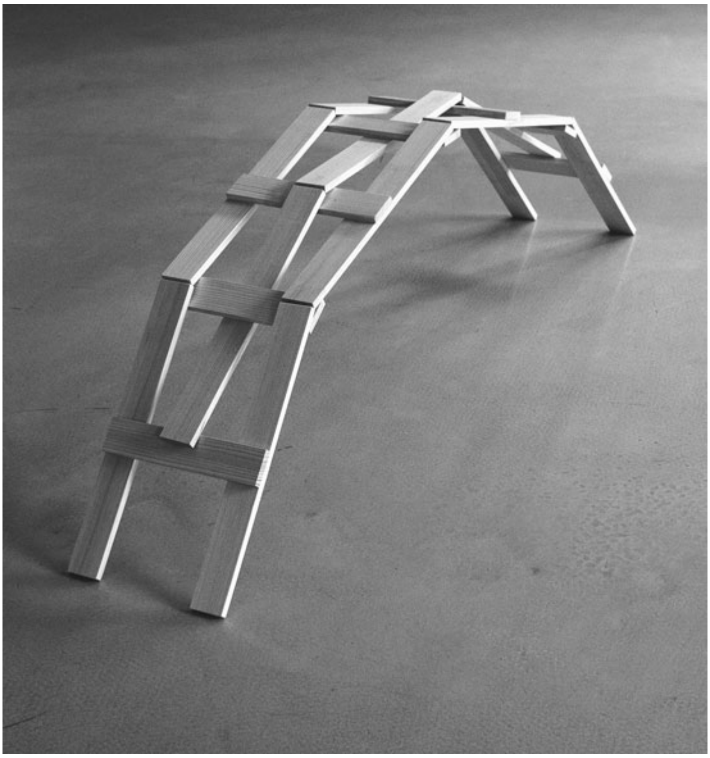
IN ORDER TO LEARN



Chapter 1

Call to Order: How Sequence Effects in Humans and Artificial Systems Illuminate Each Other

Frank E. Ritter
Josef Nerb

We start by describing and defining order effects and how they can be further developed. We introduce the first five chapters that provide overviews of the relevant areas of instructional design, machine learning, cognitive models (symbolic and connectionist), and human data. The second group of five chapters presents information processing models that predict order effects and, in many cases, provide supporting data. The final group of three chapters illustrates order effects empirically obtained (or not obtained) in educational settings. A concluding chapter pulls together the results and calls for further, more detailed exploration of order effects by using techniques and data across, rather than simply within, the relevant areas. The chapters in this book show that the order in which material is presented can strongly influence what is learned in a variety of domains in both humans and theoretical models of learning. From these chapters we compile suggestions for improving learning through the development of better sequences of learning materials, and we highlight some of the numerous questions that the chapters raise.

In medieval Europe, as part of a performance, artists built a bridge similar to the one shown in Figure 1.1. Building this bridge without nails or glue was a spectacular beginning to the performance and indeed an artistic one, for the artists then used the bridge as a stage. Leonardo da Vinci first analyzed the bridge's construction and discovered the design principles behind it. In so doing he moved the bridge from the realm of art into the realm of science: The bridge was explained by means of scientific methods so that its construction principles could be reused and not just imitated. Through this process the bridge's construction moved from art to technique.

ORDER STARTS HERE: INSTRUCTION FROM ART TO TECHNIQUE

A similar process is being performed today in instructional science; we want to uncover basic principles of instruction and learning that can be reused in different settings, moving instructional ordering from art to technique. Taking again the bridge example, what matters for the construction of the bridge is the right sequence in putting the pieces together. The correct sequence leads to success—a bridge; an incorrect sequence leads to failure—a heap of sticks.

This is true for learning as well. The order in which material is presented can strongly influence what is

FIGURE 1.1. The nailless bridge.

learned, how fast performance increases, and sometimes even whether the material is learned at all. This is true for both skills and facts and remains true whether the material is presented by an instructor or explored alone by a learner. The analogy to the bridge continues to hold true: In the same way as da Vinci's analysis of the bridge's construction moved it from art to science, as we discover the underlying principles of the order effects in learning, we move instruction away from idiosyncratic expression and closer to a controlled and predictable science.

This book presents the case that order effects are more pervasive and important than they have previously been treated, and it explores how learning order affects the final outcome of learning and how methods and findings from the range of cognate disciplines that study learning can be fruitfully combined to understand and improve learners' performance. We also include case studies and numerous questions that should lead to further research projects. These case studies and questions provide food for thought for professionals working in these areas, including professionals in education.

Order effects in learning brings together foundational topics and research in psychology, machine learning, AI, cognitive modeling, and instructional design. As a result, cross-disciplinary combinations and impact are common features in this book's chapters. To paraphrase Stellan Ohlsson's thoughts (from Chapter 11) on the implications of this research for all areas relevant to learning:

> Although several ordering principles for instruction are well established, such as the easy-before-hard principle, the existence of ordering effects in human learning poses more specific questions for research areas interested in learning. For example, in AI and machine learning, do different learning mechanisms make divergent predictions with respect to type and magnitude of ordering effects? If so, observations of such effects might turn out to be a hitherto underutilized source of empirical constraints on psychological learning theories and cognitive models. Is one combination of learning mechanisms more or less robust than another with respect to the sequencing of learning experiences? Better understanding of the relative strengths and weaknesses of different combinations of mechanisms might inform the design of machine learning systems. Finally, a deeper theory of ordering effects might allow us to go beyond the easy-before-hard principle for the sequencing of instruction.

In this chapter, after defining order effects and the intended audience for this book, we describe the chapters to introduce them, make some preliminary conclusions, and note open problems.

Definition of Order Effects

The definition this book uses when referring to order effects[1] is that they are differences in performance that arise from the same set of material being presented to learners in different orders (Langley, 1995). This strict definition of order effects explicitly excludes sets that are only nearly equivalent yet not equal. Multiple presentations of the same item are allowed, but both orders have to have the same number of presentations for them to be equivalent. This definition is consistent with its use in other areas (e.g., belief revision; see Hogarth & Einhorn, 1992).

Several chapters offer extensions to this basic definition of order. For example, Phil Pavlik Jr. reminds us in Chapter 10 that the times between presentations of stimuli are also important. Another extension is the exploration of near-order effects.

The Book's Intended Audience

Order effects are important to any field that explores learning, so we have this book to be accessible to a wide variety of readers. It should be directly accessible and of interest to researchers, practitioners, and students in the areas of cognitive science, machine learning and AI, and instructional design. It should also be useful for many related fields, including cognitive psychology, intelligent agents, and educational psychology. Teachers interested in learning theory should also find this book interesting and accessible. For example, many of these chapters and concepts speak to how to teach multiple-column subtraction and multiplication, including the multiple methods and sequences for teaching this early math skill currently in use in classrooms.

THE ORDER OF CHAPTERS

As this is a book about order, it should not surprise the reader that we had several discussions about how to order the chapters. We hope that the order we chose supports your reading. Several of the chapters show that high-knowledge learners will reorder material to suit their own needs, so we expect you will do so if necessary. To facilitate this adaptation process, the chapters begin with abstracts summarizing their contents. It is, however, important to keep in mind that many of the chapters interrelate and correlate, so you will also benefit from an exploratory reading process.

Orders of Order

One way to characterize and order the chapters is based on how they are tied to the various fields they address. This order is useful as a way to suggest how the fields are related. As a way to organize a book, however, it is does not work particularly well because it does not suggest where to begin or end. Research has also shown that the best way to organize instructional material is not necessarily the way it is organized in a learner's mental representation (McKendree, Reader, & Hammond, 1995).

We chose to organize the chapters into four groups: (a) introductory chapters that provide tutorial material, (b) chapters that describe models of learning that can provide explanations and predictions of order effects, (c) chapters that provide examples from educational settings, where students and teachers work to avoid bad orders and where order can be improved, and, finally, (d) a concluding chapter that summarizes the book.

The chapters are summarized in Table 1.1, which may help you with ordering your own reading. The third column, Fields, notes the most important fields that the chapter draws on, applies to, or both. Because most chapters have impact in several areas, in most cases these labels could have easily been shifted to similar fields such as educational psychology, artificial intelligence, and cognitive psychology, so they should be read somewhat broadly.

When a chapter speaks to a single task or uses several large examples, the Task column notes the tasks examined as an aide-mémoire; when a chapter reviews several tasks, it is noted in the Task column as "Review." While each chapter is based on at least one theory, the Model column indicates which chapters report computational models. Explicit instructional models for designing instructional sequences are noted as "IM." The Data column indicates where human data are presented in extended form. The Effect Size column indicates the largest effect size of different orders on learning reported in the chapter, from either theoretical predictions or empirical measurements as compared with the mean performance. This number may be one of several and may be approximate.

TABLE 1.1. The chapters, their authors, fields, approaches, and significant effect sizes (in percentages)

Title	*Authors*	*Fields*	*Task*	*Model*	*Data*	*Effect Size*
Introductory Chapters						
2. Order, first step to mastery	Reigeluth	InsDes	Review	No	No	NA
3. The necessity of order in machine learning	Cornuéjols	ML	Review	Several	No	NG
4. Rules of order	Nerb, Ritter, & Langley	CogSci	Review, choice reaction time	Simple Soar	No	25%
5. Order out of chaos	Lane	CogSci	Review, image recognition, and language learning	ART SRN	No	25% to ∞
6. Getting things in order	Ritter, Nerb, & Lehtinen	All	Review	No	No	NA
Models of Order						
7. An example order for cognitive skill acquisition	Renkl & Atkinson	InsDes	Instructional systems and InsDes	IM	Review	13%
8. An ordered chaos	Gobet & Lane	CogSci/ML	Grammar learning	EPAM	No	1,000%
9. Learning in order	Morik & Mühlenbrock	CogSci/ML	Learning the day/night cycle	Yes	Yes	30% to ∞
10. Timing is in order	Pavlik	CogSci	Word learning	ACT-R	Yes	11%
11. The effects of order	Ohlsson	CogSci/InsDes	Counting	HS	No	8%–223%
Empirical Studies						
12. Getting out of order	VanLehn	CogSci/InsDes	Multiplication	No	Yes	36%
13. Order or no order	Swaak & De Jong	InsDes	Electrical circuits	No	Yes	NS
14. Making your own order	Scheiter & Gerjets	InsDes/CogSci	Word problems (algebra)	IM	Yes	15%
Summary						
15. All is in order	Sweller	All	Review, paired associates	CLT	No	>70%

InsDes is instructional design. ML is machine learning. CogSci is Cognitive Science. NG indicates not given. NS is not significant. NA is not applicable.

Table 1.1 supports the conclusions that we draw below, for example, that order effects appear in many tasks. The table also shows that order effects are often large.

Section I. Introductory Chapters

There are five introductory chapters. They present the major concepts and areas, including instructional design, machine learning, cognitive science as represented by cognitive models, and empirical data gathering and preliminary analyses to study order effects. These chapters have been designed to be accessible to a wide range of readers.

2. *Order, First Step to Mastery*

Reigeluth's chapter provides an entry point for interested readers into the instructional design literature and introduces issues from this field. It shows how sequence effects relate to instruction and provides some introduction to an important context where order matters. Reigeluth reviews several of the major instructional design techniques for ordering instructional material, based on the nature of the content and their interrelationships. The chapter describes and discusses useful approaches to ordering material that fit the needs of instructional design in the field. These approaches support the development of new instructional methods beyond the ones presented here and help validate, illustrate, and teach these design principles.

The chapter gives special focus to the Elaboration Theory of Instruction, which was developed by Reigeluth in the last two decades. This theory provides holistic alternatives to the parts-to-whole sequencing that are quite typical of both education and training and synthesizes several recent ideas about sequencing instruction into a single coherent framework. The chapter closes with some general guidelines and principles for sequencing, organized by the order in which decisions need to be made.

3. *The Necessity of Order in Machine Learning: Is Order in Order?*

Cornuéjols provides a detailed introduction and overview of the theories from machine learning and introduces some of the basic theoretical concepts and models from computational studies of learning from the machine learning area of computer science. He presents ideas and directions of research that can answer questions that arise from order effects and shows that some of the results of how these models work may have significance for and counterparts in related disciplines that have an interest in learning and education.

Cornuéjols also notes some interesting new approaches in machine learning, including the concepts of helpful teachers and active learners. This chapter, like those that follow, concludes with a discussion of open research avenues, as well as questions designed to be used for class projects related to order effects in machine learning. A recent review (Selfridge, 2006) provides a related set of open questions in this area.

4. *Rules of Order: Process Models of Human Learning*

Nerb, Ritter, and Langley present the argument that, to understand sequential effects on learning in humans, we will have to have a rather complete theory of cognition—complete enough to perform a task like humans and to learn while doing so. Theories like this have typically been called *process models*. They are usually broken down into two components, architecture (the aspects of the model that do not change between tasks) and knowledge (the aspects that do change between tasks) (Newell, 1990). Where models have been used to understand sequential behavior and sequence effects on learning, they have proved to be very powerful. This chapter describes a simple, abstract model of a simple task that shows how an optimal order can lead to significantly (25%) faster learning than a poor order. This chapter also presents a list of effects in models of cognition that can give rise to order effects.

Although powerful, using models to study order effects remains difficult to apply routinely. Nerb et al. report some history and results on making this approach more tractable for application by presenting the idea of abstracted models.

5. *Order Out of Chaos: Order in Connectionist Models*

Lane provides details about order effects in neural networks, a commonly used modeling approach. The chapter examines two networks in detail, the Adaptive Resonance Theory (ART) architecture and Jeff Elman's recurrent networks. The ART model shows that about a 25% difference in recognition rates can arise from using different orders. Elman's recurrent network shows that, with the wrong order, a task might not even be learnable. This chapter also discusses why these effects arise, which is important for understanding the impact and claims of computational models (VanLehn, Brown, & Greeno, 1984).

6. *Getting Things in Order: Collecting and Analyzing Data on Learning*

Ritter, Nerb, and Lehtinen provide a tutorial on the types of data that have been used to study sequence effects, some of the data collection methodologies that have been and will continue to be used because they are necessary to study order effects, and how to use model output as data. They start by introducing the basic measurements typically used in experimental psychology, such as reaction times and errors. This chapter also examines the feasibility of using protocol data that, although used infrequently, offer a rich record to study order effects. These types of data include sequential records of subjects' eye movements, subjects' thoughts spoken aloud as they solve problems (verbal protocols), and records of task actions.

Ritter et al. also look at how these data can be "cooked down" into theories, which can then be broken down into static and dynamic process models. Static descriptions, such as simple grammars and Markov models, depict the shape of the data. Process models perform the task that a person does in a manner that a person does and so provide a more dynamic description. Process models are inherently not only more powerful but also more difficult to use. The chapter concludes with a brief discussion on using model output as data.

Section II. Fundamental Explanations of Order: Example Models

The next section of the book describes five models that predict order effects in a variety of domains. We present the models before the data chapters: As theories, the models have primacy over data. As summaries of data, they may help interpret the later, more data-oriented chapters.

7. *An Example Order for Cognitive Skill Acquisition*

Renkl and Atkinson review several learning theories that address the stages of skill acquisition, offer a model of instruction ordering to foster cognitive skill acquisition, and suggest some ways to provide better support for learning based on their model. In five experiments that explicitly test fading and example-problem pairs (Atkinson, Renkl, & Merrill, 2003, experiment 1; Renkl, Atkinson, & Große, 2004, experiment 2; Renkl, Atkinson, Maier, & Staley, 2002, three experiments), they found on average 13% more correct answers with better instructional orders.

Their review is used to create an approach to teaching by example, which is related to the literature on learning from self-explanations with decreasing levels of support as learners become more expert. Renkl and Atkinson's model is based on initially providing worked-out examples and gradually increasing the amount of work the learner is expected to perform, moving the learner toward working independently.

8. *An Ordered Chaos: How Do Order Effects Arise in a Cognitive Model?*

Gobet and Lane describe the details of EPAM, a theory of learning that arose early in the development of AI and cognitive science and has continued to be developed. Since its creation in the early 1960s, EPAM has been applied to a wide range of problems. Gobet and Lane describe EPAM as a type of unsupervised learning; that is, it learns without feedback as to what to learn or what is correct. They examine the application of a current version of EPAM to language acquisition, which shows that rather large order effects are possible. Their detailed examination of this learning mechanism allows them to find some lessons for instructional design, including the desirability of highlighting salient features of the material.

9. *Learning in Order: Steps of Acquiring the Concept of the Day/Night Cycle*

Morik and Mühlenbrock present a detailed model of children's explanations of where the sun goes at night. Knowledge of the day/night cycle is one of the first relatively complex sets of knowledge that all people acquire. Their model shows how children progress through a lattice of possible explanations (a lattice is a partially but not completely ordered set).

The task and data modeled offer an excellent basis for the investigation of order effects, with implications for modeling scientific discovery and for learning in general. It shows that some transitions are particularly difficult, that some transitions require using incomplete or incorrect knowledge, and that not all transitions are possible. Their work also shows that the order of learning can make a large difference in the amount that has to be learned and, perhaps more important, unlearned. Better orders provide about a 30% reduction in facts that have to be learned. These findings make suggestions about the instructional complexity that children and, presumably, learners in general can handle and about the use and importance of intermediate stages of learning.

10. *Timing Is in Order: Modeling Order Effects in the Learning of Information*

Pavlik examines another aspect of learning sequences by presenting a model that accounts for the effects of different times between stimuli presentations across subjects. Pavlik's model is tested within a simple language tutor that adjusts the spacing of material based on how well the stimuli are learned. This system does not strictly maintain the number of presentations but works to maintain equivalent presentation strength. This system is interesting in its own right because it shows that performance can be improved by reordering sequences with multiple presentations to provide more optimal spacing of stimuli.

Pavlik's model predicts that more widely spaced presentations lead to better overall learning. Finding the optimal spacing allows the learner to approach maximum learning with minimal time cost, but at a higher total-time cost. The model's predictions were confirmed experimentally: The model predicts about 11% better learning with the tutor (66% correct for the widest spaced vs. 73% for optimized spacing). The tutorial system led to a 12% average increase in performance for the optimized spacing condition, depending upon condition and phase of the study.

11. The Effects of Order: A Constraint-Based Explanation

Ohlsson presents a computational model that shows how information migrates from declarative to procedural knowledge and provides a powerful new learning mechanism for machine-learning algorithms. Ohlsson uses his model to examine the effects of learning three different counting tasks. The model predicts order effects that vary in several dimensions, including the number of times the model has to revise its knowledge and how long it will take to learn. Although some of these effects are quite large within a subtask, the overall effect is muted by other aspects of the task, including interaction. This model suggests that the complexity of a task's constraints is important for computing transfer between similar tasks. The model's behavior has been compared to human performance, and a general summary is provided.

Section III. Getting In and Out of Order: Techniques and Examples From Education and Instructional Design

The three chapters in this section explore order effects from experiments that represent educational settings. These experiments use a variety of techniques to look at how learners and their teachers modify and take advantage of the order in which learning materials are presented.

12. Getting Out of Order: Avoiding Order Effects Through Instruction

VanLehn reports two experiments that test his felicity-conditions hypothesis that people learn best if a task is taught one subprocedure per lesson. In these experiments, children were taught multiplication skills by a human tutor. Although there was a slight trend that presenting one topic per lesson led to fewer errors than presenting two topics, the more important finding is that there is better transfer to new problems when teaching two subprocedures per lesson—about one-third fewer errors at test (0.309 vs. 0.197 mean confusion rate per problem at transfer).

These results suggest that it is crucial to learn when to apply a particular element of knowledge. Lessons that deliberately change the element of knowledge needed from problem to problem are more difficult for learners but can enhance the learner's ability to apply different types of knowledge and to transfer their learning. This effect also suggests why textbooks have evolved to use one disjunct per lesson and is also consistent with good practice in system documentation (Weiss, 1991). This study further suggests not only that teaching multiple items per lesson is safer if there is someone to help remove any confusion but also that some small amount of reordering by a teacher can help the learner to compensate for poor orders.

13. Order or No Order: System Versus Learner Control in Sequencing Simulation-Based Scientific Discovery Learning

Swaak and de Jong present an experiment that examines how students study with an electrical circuit tutoring system that allows them to examine the relationship between current and voltage sources. Some learners were constrained in how they ordered the instructional materials, while others were allowed to choose their own order.

No major differences were found between the two groups for a range of measures and analyses, suggesting that further studies should include additional measures about what is learned besides definitions. The results also suggest that presenting model progressions and assignments will allow learners to choose their own order.

14. Making Your Own Order: Order Effects in System- and User-Controlled Settings for Learning and Problem Solving

Scheiter and Gerjets explore how order influences learning and transfer in algebra word problems and how students reorder the problems. They present two experiments in which learners were given different