





Computer Architecture A Quantitative Approach

Fourth Edition

John L. Hennessy is the president of Stanford University, where he has been a member of the faculty since 1977 in the departments of electrical engineering and computer science. Hennessy is a Fellow of the IEEE and ACM, a member of the National Academy of Engineering and the National Academy of Science, and a Fellow of the American Academy of Arts and Sciences. Among his many awards are the 2001 Eckert-Mauchly Award for his contributions to RISC technology, the 2001 Seymour Cray Computer Engineering Award, and the 2000 John von Neumann Award, which he shared with David Patterson. He has also received seven honorary doctorates.

In 1981, he started the MIPS project at Stanford with a handful of graduate students. After completing the project in 1984, he took a one-year leave from the university to cofound MIPS Computer Systems, which developed one of the first commercial RISC microprocessors. After being acquired by Silicon Graphics in 1991, MIPS Technologies became an independent company in 1998, focusing on microprocessors for the embedded marketplace. As of 2006, over 500 million MIPS microprocessors have been shipped in devices ranging from video games and palmtop computers to laser printers and network switches.

David A. Patterson has been teaching computer architecture at the University of California, Berkeley, since joining the faculty in 1977, where he holds the Pardee Chair of Computer Science. His teaching has been honored by the Abacus Award from Upsilon Pi Epsilon, the Distinguished Teaching Award from the University of California, the Karlstrom Award from ACM, and the Mulligan Education Medal and Undergraduate Teaching Award from IEEE. Patterson received the IEEE Technical Achievement Award for contributions to RISC and shared the IEEE Johnson Information Storage Award for contributions to RAID. He then shared the IEEE John von Neumann Medal and the C & C Prize with John Hennessy. Like his co-author, Patterson is a Fellow of the American Academy of Arts and Sciences, ACM, and IEEE, and he was elected to the National Academy of Engineering, the National Academy of Sciences, and the Silicon Valley Engineering Hall of Fame. He served on the Information Technology Advisory Committee to the U.S. President, as chair of the CS division in the Berkeley EECS department, as chair of the Computing Research Association, and as President of ACM. This record led to a Distinguished Service Award from CRA.

At Berkeley, Patterson led the design and implementation of RISC I, likely the first VLSI reduced instruction set computer. This research became the foundation of the SPARC architecture, currently used by Sun Microsystems, Fujitsu, and others. He was a leader of the Redundant Arrays of Inexpensive Disks (RAID) project, which led to dependable storage systems from many companies. He was also involved in the Network of Workstations (NOW) project, which led to cluster technology used by Internet companies. These projects earned three dissertation awards from the ACM. His current research projects are the RAD Lab, which is inventing technology for reliable, adaptive, distributed Internet services, and the Research Accelerator for Multiple Processors (RAMP) project, which is developing and distributing low-cost, highly scalable, parallel computers based on FPGAs and open-source hardware and software.



Computer Architecture

A Quantitative Approach

Fourth Edition

John L. Hennessy

Stanford University

David A. Patterson

University of California at Berkeley

With Contributions by

Andrea C. Arpaci-Dusseau

University of Wisconsin–Madison

Remzi H. Arpaci-Dusseau

University of Wisconsin–Madison

Krste Asanovic

Massachusetts Institute of Technology

Robert P. Colwell

R&E Colwell & Associates, Inc.

Thomas M. Conte

North Carolina State University

José Duato

Universitat Politècnica de València and Simula

Diana Franklin

California Polytechnic State University, San Luis Obispo

David Goldberg

Xerox Palo Alto Research Center

Wen-mei W. Hwu

University of Illinois at Urbana–Champaign

Norman P. Jouppi

HP Labs

Timothy M. Pinkston

University of Southern California

John W. Sias

University of Illinois at Urbana–Champaign

David A. Wood

University of Wisconsin–Madison



Amsterdam • Boston • Heidelberg • London
New York • Oxford • Paris • San Diego



**DOCKET
ALARM**

Find authenticated court documents without watermarks at docketalarm.com.

Publisher Denise E. M. Penrose
Project Manager Dusty Friedman, The Book Company
In-house Senior Project Manager Brandy Lilly
Developmental Editor Nate McFadden
Editorial Assistant Kimberlee Honjo
Cover Design Elisabeth Beller and Ross Carron Design
Cover Image Richard F Anson's Collection: Lonely Planet Images
Composition Nancy Logan
Text Design: Rebecca Evans & Associates
Technical Illustration David Ruppe, Impact Publications
Copyeditor Ken Della Penta
Proofreader Jamie Thaman
Indexer Nancy Ball
Printer Maple-Vail Book Manufacturing Group

Morgan Kaufmann Publishers is an Imprint of Elsevier
500 Sansome Street, Suite 400, San Francisco, CA 94111

This book is printed on acid-free paper.

© 1990, 1996, 2003, 2007 by Elsevier, Inc.
All rights reserved.

Published 1990. Fourth edition 2007

Designations used by companies to distinguish their products are often claimed as trademarks or registered trademarks. In all instances in which Morgan Kaufmann Publishers is aware of a claim, the product names appear in initial capital or all capital letters. Readers, however, should contact the appropriate companies for more complete information regarding trademarks and registration.

Permissions may be sought directly from Elsevier's Science & Technology Rights Department in Oxford, UK: phone: (+44) 1865 843830, fax: (+44) 1865 853333, e-mail: permissions@elsevier.com. You may also complete your request on-line via the Elsevier Science homepage (<http://elsevier.com>), by selecting "Customer Support" and then "Obtaining Permissions."

Library of Congress Cataloging-in-Publication Data

Hennessy, John L.

Computer architecture : a quantitative approach / John L. Hennessy, David A. Patterson ; with contributions by Andrea C. Arpaci-Dusseau . . . [et al.].
—4th ed.

p.cm.

Includes bibliographical references and index.

ISBN 13: 978-0-12-370490-0 (pbk. : alk. paper)

ISBN 10: 0-12-370490-1 (pbk. : alk. paper) I. Computer architecture. I. Patterson, David A. II. Arpaci-Dusseau, Andrea C. III. Title.

QA76.9.A73P377 2006

004.2'2—dc22

2006024358

For all information on all Morgan Kaufmann publications,
visit our website at www.mkp.com or www.books.elsevier.com

Printed in the United States of America

06 07 08 09 10 5 4 3 2 1

Working together to grow
libraries in developing countries

www.elsevier.com | www.bookaid.org | www.sabre.org

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.