

---

# **EXPLORATIONS IN PARALLEL DISTRIBUTED PROCESSING**

**A Handbook of Models, Programs,  
and Exercises**

---

**James L. McClelland**

**David E. Rumelhart**

A Bradford Book

The MIT Press  
Cambridge, Massachusetts  
London, England

---

## **Computational Models of Cognition and Perception**

Editors

Jerome A. Feldman  
Patrick J. Hayes  
David E. Rumelhart

*Parallel Distributed Processing: Explorations in the Microstructure of Cognition. Volume 1: Foundations*, by David E. Rumelhart, James L. McClelland, and the PDP Research Group

*Parallel Distributed Processing: Explorations in the Microstructure of Cognition. Volume 2: Psychological and Biological Models*, by James L. McClelland, David E. Rumelhart, and the PDP Research Group

*Neurophilosophy: Toward a Unified Science of the Mind-Brain*, by Patricia Smith Churchland

*Qualitative Reasoning About Physical Systems*, edited by Daniel G. Bobrow

*Induction: Processes of Inference, Learning, and Memory*, by John H. Holland, Keith J. Holyoak, Richard E. Nisbett, and Paul R. Thagard

*Production System Models of Learning and Development*, edited by David Klahr, Pat Langley, and Robert Neches

*Minimal Rationality*, by Christopher Cherniak

*Vision, Brain, and Cooperative Computation*, edited by Michael A. Arbib and Allen R. Hanson

*Computational Complexity and Natural Language*, by G. Edward Barton, Jr., Robert C. Berwick, and Eric Sven Ristad

*Explorations in Parallel Distributed Processing: A Handbook of Models, Programs, and Exercises*, by James L. McClelland and David E. Rumelhart

---

## Contents

---

<b>Preface</b>	vii
<b>1 Introduction</b>	1
<b>2 Interactive Activation and Competition</b>	11
<b>3 Constraint Satisfaction in PDP Systems</b>	49
<b>4 Learning in PDP Models: The Pattern Associator</b>	83
<b>5 Training Hidden Units: The Generalized Delta Rule</b>	121
<b>6 Other Learning Models: Auto-Associators and Competitive Learning</b>	161
<b>7 Modeling Cognitive Processes: The Interactive Activation Model</b>	203

<b>Appendix A: Setting Up the PDP Software on the PC</b>	241
<b>Appendix B: Command and Variable Summary</b>	245
<b>Appendix C: File Formats for Network, Weight, Template, Look, and Pattern Files</b>	263
<b>Appendix D: Plot and Colex: Utility Programs for Making Graphs</b>	283
<b>Appendix E: Answers to Questions in the Exercises</b>	289
<b>Appendix F: An Overview of the PDP Software</b>	321
<b>Appendix G: Instructions for Recompiling the PDP Programs</b>	325
<b>References</b>	329
<b>Index</b>	333

---

## Preface

---

### Uses of This Handbook

We have produced this handbook primarily to help others who wish to undertake their own explorations in parallel distributed processing. The handbook can be used in a self-guided program of exploration. We provide tutorials on the theoretical background of all the models considered, as well as simple exercises to help the reader develop a feeling for the basic concepts of PDP and for the simulation models that embody these principles.

The material covered comes largely from the two volumes on parallel distributed processing that grew out of our work with the PDP research group at UCSD (McClelland, Rumelhart, & the PDP Research group, 1986; Rumelhart, McClelland, & the PDP Research Group, 1986). This represents fairly broad coverage, since many prominent workers in the field contributed to these volumes and many of the models built upon the pioneering work of others.

The range of models covered should be sufficiently broad to let this volume serve as a primer in PDP or connectionist modeling. There are some gaps, but we have found that once students have gained some hands-on experience with a subset of models in the field, there is considerable positive transfer, and they are able to assimilate written material about other models better once they have had this experience.

The handbook should prove suitable for courses that serve as a first introduction to PDP or connectionist modeling. We have used this material successfully in courses for juniors, seniors, and graduate students who have

had no prior experience in the area. We hope that the coverage of basic theoretical material provided in each chapter will help to free instructors to devote some lectures and discussions to the ideas and motivations behind the models and to introduce material we have not covered here.

We have given answers to the questions posed in the exercises to encourage students to use the questions to test their own understanding of the material and to help anyone who uses the handbook for self-study purposes to stay on track. We have also tried to make it possible for students to explore applications of the various models to problems they pose for themselves. In some cases, it may even be feasible for students with programming experience to extend the software and explore variants of the models that we have not implemented or even to develop new models of their own. However, our experience has been that most students do not have the time, within a course that lasts a single quarter or semester, to do too much extension of the programs themselves; this is often better left for a follow-up, independent study course in a later term.

An additional goal of the handbook is to make our simulation programs available to researchers who already have some specific research interest in PDP. Over the years we have frequently been asked for copies of our programs by researchers who wished to try our simulation models on their own problems or to modify and extend the models. Judging from our own experience, the software provided with this handbook will prove useful in meeting many of these needs; we find that the **bp** program, in particular, has become a major workhorse that has been adapted by us and many of our graduate students for use in a number of ongoing research projects.

We have retained copyright to the text and accompanying software, but encourage the use and modification of the software for educational and research purposes. We reserve all rights to market the text and software, both source and object code.

### Acknowledgments

This book grew out of courses we have taught at Carnegie-Mellon and UCSD over the last three years. At first, we only intended to make the simulation programs we had developed in the course of our research available for students in our home institutions, but the response to the opportunity to learn about PDP by using the programs has been so enthusiastic that it seemed clear there would be a broader audience. It is to our students, then, that we owe the inspiration to produce this handbook.

The specific suggestion to publish a version of the software came from Eric Jenkins, who was at the time (March, 1986) a first-year psychology graduate student at Carnegie-Mellon. In an early conversation with Eric, several basic elements of the philosophy behind the design of the software were laid out.

This handbook also owes a great deal to the students in a course taught by Dave Rumelhart at UCSD in the fall of 1986 and to the students in a course taught by Jay McClelland at Carnegie-Mellon in the spring of 1987. These students made do with sometimes buggy versions of the programs and often sketchy drafts of the chapters, and provided us with very useful feedback and suggestions. We would like to mention particularly the useful comments we received from Benoit Mulsant, who caught a number of glaring errors. We also received very useful feedback on a portion of the handbook from Jeremy Roschelle at Berkeley.

Elliot Jaffe, then a research programmer at CMU, played a major role in the development of the user interface that we are now using in our research simulators, as well as in the programs distributed with this handbook. Elliot did an excellent job designing this user interface to our specifications and implementing the first version of the programs, adapting our existing simulators to work with the new interface. Elliot's work was supported by a contract from the Office of Naval Research (N00014-82-C-0374, NR 442a-483). We have done the fine-tuning of the software for educational use, with assistance from Michael Franzini at Carnegie-Mellon. Mike has played a particularly important role in streamlining the PC-specific input/output routines and in finalizing the PC version of the software.

Copyediting and production of the handbook was done at UCSD. We would like to thank Don Norman, director of the Institute for Cognitive Science at UCSD, and Sondra Buffett, administrative director, for their general support and understanding as this project has continued even after both of us have left our former home at UCSD. To Kathy Farrelly at UCSD we owe a very large debt of gratitude. As with the earlier PDP volumes, she has taken care of the copyediting, the preparation of figures, the production of camera-ready copy, and a thousand other things with extraordinary thoughtfulness and efficiency. We would also like to thank Rebecca Duxbury at Carnegie-Mellon for meticulous secretarial assistance in all phases of the preparation of the text.

Finally, we would like to thank Harry and Betty Stanton and their associates at MIT Press for their support. The Press provided the use of a PC for software development as well as financial assistance for the production of camera-ready copy of the text, and has still been able to keep the handbook affordable. We also thank the Stantons for understanding when we did not meet the wildly optimistic target date we gave them for completing this handbook. In retrospect, the eighteen months it has taken seems very good for a project such as this, even though we never dreamed it would take that long when we began.

September 1987

James L. McClelland  
PITTSBURGH, PENNSYLVANIA

David E. Rumelhart  
PALO ALTO, CALIFORNIA