

LIBRARY OF CONGRESS



0 007 615 824 1

LIBRARY OF CONGRESS



0 003 493 993 7



PATT  
HEN

THE HARDWARE/SOFTWAR

FT  
Ge

QA  
.C64  
19

COP

MO  
KAUF

**Morgan Kaufmann Publishers**  
2929 Campus Drive, Suite 260  
San Mateo, CA 94403

**Computer Systems and Design**  
Electrical Engineering  
ISBN 1-55860-281-X

---

# Computer Organization and Design

THE HARDWARE / SOFTWARE INTERFACE

**John L. Hennessy**  
Stanford University

**David A. Patterson**  
University of California at Berkeley

With a contribution by  
James R. Larus  
University of Wisconsin

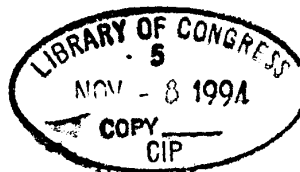
Morgan Kaufmann Publishers  
*San Mateo, California*

**Senior Editor:** Bruce M. Spatz  
**Production Manager:** Yonie Overton  
**Editorial Coordinator:** Douglas Sery  
**Copyediting:** Steve Hiatt and Gary Morris  
**Text Design:** Ross Carron Design  
**Illustration:** Alexander Teshin Associates  
**Composition/Color Separation/Postscript Programming:** Edward W. Szynter, Babel Press  
**Cover Design:** David Lance Goines  
**Additional Cover Mechanical Art:** Patty King  
**Chapter Opener Illustrations:** Jo Jackson  
**Indexing:** Steve Rath  
**Proofreading:** Gary Morris  
**Electronic Prepress:** The Courier Connection  
**Printer:** Courier Corporation

Morgan Kaufmann Publishers, Inc.  
Editorial Office:  
2929 Campus Drive, Suite 260  
San Mateo, CA 94403

© 1994 by Morgan Kaufmann Publishers, Inc.  
All rights reserved  
Printed in the United States of America

97 96 95 94 5 4 3 2 1



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.

**Advice, Praise, and Errors:** Any correspondence related to this publication or intended for the authors should be addressed to the editorial offices of Morgan Kaufmann Publishers, Inc., Dept. P&H APE. Information regarding error sightings is encouraged. Any error sightings that are accepted for correction in subsequent printings will be rewarded by the authors with a payment of \$1.00 (U.S.) per correction at the time of their implementation in a reprint. Electronic mail can be sent to [errors@cs.berkeley.edu](mailto:errors@cs.berkeley.edu).

**Instructor Support:** For information on the SPIM software simulator and other instructor materials available to adoptors, please contact the editorial offices of Morgan Kaufmann Publishers, Inc.

#### Cataloging-in-Publication Data

Patterson, David A.

Computer organization and design: the hardware/software interface  
/ David A. Patterson, John L. Hennessy.  
p. cm.

Includes bibliographical references and index.  
ISBN 1-55860-281-X

1. Computer organization. 2. Computers--Design and construction.

3. Computer interfaces. I. Hennessy, John L. II. Title

QA76.9.C643P37 1994

004.2'2--dc20

93-  
17639  
CIP

# Contents

**Foreword** vi  
*by Maurice V. Wilkes*

**Preface** xiii

**The SPIM Simulator for the MIPS R2000/R3000** xxiii  
*by James R. Larus, University of Wisconsin*

## C H A P T E R S

<b>1</b>	<b>Computer Abstractions and Technology</b>	<b>2</b>
1.1	Introduction	3
1.2	Below Your Program	5
1.3	Under the Covers	10
1.4	Integrated Circuits: Fueling Innovation	21
1.5	Fallacies and Pitfalls	26
1.6	Concluding Remarks	28
1.7	Historical Perspective and Further Reading	30
1.8	Exercises	41

<b>2</b>	<b>The Role of Performance</b>	<b>46</b>
2.1	Introduction	48
2.2	Measuring Performance	52
2.3	Relating the Metrics	54
2.4	Popular Performance Metrics	60
2.5	Choosing Programs to Evaluate Performance	66
2.6	Comparing and Summarizing Performance	68
2.7	Fallacies and Pitfalls	70
2.8	Concluding Remarks	76
2.9	Historical Perspective and Further Reading	77
2.10	Exercises	81

**3****Instructions: Language of the Machine 92**

- 3.1 Introduction 94**
- 3.2 Operations of the Computer Hardware 95**
- 3.3 Operands of the Computer Hardware 97**
- 3.4 Representing Instructions in the Computer 103**
- 3.5 Instructions for Making Decisions 110**
- 3.6 Supporting Procedures in Computer Hardware 119**
- 3.7 Other Styles of MIPS Addressing 124**
- 3.8 Alternatives to the MIPS Approach 130**
- 3.9 An Example to Put It All Together 135**
- 3.10 A Longer Example 138**
- 3.11 Arrays versus Pointers 143**
- 3.12 Fallacies and Pitfalls 147**
- 3.13 Concluding Remarks 148**
- 3.14 Historical Perspective and Further Reading 150**
- 3.15 Exercises 155**

**4****Arithmetic for Computers 166**

- 4.1 Introduction 168**
- 4.2 Negative Numbers 168**
- 4.3 Addition and Subtraction 175**
- 4.4 Logical Operations 179**
- 4.5 Constructing an Arithmetic Logic Unit 182**
- 4.6 Multiplication 198**
- 4.7 Division 212**
- 4.8 Floating Point 225**
- 4.9 Fallacies and Pitfalls 244**
- 4.10 Concluding Remarks 246**
- 4.11 Historical Perspective and Further Reading 249**
- 4.12 Exercises 258**

**5****The Processor: Datapath and Control 268**

- 5.1 Introduction 270**
- 5.2 Building a Datapath 276**
- 5.3 A Simple Implementation Scheme 283**
- 5.4 A Multiple Clock Cycle Implementation 312**
- 5.5 Microprogramming: Simplifying Control Design 333**
- 5.6 Exceptions 344**
- 5.7 Fallacies and Pitfalls 350**
- 5.8 Concluding Remarks 351**
- 5.9 Historical Perspective and Further Reading 353**
- 5.10 Exercises 357**

# Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

## Real-Time Litigation Alerts



Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

## Advanced Docket Research



With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

## Analytics At Your Fingertips



Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

## API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

## LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

## FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

## E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.