Stuart
Russell

Peter
Norvig

Artificial Intelligence
A Modern Approach
Third Edition

ALWAYS LEARNING

PEARSON

Artificial Intelligence

A Modern Approach

Third Edition

PRENTICE HALL SERIES
IN ARTIFICIAL INTELLIGENCE
Stuart Russell and Peter Norvig, Editors

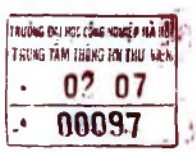
FORSYTH & PONCE	*Computer Vision: A Modern Approach*
GRAHAM	ANSI *Common Lisp*
JURAFSKY & MARTIN	*Speech and Language Processing, 2nd ed.*
NEAPOLITAN	*Learning Bayesian Networks*
RUSSELL & NORVIG	*Artificial Intelligence: A Modern Approach, 3rd ed.*

Artificial Intelligence

A Modern Approach

Third Edition

Stuart J. Russell and Peter Norvig



Contributing writers:
Ernest Davis
Douglas D. Edwards
David Forsyth
Nicholas J. Hay
Jitendra M. Malik
Vibhu Mittal
Mehran Sahami
Sebastian Thrun

Boston Columbus Indianapolis New York San Francisco Upper Saddle River
Amsterdam Cape Town Dubai London Madrid Milan Munich Paris Montreal Toronto
Delhi Mexico City Sao Paulo Sydney Hong Kong Seoul Singapore Taipei Tokyo

Pearson Education Limited
Edinburgh Gate
Harlow
Essex CM20 2JE
England

and Associated Companies throughout the world

Visit us on the World Wide Web at:
www.pearsonglobaleditions.com

© Pearson Education Limited 2016

The rights of Stuart J. Russell and Peter Norvig to be identified as the authors of this work have been asserted by them in accordance with the Copyright, Designs and Patents Act 1988.

Authorized adaptation from the United States edition, entitled Artificial Intelligence: A Modern Approach, Third Edition, ISBN 9780136042594, by Stuart J. Russell and Peter Norvig published by Pearson Education © 2010.

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 either the prior written permission of the publisher or a license permitting restricted copying in the United Kingdom issued by the Copyright Licensing Agency Ltd, Saffron House, 6–10 Kirby Street, London EC1N 8TS.

All trademarks used herein are the property of their respective owners. The use of any trademark in this text does not vest in the author or publisher any trademark ownership rights in such trademarks, nor does the use of such trademarks imply any affiliation with or endorsement of this book by such owners.

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

10 9 8 7 6

20 19 18

ISBN 10: 1292153962

ISBN 13: 9781292153964

Printed and bound in Malaysia (CTP-VVP)

For Loy, Gordon, Lucy, George, and Isaac — S.J.R.

For Kris, Isabella, and Juliet — P.N.

Preface

Artificial Intelligence (AI) is a big field, and this is a big book. We have tried to explore the full breadth of the field, which encompasses logic, probability, and continuous mathematics; perception, reasoning, learning, and action; and everything from microelectronic devices to robotic planetary explorers. The book is also big because we go into some depth.

The subtitle of this book is "A Modern Approach." The intended meaning of this rather empty phrase is that we have tried to synthesize what is now known into a common framework, rather than trying to explain each subfield of AI in its own historical context. We apologize to those whose subfields are, as a result, less recognizable.

New to this edition

This edition captures the changes in AI that have taken place since the last edition in 2003. There have been important applications of AI technology, such as the widespread deployment of practical speech recognition, machine translation, autonomous vehicles, and household robotics. There have been algorithmic landmarks, such as the solution of the game of checkers. And there has been a great deal of theoretical progress, particularly in areas such as probabilistic reasoning, machine learning, and computer vision. Most important from our point of view is the continued evolution in how we think about the field, and thus how we organize the book. The major changes are as follows:

- We place more emphasis on partially observable and nondeterministic environments, especially in the nonprobabilistic settings of search and planning. The concepts of *belief state* (a set of possible worlds) and *state estimation* (maintaining the belief state) are introduced in these settings; later in the book, we add probabilities.
- In addition to discussing the types of environments and types of agents, we now cover in more depth the types of *representations* that an agent can use. We distinguish among *atomic* representations (in which each state of the world is treated as a black box), *factored* representations (in which a state is a set of attribute/value pairs), and *structured* representations (in which the world consists of objects and relations between them).
- Our coverage of planning goes into more depth on contingent planning in partially observable environments and includes a new approach to hierarchical planning.
- We have added new material on first-order probabilistic models, including *open-universe* models for cases where there is uncertainty as to what objects exist.
- We have completely rewritten the introductory machine-learning chapter, stressing a wider variety of more modern learning algorithms and placing them on a firmer theoretical footing.
- We have expanded coverage of Web search and information extraction, and of techniques for learning from very large data sets.
- 20% of the citations in this edition are to works published after 2003.
- We estimate that about 20% of the material is brand new. The remaining 80% reflects older work but has been largely rewritten to present a more unified picture of the field.

Overview of the book

The main unifying theme is the idea of an **intelligent agent**. We define AI as the study of agents that receive percepts from the environment and perform actions. Each such agent implements a function that maps percept sequences to actions, and we cover different ways to represent these functions, such as reactive agents, real-time planners, and decision-theoretic systems. We explain the role of learning as extending the reach of the designer into unknown environments, and we show how that role constrains agent design, favoring explicit knowledge representation and reasoning. We treat robotics and vision not as independently defined problems, but as occurring in the service of achieving goals. We stress the importance of the task environment in determining the appropriate agent design.

Our primary aim is to convey the *ideas* that have emerged over the past fifty years of AI research and the past two millennia of related work. We have tried to avoid excessive formality in the presentation of these ideas while retaining precision. We have included pseudocode algorithms to make the key ideas concrete; our pseudocode is described in Appendix B.

This book is primarily intended for use in an undergraduate course or course sequence. The book has 27 chapters, each requiring about a week's worth of lectures, so working through the whole book requires a two-semester sequence. A one-semester course can use selected chapters to suit the interests of the instructor and students. The book can also be used in a graduate-level course (perhaps with the addition of some of the primary sources suggested in the bibliographical notes). Sample syllabi are available at the book's Web site, `aima.cs.berkeley.edu`. The only prerequisite is familiarity with basic concepts of computer science (algorithms, data structures, complexity) at a sophomore level. Freshman calculus and linear algebra are useful for some of the topics; the required mathematical background is supplied in Appendix A.

Exercises are given at the end of each chapter. Exercises requiring significant programming are marked with a **keyboard** icon. These exercises can best be solved by taking advantage of the code repository at `aima.cs.berkeley.edu`. Some of them are large enough to be considered term projects. A number of exercises require some investigation of the literature; these are marked with a **book** icon.

Throughout the book, important points are marked with a *pointing* icon. We have included an extensive index of around 6,000 items to make it easy to find things in the book. Wherever a **new term** is first defined, it is also marked in the margin.

NEW TERM

About the Web site

`aima.cs.berkeley.edu`, the Web site for the book, contains

- implementations of the algorithms in the book in several programming languages,
- a list of over 1000 schools that have used the book, many with links to online course materials and syllabi,
- an annotated list of over 800 links to sites around the Web with useful AI content,
- a chapter-by-chapter list of supplementary material and links,
- instructions on how to join a discussion group for the book,