

ARTIFICIAL INTELLIGENCE and TUTORING SYSTEMS

Computational and Cognitive
Approaches to the
Communication of Knowledge

Etienne Wenger

Foreword by
JOHN SEELY BROWN
and JAMES GREENO

TP18
W474

8864214

ARTIFICIAL INTELLIGENCE and TUTORING SYSTEMS

Computational and Cognitive
Approaches to the
Communication of Knowledge

BY

Etienne Wenger

University of California, Irvine

FOREWORD BY

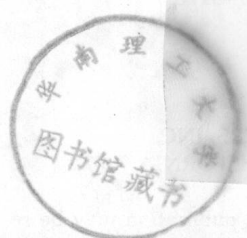
John Seely Brown

Xerox Palo Alto Research Center

and

James Greeno

University of California, Berkeley



E8864214

MORGAN KAUFMANN PUBLISHERS, INC.

95 FIRST STREET

LOS ALTOS, CALIFORNIA 94022

Editor and President *Michael B. Morgan*
Production Manager *Jennifer M. Ballentine*
Production Assistant *Todd R. Armstrong*
Composition *The Font Factory*
Book Design *Beverly Kennon-Kelley*
Cover Design *Irene Imfeld*
Illustrations *Matthew Bennett*
Copyediting *Adam Cornford*

Figure credits can be found following the Bibliography.

Library of Congress Cataloging-in-Publication Data

Wenger, Etienne, 1952-

Artificial intelligence and tutoring systems.

"January 12, 1987."

Bibliography: p.

Includes index.

1. Artificial intelligence—Data processing.

2. Computer-assisted instruction. 3. Knowledge,

Theory of. I. Title. II. Title: Tutoring systems.

Q336.W46 1987 006.3 87-3170

ISBN 0-934613-26-5

Copyright ©1987

MORGAN KAUFMANN PUBLISHERS, INC.

95 FIRST STREET, LOS ALTOS, CALIFORNIA 94022

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of the publisher. Printed in the United States of America, Library of Congress Catalog Card Number 87-3170.

ISBN 0-934613-26-5

ARTIFICIAL INTELLIGENCE and TUTORING SYSTEMS

Computational and Cognitive
Approaches to the
Communication of Knowledge



A mes parents
Alfred et Liliane Wenger



Foreword

It is always a pleasure to introduce a fine book by a young author. Etienne Wenger's *Artificial Intelligence and Tutoring Systems* is the fruit of an ambitious effort that has succeeded remarkably well. In this book, Wenger has taken on the task of reviewing the state of the art and science of intelligent tutoring systems. The result is a work that provides a new level of conceptual coherence and analytic structure to ITS research, thereby helping to define the field as a legitimate, and potentially very important, scientific and technological domain.

Let's consider Wenger's accomplishments in turn. To start with, he has given us an insightful review of AI-based instructional systems. His treatment will be valuable as an introductory text, for it provides informative descriptions of each system as a whole and useful comparisons of significant features. In doing so, he has also conveyed a sense of the

intellectual history of the field, for he shows how specific features of tutoring programs resulted from theoretical and practical attempts to address system deficiencies. As an example, Wenger's excellent discussions of mental models show how they emerged as a response to system failures to handle certain kinds of communication tasks. Wenger also gives an exceptionally penetrating discussion of diagnostic systems, showing the respective advantages and disadvantages of top-down (model-driven) and bottom-up (data-driven) methods of student modeling.

But this book is no mere catalog of programs and techniques. Most significantly from our point of view, he has also laid out a provocative framework for analyzing and comparing intelligent tutoring systems. This framework addresses fundamental scientific issues concerning the nature of knowledge, learning, and communication, which are at the heart of ITS design. It is relative to this framework that Wenger's discussions reveal how research on intelligent tutoring systems contributes not only to the fields of artificial intelligence and education, but also to basic scientific problems in linguistics, psychology, and philosophy.

Wenger's framework for understanding intelligent tutoring systems centers on the notion of communicable knowledge. In this view, the primary function of a tutoring system is as a vehicle of communication. In developing this notion, Wenger makes very productive use of an epistemological assumption, developed by Philip Kitcher, that knowledge is warranted belief. Wenger takes a warrant for a belief to be the set of experiential or conceptual episodes provided by the system that give rise to the belief and justify it for a particular person. The key notion is that knowledge can only be communicated—and therefore learned—through the mediation of warrants that connect with the individual's present understanding. It therefore becomes crucial that system designers pay close attention to the various kinds of warrants for belief (e.g., causal, functional, teleological) and to the various ways that these justifications become manifest, ranging from sequences of experiences to verbal explanations. Wenger's framework unifies a number of issues surrounding knowledge communication in ITS, including the problem of explanations—a topic frequently alluded to but all too often finessed in expert systems research.

One emerges from this book with an altered vision of intelligent tutoring systems in which informed presentational schemes—presentational schemes based on knowledge about the warranting conditions for new beliefs—play a newly important role. Wenger's epistemological view and theoretical framework together expand the universe of intelligent tutoring systems, building conceptual links between systems that demonstrate their processes of reasoning explicitly, that enable students to reflect on their own reasoning, and that provide rich environments for exploratory learning. Thus, tutoring programs that have emphasized methods as diverse as interaction with computational experts, coaching, and free

exploration are interpretable within a single, coherent conceptual framework.

But we believe that there is more to Wenger's accomplishment than its manifest contribution to ITS theory. The rapid pace of technological and social change and the growth of information have created pressing new educational needs. It is no longer appropriate to think of education as transpiring solely in school or between the ages of six and eighteen. Instead, it is imperative that people acquire the cognitive and interactional skills necessary for self-directed, life-long learning. We believe that this agenda requires an examination of fundamental assumptions about knowledge and learning, a fresh look at alternatives to the didacticism that currently dominates our educational system, and the development of new kinds of educational resources. The expanded view of the requirements of successful knowledge communication implicit in Wenger's framework begins to address several of the issues that will be important to this reformulation of educational means and ends. Wenger's work has obvious implications for the development not only of instructional systems per se, but also of information systems more generally. But the implications of this work extend even beyond that. We believe that a better understanding of the nature of knowledge and its warrants will result in increased attention to the social and physical contexts in which learning takes place, as these often determine the situational characteristics that bring about growth in knowledge. Wenger's analytic framework and his focus on learning as a process of communication will contribute significantly to inquiry into the various ways that individuals come to know, either articulately or tacitly, in a range of everyday situations, including free exploration, apprenticeship, collaboration, and reflection.

Wenger's book is a particularly timely contribution. It could not have been written as recently as five years ago, since a critical mass of information about intelligent tutoring systems sufficient for this kind of conceptual analysis had not yet developed. Nor could it have been written five years from now, for by then there will be too much material to review in the thorough manner employed here. *Artificial Intelligence and Tutoring Systems*, therefore, stands as a unique document revealing a young field's accomplishments and, more importantly, its promise at an important threshold of development.

John Seely Brown, Xerox Palo Alto Research Center
James G. Greeno, University of California, Berkeley

Acknowledgments

This book was not a planned project; it could not have been. It grew out of research I was doing as a graduate student at the University of California at Irvine, and surreptitiously became "the book." In the process of making room for this new entity and bringing the project to completion, many people had to go out of their way: it is my great pleasure to thank them all here and to give explicit recognition to some of them.

I want to thank Susan Chipman and Michael Shafto of the Personnel and Training Division of the Office of Naval Research and Dorothy Fischer of the Joseph Fischer Foundation for their appreciation for my work. The ONR contract N00014-85-K-0373 provided some financial support, and an award from the Fischer Foundation helped with student fees. The University also awarded me several tuition fellowships. I gratefully acknowledge the support of these organizations.

I want to thank everyone in the Department of Information and Computer Science at UCI for the friendly atmosphere and for the sophisticated

and reliable working environment I have enjoyed while writing. Some people deserve special mention: the department's chair, John King, who on several occasions made exceptional use of his administrative talents to allow me to continue working on this project free of other worries; my advisor, Dennis Kibler, who as a scholar believed in me through the endless saga of the book and fended for me whenever the reasonable opinion was expressed that graduate students should just concentrate on finishing their dissertations and getting out; my office mate, Rogers Hall, faithful friend and delightful intellectual companion, who I know would have preferred me to move on to other projects with him, but who never showed impatience as I remained absorbed in my writing.

I want to thank the book's reviewers for taking time out of their busy schedules to comment on the draft: Jeffrey Bonar, Lewis Johnson, Bob London, Derek Sleeman, and Kurt VanLehn. I also want to thank Adam Cornford for his careful copyediting. Michael Morgan and Jennifer Ballentine of Morgan Kaufmann Publishers have been just what I expected from my editors: dedicated to the intellectual and physical quality of the book, and very concerned with my every opinion and with my personal experience of the whole process. It is still somewhat hard for me to believe that such fine scientists and visionary thinkers as John Seely Brown and Jim Greeno would care to write a foreword to anything I wrote. But knowing that they have, I can only thank them wholeheartedly; such honor is probably my greatest surprise in this adventure.

I want to thank my parents, to whom this book is dedicated, not only for their encouragement and support ever since I went back to studying, but more generally for always taking parenting as seriously as they have. I know their love and dedication is a key to what I have become, and the prominence of their names in this book is a small token of my gratitude.

I want to thank my wonderful wife Paula. Her love and support have given me endless reasons to dedicate this book to her, including her candid but firm insistence that this honor should just go to my parents. Such tender paradoxes, only the heart knows how to resolve. With just more love.

And I want to thank my son Jad for carrying around the young beauty of his soul. One day, as I was grabbing the folder containing the precious manuscript on my busy way out, he said to me with his two-and-a-half-year-old innocence: "You want me to write it for you, your book?" In your own simple way, Jad, you have, and through you, this book is silently dedicated to all the children—young and old—who grow up in this world: may you always see learning as the greatest game in life, yet never as a reason to lose what you already know.

Etienne Wenger

Contents

Part I A first glance: introducing the field

Chapter 1 Knowledge communication systems	3
1.1 Implicit versus explicit encoding of knowledge	4
Educational software engineering: encoding of decisions	
Artificial intelligence: explicit encoding of knowledge	
1.2 Knowledge communication	6
1.3 Practical and theoretical implications	7
Toward a cognitively oriented form of software engineering	
Toward a communication-oriented epistemology	
1.4 An interdisciplinary enterprise.....	9
Summary and conclusion	11
Bibliographical notes	11

Chapter 2 Basic issues	13
2.1 Domain knowledge: the object of communication	14
The functions of the expert module	
Aspects of communicability	
2.2 Student model: the recipient of communication	16
The student model: information	
The student model: representation	
The diagnostic process: accounting for data	
2.3 Pedagogical knowledge: the skill of communication	19
2.4 Interface: the form of communication	21
Summary and conclusion	23
Bibliographical notes	23

Part II A panorama: people, ideas, and systems

Chapter 3 Tutorial dialogues: from semantic nets to mental models	29
3.1 SCHOLAR: launching a new paradigm	30
A system to conduct tutorial dialogues	
3.2 Natural reasoning and tutorial dialogues	35
3.2.1 Natural reasoning: plausible inferences	35
Techniques supported by simple extensions to SCHOLAR	
More complex inference techniques	
3.2.2 An inquiry into the nature of tutorial dialogues	37
3.3 WHY: the Socratic method	39
Toward a computational model of Socratic tutorial strategies	
A system implementing the Socratic method	
3.4 From local strategies to multiple mental models	41
3.4.1 Considering global goals	42
3.4.2 Domain knowledge: multiple viewpoints	44
The functional perspective: a second viewpoint on physical processes	
Additional open issues in domain-specific knowledge	
3.4.3 From multiple viewpoints to multiple mental models ...	45
Learning about physical processes viewed as model tuning	
Componential views of mental models	

Summary and conclusion	48
Bibliographical notes	49
Chapter 4 SOPHIE: from quantitative to qualitative simulation	51
4.1 Simulation: dialogues and learning environments	52
4.1.1 The METEOROLOGY tutor: question answering	52
4.1.2 A reactive learning environment for troubleshooting ...	55
4.2 Natural-language interface: semantic grammars	55
Efficiency and habitability: semantic parsing	
A robust interface	
4.3 SOPHIE-I: simulation-based inferences	59
SOPHIE's instructional tasks	
The value of quantitative simulations	
4.4 SOPHIE-II: an articulate expert	62
SOPHIE-I and II in actual use	
4.5 SOPHIE-III: humanlike reasoning	64
4.5.1 Paradigmatic systems: the BLOCKS tutor.....	65
4.5.2 Toward humanlike reasoning in electronics	67
Further problems with SOPHIE-III	
4.6 Mental models: qualitative reasoning.....	70
Function from structure: envisioning	
Principled construction of causal models: robustness	
and learning	
Prescriptive and descriptive theories	
Qualitative physics	
Summary and conclusion	76
Bibliographical notes	77
Chapter 5 Interactive simulations: communicating mental models	79
5.1 STEAMER: simulation and abstraction	80
5.1.1 Manipulable simulation of a steam plant	80
5.1.2 Tutorial capabilities: the use of abstractions	82
Explanations of procedures: abstract objects	
Structure of components: abstract functionality	
5.1.3 Inspectable simulations: conceptual fidelity.....	83
5.1.4 From graphic abstractions to qualitative processes	86
5.2 QUEST: progressions of qualitative models	88
5.2.1 Mental models: a developmental approach.....	89
Differences between models	
Understanding and learning	

5.2.2 A learning environment for zero-order qualitative models	94
The system in practice: evaluation and comments	
Progressions of models and knowledge communication	
Summary and conclusion	97
Bibliographical notes	99
Chapter 6 Existing CAI traditions: other early contributions ..	101
6.1 Early attempts to tailor problem-solving experiences.....	102
6.1.1 EXCHECK: understanding natural proof procedures	102
Natural proof procedures: a learning environment with informed feedback	
6.1.2 A probabilistic model for judgmental knowledge	105
Numerical representation of expertise	
Learning by adapting probabilistic values	
6.1.3 BIP: curriculum information networks	108
BIP-I: layered curriculum organization	
BIP-II: pedagogically organized information	
Problem-solving guidance: limited diagnostic information	
6.2 Pedagogical experiments: teaching expertise.....	111
6.2.1 Self-improving tutors: tuning strategies empirically.....	112
The QUADRATIC tutor	
Self-improvement by experimentation	
Empirical versus analytical learning	
6.2.2 Concept teaching: a formal analytical approach	117
Teaching and learning models	
The value of formal experiments	
Summary and conclusion	120
Bibliographical notes	121
Chapter 7 Learning environments: coaching ongoing activities	123
7.1 LOGO: knowledge communication as learning	124
LOGO: programming as a discovery tool	
Knowledge communication as a learning process	
7.2 WEST: relevance and memorability of interventions	126
7.2.1 Tutoring with issues and examples	127
The role of WEST's expert	
7.2.2 Pedagogical principles for coaching.....	132
WEST in actual use: an encouraging success	

7.3 The design of learning environments	133
Toward a theory of pedagogical simplification	
7.4 WUSOR: toward learner-oriented models of expertise	135
7.4.1 WUSOR-I: an expert-based coach	136
7.4.2 Overlays: a rule-based paradigm for student modeling .	137
The overlay architecture	
Limitations of the overlay paradigm	
7.4.3 The overlay theory in WUSOR-II.....	140
7.4.4 WUSOR-III: the genetic graph.....	140
The topology of the graph: a source of pedagogical information	
Representing problem-solving expertise for teaching	
7.5 Architectures organized around curricula	144
7.5.1 The bite-sized architecture.....	145
7.5.2 Curriculum organization and steering testing	146
Summary and conclusion	149
Bibliographical notes	151

Chapter 8 Bugs in procedural skills: the 'buggy repair step' story	153
8.1 BUGGY: an enumerative theory of bugs.....	154
8.1.1 A modular representation of subskills	154
Limitations of enumerative theories of bugs	
8.1.2 The nature of bugs in procedural skills	157
8.2 DEBUGGY: a diagnostic system	159
8.2.1 Off-line diagnosis: heuristic search strategies	159
8.2.2 Coercions: a model-driven analysis of noisy data.....	160
Coercions and bugs	
8.2.3 IDEBUGGY: an on-line version.....	162
Problem generation	
Managing the space of hypotheses	
8.2.4 Diagnostic tests and the notion of subskill	164
Primitive subskills: a formal definition	
8.3 REPAIR theory: a generative theory of bugs.....	165
8.3.1 Representation of procedural skills	166
8.3.2 Mechanisms for the generation of bugs.....	167
Generative principles for repairs and impasses	
Filtering principles for impasses and repairs	

8.3.3 Explanatory power and observational coverage	170
8.4 STEP theory: a learning model of bug generation	171
8.4.1 Planning nets: teleological reasoning	172
8.4.2 The nature of learning in procedural skills.....	175
The teaching sequence: supporting inductive learning	
Induction from examples: a source of mislearning	
8.4.3 SIERRA: a model of the generation of core procedures .	177
The learning model	
Sources of impasses	
8.4.4 Coverage and validation: competitive argumentation ...	179
Competitive argumentation: the role of assumptions	
Methodological considerations	
Summary and conclusion	182
Bibliographical notes	183
 Chapter 9 More on student modeling: toward domain-	
independent mechanisms	185
9.1 PSM/ACE: interactive diagnosis	186
Following explanations of the student's reasoning	
Domain knowledge and understanding of explanations	
9.2 LMS: inferential diagnosis with rules and mal-rules	190
9.2.1 Representing procedural skills with production systems	190
9.2.2 Containing the combinatorics of the modeling task	191
9.2.3 Automated test generation	193
9.3 PIXIE: generating mal-rules	194
9.3.1 Diagnosis by reconstruction	194
Toward remedial dialogues	
9.3.2 Student interviews: toward a generative theory of bugs	197
Misgeneralization as a generative principle	
The attitude of the learner: a controversy	
9.4 UMFE: a generic modeling subsystem	198
The propagation of diagnostic information	
A prototype: limitations and possibilities	
Summary and conclusion	201
Bibliographical notes	202

Chapter 10 Bug reconstruction: beyond libraries of bugs	205
10.1 Extending past knowledge with general operators	206
10.2 Syntactic manipulations on production systems	207
Syntactic manipulations: practical and theoretical limitations	
10.3 ACM: machine learning techniques for diagnosis	210
Machine learning techniques for diagnosis	
10.3.1 ACM's modeling process	212
Path hypotheses: diagnostic and psychological heuristics	
Inferring production rules: learning from examples	
10.4 Primitive operators versus bugs	218
Bug reconstruction: low granularity of primitives	
Defining the right primitives	
Summary and conclusion	220
Bibliographical notes	222
 Chapter 11 Problem solving and design: diagnostic plan analysis	 223
11.1 The FLOW tutor: structured memory organization	224
Teaching strategies expressed in terms of schemata	
Tutors built on top of active structural networks	
11.2 SPADE: toward a tutor based on a theory of design	227
11.2.1 Ideas for a theory of design	227
A linguistic view of the design process	
Diagnostic concerns: parsing protocols with PATN	
11.2.2 SPADE-0: a plan-based editor	230
An experimental didactic system	
11.3 The MACSYMA ADVISOR: plans and beliefs	232
The dependency graph: a plan annotated with assumptions	
Inferring misconceptions and interactive diagnosis	
11.4 MENO: debugging and tutoring	236
11.4.1 MENO-II: error-oriented program analysis	236
11.4.2 The knowledge of novice programmers	237
Toward a generative theory of bugs for looping plans	
BRIDGE: from natural language to programming	