LIBRARY OF CONGRESS

0 007 615 824 1



PATI HEN

HE HARDWARE/SOFTWAR

FT Ge

QA

.C64

COF

MOI

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. PattersonUniversity 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. Sznyter, 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

NOW - 8 1994
COPY
CIP

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.

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



sodika intakonomina dalahan kan kan kan kan kan kan kan di manga sada sa kan kan kan kan kan kan merin sa sa

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

CHAPTERS



Computer Abstractions and Technology 2

- 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



The Role of Performance 46

- 2.1 Introduction 48
- **2.2** Measuring Performance 52
- $\textbf{2.3} \quad \textbf{Relating the Metrics} \quad 54 \\$
- 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





Instructions: Language of the Machine 92

~ 4	Indian day		0.4
3.1	Introduc	ction	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



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



The Processor: Datapath and Control 268

- 5.1 Introduction 270
- 5.2 Building a Datapath 276
- 5.3 A Simple Implementation Scheme 283
- $\textbf{5.4} \quad \textbf{A Multiple Clock Cycle Implementation} \quad 312$
- 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



DOCKET

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.

