

*In order to learn: How the sequences of topics affect learning.* (2007). Frank E. Ritter, Josef Nerb, Erno Lehtinen, and Tim O'Shea (eds). 3-15. Oxford University Press. NY, NY.

## **1 Call to order: How sequence effects in humans and artificial systems illuminate each other**

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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 present information processing models that predict order effects as well as provide supporting data in many cases. 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 and in both humans and theoretical models of learning. From these chapters we compile suggestions for improving learning through better sequences of learning materials and 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. 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.



**Figure 1. The nailless bridge.**

## **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 together the pieces. 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 learned, how fast performance increases, and sometimes, even that 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 Leonardo'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 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<sup>i</sup> 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: Hogarth & Einhorn, 1992).

Several chapters offer extensions to this basic definition of order. For example, Phil Pavlik, 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 created 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 will speak to how to teach multiple-column subtraction 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 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 describing 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, which may help you with ordering your own reading. The first 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-memoire*; 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 how to design instructional sequences are noted as "IM". The Data column indicates where human data is

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 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.

**Table 1.** The chapters, their authors, their fields, approaches, and significant effect sizes (in percent) discussed or reported. InsDes is instructional design. ML is machine learning. CogSci is Cognitive Science. ng indicates not given. ns is not significant. na is not applicable.

| <b>Title</b>                    | <b>Authors</b>           | <b>Fields</b> | <b>Task(s)</b>                                   | <b>Model</b> | <b>Data</b> | <b>Effect size</b> |
|---------------------------------|--------------------------|---------------|--|--------------|-------------|--------------------|
| <b>Introductory</b>             |                          |               |  |              |             |                    |
| 2. Order, first step to mastery | Reigeluth                | InsDes        | Review   | No           | No          | na                 |
| 3. Is order in order?           | 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                 |
| <b>Models of order</b>          |                          |               |  |              |             |                    |
| 7. An example order             | Renkl & Atkinson         | InsDes        | Instructional systems and Instructional design   | 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% to 223%         |
| <b>Empirical studies</b>        |                          |               |  |              |             |                    |
| 12. Order or no order           | Swaak & De Jong          | InsDes        | Electrical circuits                              | No           | Yes         | ns                 |
| 13. Getting out of order        | VanLehn                  | CogSci/InsDes | Multiplication                                   | No           | Yes         | 36%                |
| 14. Making your own order       | Scheiter & Gerjets       | InsDes/CogSci | Word problems (algebra)                          | IM           | Yes         | 15%                |
| <b>Summary</b>                  |                          |               |  |              |             |                    |
| 15. All is in order             | Sweller                  | All           | Review, paired associates                        | CLT          | No          | >70%               |

## **Section 1. 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 is the 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 that 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. Machine learning: The necessity of order (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 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 starts to create a list of effects in models of cognition that can give rise to order effects.

Using models to study order effects, while powerful, 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, the task might not even be learnable. This chapter also notes why these effects arise, which is important for understanding the impact and claims of computational models (VanLehn, Brown, & Greeno, 1984).

#### **6. Putting 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 start to 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, provide a description of 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 more powerful, but more difficult to use. The chapter concludes with a brief discussion on using model output as data.

## **Section 2. 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, and 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. Over 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: Sequences and mental structures**

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 Gobet and Lane 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 his 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 model of transfer and critiquing**

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 3. 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 1/3 fewer errors at test (0.309 vs. 0.197 mean confusion rate per problem at transfer).

These results suggest that a crucial skill to learn is 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 that teaching multiple items per lesson is safer if there is a tutor to help remove any confusion, and that some small amount of reordering by a teacher can help the learner to compensate for poor orders.

### **13. Order or no order: System vs. learner control in sequencing simulation-based discovery learning**

Swaak and De Jong present an experiment that examines how students study with an electrical circuit tutor 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 orders; in the second experiment learners could also reorder their problems.

Sequences that varied the structure of problems helped students learn more than sequences that only varied the cover story, suggesting that forcing learners to differentiate the types of problems fostered learning (c.f. VanLehn, Chapter 13, this volume). Learners who reordered their problems learned more, but only if they had sufficient domain knowledge, suggesting that allowing better learners to reorder their learning tasks might lead to deeper processing and thus more learning.

## **Section 4. Conclusions**

### **15. All is in order**

Sweller provides a useful overview and discussion of the chapters. He discusses and amplifies the results of each chapter using Cognitive Complexity Theory, a theory of how learning is constrained by the task's load on working memory capacity, and shows the effects that working memory load can have on learning with respect to order. The old maxim of ordering your reading of a text—that of first reading the introduction and then the conclusions—might be applied with some good effect in this case.

## **Themes within order**

The chapters in this book provide lessons for work in cognitive science, education, and machine learning including AI, and combining these areas to pursue theories of learning. Order effects occur

in many places and ways, both predicted and observed, and also on a number of levels of analyses, from single problems and stimuli to larger structures, such as hour-long lessons. They occur in a wide range of theories, including machine learning (Cornuéjols) and connectionist theories (Lane), larger scale learning theories like EPAM (Gobet & Lane), and constraint-based models (Ohlsson), and they do so for a variety of reasons. These effects have been established not only in the theories and data reported here, but also in prior reports of research.

Order effects are useful phenomena that help us explore, understand, and choose between learning mechanisms. Indeed, we can all imagine orders so bad that, as Morik and Mühlenbrock's and Gobet and Lane's models predict, the material cannot be learned at all because learners simply give up! Reordering thus offers a way to test and improve instructional design. We take up first the lessons and then the future research problems raised by these chapters.

### **Significant order effects are predicted**

Models in this book predict that the order in which materials are presented has a large impact on learning. With the ART model, Lane demonstrated up to a 25% difference in error rate. Ohlsson found differences of about 25% on transfer between learning different ways to count. Using a model based on an early Soar model, Nerb, Ritter, and Langley showed that different orders could lead to a 25% difference in learning. With the EPAM model, Gobet and Lane have approximately a 25% difference in percent correct between possible orders (approximately 30% correct for one order and less than 5% for the worst order), which represents almost an order of magnitude difference in performance. Their model also illustrates how different orders vary depending upon their use—retraining vs. learning for the first time. Morik and Mühlenbrock's model of learning the day-night cycle predicts differences of over 30% on some measures between different orders, which suggests real differences in learning and time to learn.

Previous models have also found order effects. Ohlsson (1992) created a model of subtraction using HS (the same architecture reported in Chapter 11) to examine different methods of performing and learning subtraction. For subtraction, HS predicted about 8% more procedural knowledge to be learned using one approach. Although this difference might not appear to be significant in an instructional setting, it is quite interesting that both approaches to learning subtraction were very sensitive to the training materials and their order. HS predicted that differences in learning and performance between combinations of approaches and training materials could be as great as 230%. Indeed, early work on modeling the instruction of subtraction focused on how to order tasks so that learners would always learn the correct rules rather than the

buggy ones (Brown & Burton, 1980). Similar results would be shown by Selfridge's (2006) Count system.

### **Order effects are found empirically**

Studies with people show similar effects of good and bad orders—order effects appear in a variety of materials and for a variety of subjects and tasks. As the effect-size column in Table 1 repeatedly shows, the order effects demonstrated in this volume are significant; they are large enough, in fact, to be important in most learning situations. Several of the chapters show how order effects can be tested and how to find them in empirical data.

Pavlik (Chapter 10) found an 11% difference in percent correct at test in subjects trained with a better, dynamic schedule. VanLehn (Chapter 13) examined a wide range of measures for two orders that differed in several ways and showed errors on later transfer ranging from 15% to 52% across orders. Scheiter and Gerjets (Chapter 14) found differences in performance on a variety of measures, such as error rate, where the better order had 10-15% fewer errors.

While we examine order effects in educational and learning settings, order effects can also occur in other areas. To choose one example, reviews and models of order effects in belief updating (Baumann & Krems, 2002; Hogarth & Einhorn, 1992; Wang, Johnson & Zhang, in press), find effects similar to those presented in these chapters (i.e., 5-20% differences between orders).

Previous studies of order effects are consistent with the results presented in this volume, and show that presentation order can have long-term effects. For example, Sweller (1976 and reviewed in his chapter) showed that the order for teaching word pairs could improve the rate of mastery to only 5.9 trials for each pair from 8.4. Moreover, when transferred to the alternate stimuli set, the group exposed to the better order learned the “bad” pairs in just over one trial, whereas the group first exposed to the bad order needed almost three trials to learn the “good” pairs. Depending on the measure chosen (learning, transfer, total), the better order improved learning time by 31-71%.

### **Order effects can help test theories**

Because order effects are both significant and pervasive, they can provide insights into the architecture of cognition. For example, simple normative descriptions of belief updating, such as those based on Bayes' theorem, do not exhibit order effects. And yet order effects often occur. The chapters that present models (Cornu jols; Nerb, Ritter & Langley; Lane; Gobet & Lane; Morik and M hlenbrock; Pavlik; Ohlsson) demonstrate how order effects can arise from cognitive architectures. Other models, for example UECHO (Wang et al., in press), use order effects to test

models as well. Confirming these order effects empirically will be important for building and testing cognitive architectures that learn.

### **Order effects have more aspects, including timing**

The models and studies presented here used many measures of learning and transfer. Examining the types of problems presented in more detail, as well as learners' performance on the component subtasks will be important for understanding both learning and the effects of sequences.

We have seen that the concept of order effects in learning can be developed further in several ways. For example, Pavlik (Chapter 10) explores the pace at which items are presented, underscoring the importance of the temporal dimension. Further areas remain to be explored, including how different orders of presentation and variations in timing between items presented can cause both short and long-term effects on particular types of learning and the relationship between stress and learning.

Several chapters approach the effects of order on learning by examining more details of the problems involved in a problem-solving sequences. Scheiter and Gerjets (Chapter 14), for example, examine how varying the surface features of consecutive problems affect learning. In this way they are able to show how several orders of problems with the same surface features, but with different deep structures, have different effects on learning. Reigeluth (Chapter 2) examines scope and sequencing.

Gobet and Lane note how the learner's representation of information can influence predictions of order effects. Because EPAM has a hierarchical representation of knowledge, it appears to be more susceptible to order effects than systems with flat knowledge representations (like Kieras' CCT, explained below). Gobet and Lane also suggest that problem-solving-oriented tasks, such as many modeled by ACT-R, may be less susceptible to order effects.

### **Order effects can be mitigated**

On the other hand, mitigation or avoidance of poor orders by learners and their instructors is both possible and important. Indeed, there are even some models and data where order effects are not predicted and do not occur.

Several chapters found that learners and instructors both have ways to mitigate the effects of a bad stimuli order. Reigeluth (Chapter 2) suggests that for short lessons, order can often be ignored. For longer lessons, Scheiter and Gerjets (Chapter 14), and Swaak and De Jong (Chapter 12), found

that learners will often reorder to improve learning. VanLehn (Chapter 13) found that instructors can help with reordering. Reordering might in the future be seen as a type of feedback to instructors: sequences that learners prefer to reorder can be considered as a place for improvement. Even Polya (1945) suggested reordering problem subtasks as a heuristic for solving difficult problems.

Scheiter and Gerjets (Chapter 14) also found that knowledge (expertise) mitigated bad orders. Indeed, the people with the most knowledge, the instructors setting the order, are the least effected by poor order; as a result, instructors may need advice about ordering if they are to overcome their own perspectives enough to benefit those they are instructing.

This finding that people with more expertise are less effected by order is consistent with several of the theories reported in this book. Cognitive load theory (Sweller, Chapter 15) and Morik and Mühlenbrock's theory (Chapter 9) would both explain that order effects might be limited in relatively simple transitions from one state of knowledge to the next. For both of these theories, order effects occur only when the transition from one knowledge state to the next is particularly complex.

The lack of order effects can also be seen in previous models and show us where order effects may be avoided, for example, Cognitive Complexity Theory (CCT) and studies testing it (Bovair, Kieras, & Polson, 1990; Kieras & Bovair, 1986). In several studies users were taught to use text editors for several tasks in different orders (AB and BA), and the CCT model predicted transfer between the editors and tasks based on how much knowledge the two task/editor combinations shared using production rules as the unit of measure. While CCT predicted that different tasks would take different amounts of time to perform and learn, it also predicted that there would be no order effects. That is, for any order of tasks, CCT predicted that the user would end up with the same knowledge. As it turned out, their data supported these predictions (with a high correlation); the users appeared to learn the same amount across orders. Thus, for text editing, the order of materials does not appear to influence learning.

### **Order effects can be applied to improve learning**

As noted above, the order in which learning material is presented can have large effects both theoretically and experimentally. For the education of large populations, the savings are significant enough that it will often be worthwhile to compute the optimal order rather than to guess it. Where this computation is not possible, allowing or encouraging students to find their own order appears

to lead to better performance, so in cases with high-knowledge learners, reordering should also be encouraged.

Table 2 provides an informal summary of the design rules arising from the material presented in this book. Many of the conclusions are tentative and, so, our rules are really heuristics, and are neither final nor complete. This limitation is not surprising given the complexity of how and why order effects can arise.

### **Table 2. Heuristics for ordering learning materials.**

1. Be concerned about order only when there is a strong relationship among the topics with respect to the time to learn.
2. Consider the scope and context of what you are trying to teach.
3. Start with comprehensible but small items to learn (define the language).
4. Progress from smaller to larger items or examples, but learners also need to know about the big picture and to stay motivated.
5. Keep in mind the amount of novelty and the amount to learn, attempting to maximize this without overwhelming the learner.
6. Avoid overwhelming the learner with new material such that they cannot learn or that it decreases their motivation.
7. Keep in mind the time and/or repetitions it takes to learn an object or skill, and the spacing of practice.
8. Switch between types of problems or make learners choose which knowledge to apply if you want to encourage them to transfer and apply the knowledge later.
9. Constrain novice learners more than more expert learners. Allow better learners to reorder where they think it is appropriate, and support them with information about the materials.

### **Future research: Questions within the core areas**

The work reported in this book allows us to identify some meta-issues related to order effects in each of these core areas of psychology, machine learning, and instructional design. We also note several topics for further research within these core areas.

There are many high-level questions in psychology, machine learning, and instructional design that can be kept in mind while reading this book. We introduce just a few of them here<sup>1</sup>. For example, for psychology, can we discover new ordering effects in human learning? Can we understand when they occur and what factors influence human learners? How do humans vary with respect to order effects?

For machine learning, can we develop flexible and powerful incremental learning algorithms that have benign or minimal ordering effects? How do algorithm complexity, speed, and space requirements influence order effects?

And finally, for instructional design, what is an optimal order for human learners? Can we determine that order experimentally or computationally, and how can we create tools to help compute that optimal order automatically, and even tailor it to individual learners? And what is the space of instructional-design activities in which ordering can be safely ignored?

There are also important areas where theories of learning will have to be extended. Each of these areas, and particularly psychology and instructional design, will need to consider the impact of motivation and emotion on learning. While this consideration is not directly addressed in the book, changes in emotion and in motivation can arise from different orders. It is important to remember that whereas most machine learning algorithms are quite content to continue to work on impossible problems, human learners can become demotivated or bored depending on the order of problems, even when these problems are solvable. Instructional design and psychology are both interested in these topics.

The relationship between stress and workload is also an important factor in learning. We know that under stress (such as that brought about by high workload) the order of subtask performance changes (e.g., Kuk, Arnold, & Ritter, 1999). VanLehn (Chapter 13) and Swaak and De Jong (Chapter 12) suggest that when faced with bad orders, learners will reorder their tasks. The changes seen in the order of subtask performance under stress and the changes that learners make when faced with bad orders may be related. It is important to keep in mind that learners affected by external stressors (e.g., unsupportive educational environments), are likely to behave differently, and they may be more sensitive to order.

As briefly reviewed by Sweller (Chapter 15), working memory capacity influences learning, and we know that anxiety and worry can influence working memory capacity (e.g., Ashcraft, 2002;

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<sup>1</sup> We thank Tim O'Shea for suggesting these meta-questions.

Beilock & Carr, 2005). As a result, orders that increase stress will be worse, and some orders may be less susceptible to the effects of stress. Perhaps we will also have to modify the order to support users who are inclined to rearrange subtasks, or we will have to encourage a finer-grained view of order, to help learners order their subtasks within each problem to optimize learning.

Finally, we will have to examine long-term objectives and influences. The chapters here examine mostly direct and short-term effects and results. Different orders may also have longer-term and more subtle effects, including the quality of long-term performance, long-term learning, transfer to different problem types, short- and long-term motivation, and other qualities yet to be measured.

### **Back to the bridge: Future research questions linking these areas**

There remain at least three meta-questions that link the relevant disciplines studying learning, and each chapter addresses at least one of them. These questions help unify the chapters, so that a reader interested in or knowledgeable about multiple relevant fields may find insights for their own use. These questions are:

(a) Can we develop machine-learning algorithms that model the effects of order on humans?

Several chapters provide steps toward an answer to this question, showing how some cognitive architecture mechanisms give rise to order effects. (Similarly, these architectures must avoid effects where none exist.)

(b) Can we use theories from AI and data from cognitive psychology to develop approaches to instructional design that take advantage of human ordering effects? This is clearly one of the broadest possible practical applications of this research, if not the most important.

(c) How do interfaces and learning environments affect the individual's need to consider order when organizing attempts at learning? Or is the rapid progress in computing environments (and cheap access to them) going to make this issue moot through improved interfaces alone?

In her poem "Girder", Nan Cohen noted that bridges lead in two directions. We hope that this book serves as a bridge between these areas and in doing so helps knowledge move more effectively between these increasingly related fields.

### **Problems in order**

Each chapter includes a short list of problems for the reader to pursue. These problems support the use of this book as a textbook and as a primer for someone preparing to do a PhD (or similarly-

sized research project) on the topic of order effects. We have attempted to make these lists uniform, but because of the subject matter they vary in size and approach, which is appropriate. Some of the problems are short, and could be done within a small class project; others are large enough to be a class-length research project or even a springboard into a PhD project. Some are probably large enough to span a career. Many of the problems are novel and open-ended, and could lead to practical (and publishable) research. Some problems have already been used in this way, and indeed, all of the chapters ask more interesting questions than can be answered currently, suggesting this will be an important area for further research. Here are our introductory problems:

1. How should these chapters be ordered? Come up with an order before you read the book. Compare this order to the order you create after you skim and then read the book.
2. What are important order effects in your area of study? As you read the book, summarize the chapters and their references with respect to your area of study.
3. Review the literature in your field with respect to one of the questions within the core areas or the meta-questions linking the areas noted above.
4. Design a pilot study to study one of the meta-issues noted above.
5. Explore one of the range of relevant issues not covered in this book, such as how order interacts with other factors (e.g., development, fatigue and individual differences in working memory capacity, gender, etc.). Prepare either a short review or small pilot study with humans or models to examine such differences. A computational pilot study might be fruitfully done by using an abstracted model rather than a computer program. That is, you might not have to run an ACT-R or a PDP program to understand its predictions.
6. Examine the results from Sweller's (1976) paper on pair-associate learning. Consider how they might have arisen, and come up with four possible mechanisms. Note three places in education where this effect and the possible mechanisms could be applied.
7. Design a software program you could teach something. Consider what representations would be required to start learning, and what representations would be learned. As a larger project, consider implementing it (e.g., like the Count program referenced in Selfridge, 2006), or consider the application of such a program to teach teachers and learners about learning. (Many of the chapters will provide additional insights into this question.)

## How to order a bridge

The bridge shown on the cover of the book can be ordered from [www.leobridge.com](http://www.leobridge.com) for 19.90 € (approximately 25 US\$) plus shipping. It can also be easily made from most kinds of materials. The dimensions of this version of the bridge are 4 cm x 0.9 cm x 34 cm (11 pieces), and 4 cm x 0.9 cm x 20 cm (7 pieces). The building instructions are left as an exercise for the reader.

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<sup>i</sup> This book uses order and sequence effects as interchangeable terms.