ENGINEERING DESIGN, SECOND EDITION

Contrary to popular mythology, the designs of successful products and systems do not suddenly or magically appear. The authors believe that symbolic representation, and related problem-solving methods, offer significant opportunities to clarify and articulate concepts of design to lay a better framework for design research and design education. Artificial intelligence (AI) provides a substantial body of material concerned with understanding and modeling cognitive processes. This book adopts the vocabulary and paradigms of AI to enhance the presentation and explanation of design. It includes concepts from AI because of their explanatory power and their utility as possible ingredients of practical design activity. This second edition is enriched by the inclusion of recent work on design reasoning, computational design, AI in design, and design cognition, with pointers to a wide cross section of the current literature.

Clive L. Dym is Fletcher Jones Professor of Engineering Design and Director of the Center for Design Education at Harvey Mudd College. His primary interests are engineering design and structural mechanics. Dym is the author of several books, including *Engineering Design: A Synthesis of Views* (1994); *Structural Modeling and Analysis* (1997); *Principles of Mathematical Modeling, Second Edition* (2004); and *Engineering Design: A Project-Based Introduction, Third Edition*, coauthored with Patrick Little (2008). He has published more than 90 refereed journal articles and is the founding editor of *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*. Dym has served on the editorial boards of several other journals, including the American Society of Mechanical Engineers' *Journal of Mechanical Design*. Dym is co-winner of the NAE's 2012 Bernard M. Gordon Prize.

David C. Brown is Professor of Computer Science and has a collaborative appointment as Professor of Mechanical Engineering at Worcester Polytechnic Institute. He is also affiliated with the Manufacturing, Robotics, and Learning Sciences programs. Brown's research interests include computational models of engineering design and the applications of artificial intelligence to engineering and manufacturing. He authored *Design Problem Solving: Knowledge Structures and Control Strategies*, with B. Chandrasekaran (1990), and edited *Intelligent Computer Aided Design*, with M. B. Waldron and H. Yoshikawa (1992). From 2001 to 2011, Brown was Editor in Chief of *Artificial Intelligence in Engineering Design, Analysis and Manufacturing*, and he has served on the editorial boards for *Concurrent Engineering: Research and Application, Research in Engineering Design*, and *The International Journal of Design Computing*.

Engineering Design

REPRESENTATION AND REASONING

Second Edition

Clive L. Dym
Harvey Mudd College

David C. Brown
Worcester Polytechnic Institute

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town,
Singapore, São Paulo, Delhi, Mexico City

Cambridge University Press
32 Avenue of the Americas, New York, NY 10013-2473, USA

www.cambridge.org
Information on this title: www.cambridge.org/9780521514293

First edition published as *Engineering Design: A Synthesis of Views* 1994
Second edition first published 2012

Printed in the United States of America

A catalog record for this publication is available from the British Library.

Library of Congress Cataloging in Publication Data

Dym, Clive L.
Engineering design : representation and reasoning / Clive L. Dym, David C. Brown. – 2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-521-51429-3 (hardback)
1. Engineering design – Data processing. 2. Computer-aided engineering. I. Brown, David C., 1947– II. Title.
TA174.D964 2012
620′.004201–dc23 2011041119

ISBN 978-0-521-51429-3 Hardback

We dedicate this book to our brothers,

Harry Dym and Martin Brown

Reflections

Knowledge is an artifact, worthy of design.

– Stefik and Conway (1982)

It has often been said that a person doesn't really understand something until he teaches it to someone else. Actually a person doesn't understand something until he can teach it to a computer, i.e., express it as an algorithm . . .

The attempt to formalize things as algorithms leads to a much deeper understanding than if we simply try to understand things in the traditional way.

– Knuth (1973)

Contents

Preface

More than 15 years have passed since the publication of *Engineering Design: A Synthesis of Views*. Significant new material has emerged during this time that deserves to be incorporated into the unified view presented in the first edition. In addition, a larger group of people now believe that designing is not just analysis and that research in design offers the possibility of studying a collection of cognitive processes that allows significant insights. Thus, for this new edition, we replace the first edition subtitle with *Representation and Reasoning* to make its focus more explicit.

Our approach was to leave the first edition more or less untouched while adding material that clarifies, updates, and extends the original text. This new material was placed in sidebars that are keyed to appropriate points in the (original) text. Any new references were added to the end of the book to allow students and scholars to explore topics that interest them in more detail. We hope that these additions will extend the life of the book for another 15 years (or even more!).

The first edition leaned heavily on the field of artificial intelligence (AI). AI-based models of design, and the techniques AI brings to bear, have changed since 1994. For example, as the field's understanding of routine and near-routine design strengthened, researchers moved on to consider nonroutine tasks.

Although design education has changed, it has changed slowly. There are still many educators and engineers who would benefit from the lessons of the first edition as well as from the updated material. Engineering design education and design research in general have grown in importance – and it would be nice to think that the first edition has played a constructive role in this growth. There is now a new and wider audience for an expanded and updated "synthesis of views."

We intend our audience to be engineers interested in understanding more about engineering design, designers interested in understanding more about the utility of AI, and AI researchers interested in design. We believe that this book will continue to attract engineers who do not have any prior knowledge or commitment to this updated view of design as an area of research and study.

The authors still believe this statement from the Preface of the first edition:

> . . . symbolic representation and related problem-solving methods, offer significant opportunities to clarify and articulate concepts of design so as to lay a better framework for design research and design education. Inasmuch as there is within AI a substantial body of material concerned with understanding and modeling cognitive processes, and because the level of articulation in this work transcends in many ways the common vocabulary of engineering design, we may find it useful to adapt (where possible) and appropriate the vocabulary and paradigms of AI to enhance our understanding of design.

As a consequence, this second edition continues to include concepts from AI not only because of their explanatory power but also because of their utility as possible ingredients of practical design activity. Of course, much has changed in the AI modeling of design and in AI in general, so we have updated the material appropriately. With the growth in cognitively influenced studies of design since the first edition, we have also selectively incorporated material from that field. Our goal is still to provide a focused, concise synthesis, without being so comprehensive that the book becomes cumbersome.

As you can see, we have retained the Preface to the first edition because much of it is still highly relevant, and it still sets the tone for the approach used in this second edition. Some of the updated topics include features, functional representation and reasoning, affordances, design rationale, ontologies, grammars, genetic algorithms, routineness, creativity, assumptions, design decision making, analogy, and collections of agents as representations of teams.

Because we have published widely in this field for many years and share a long history of association with the Cambridge University Press journal *AIEDAM: Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, it should be no surprise that we lean heavily on our papers and this journal in what we cite. We have included a wide variety of the work of others, but we hope you will forgive us for any unintentional bias.

Engineering design education and design research has changed and grown in importance since the first edition. We hope that many more engineers, students, and teachers should now be able to benefit from this updated synthesis of views about representation and reasoning in engineering design.

Clive L. Dym
Harvey Mudd College
Claremont, California

David C. Brown
Worcester Polytechnic Institute
Worcester, Massachusetts

Preface to the First Edition

Design is a central activity in engineering. Indeed, Herbert A. Simon has argued that design is *the* central activity that defines engineering – or, at the very least, distinguishes it from the "pure" sciences – because the role of engineering is the creation of artifacts. And yet, many of us within the engineering community believe that design is a misunderstood activity that is not well represented in engineering education or research. We are very much aware that engineering science dominates the intellectual landscape of engineering today, and it is certainly arguable that analysis dominates both engineering education and research. Indeed, it has long been a concern that design is improperly taught and inadequately represented in engineering curricula and that too often design is seen as legitimate only when it can be explained in terms of analysis (as in the notion that design is "iterative analysis").

One of the problems that design educators and design researchers have faced is a perceived lack of rigor, and this perception has in turn led to calls for a more organized, more "scientific" focus to research about design. One aspect of this perception is that design is viewed as a "soft" subject: design is not a "hard" discipline because it is not sufficiently mathematical. Another aspect is that the vocabulary for analyzing and describing design is not shared, even within the design community, although this situation has begun to improve.

We do not intend to revisit the (familiar) arguments about how this state of affairs has evolved or who, if anyone, is to blame. Instead, we focus on how our understanding of the discipline of design can be broadened and strengthened and on ways in which we can discuss design in a more coherent and precise way. In particular, we will try to demonstrate that recent advances in the field of artificial intelligence (AI), particularly symbolic representation and related problem-solving methods, offer significant opportunities to clarify and articulate concepts of design so as to lay a better framework for design research and design education. Inasmuch as there is within AI a substantial body of material concerned with understanding and modeling cognitive processes, and because the level of articulation in this work transcends in many ways the common vocabulary of engineering design, we may find it useful to adapt (where possible) and appropriate the vocabulary and paradigms of AI to enhance our understanding of design.

We recognize first that the modeling techniques that currently occupy most of the various engineering curricula, rooted in applied mathematics and usually quite adequate for analysis, do not in fact represent a vocabulary complete enough for the synthesis task of generating and choosing among different designs. The situation is perhaps confused because analytical tools are often used to explore particular conceptual designs down through a chain of detailed designs to a final design. What appears to be missing is a language or a means of representing designs more abstractly than is required for detailed design, for example, but with enough structure (e.g., hierarchies and networks) to allow sensible articulation of the issues involved in the validation of a design at their corresponding levels of detail. Furthermore, this vocabulary (or language or, even, set of languages) ought to be recognizable and useful across all engineering disciplines, even if it is not fully applied in every single instance.

Our basic thesis is that recent advances in AI research offer useful prospects for representing the kinds of intelligent, informed design knowledge that is beyond the current scope of mathematical modeling. The single most relevant development of interest here is the idea of *symbolic representation*, which allows in computational terms the processing of lists of words, which in turn facilitates – and even encourages – the representation of objects and their attributes in a fairly general way. Inasmuch as these objects can be conceptual as well as physical, the foundation has been laid for representing qualitative aspects of our thinking about design in ways that we could not achieve heretofore. The vocabulary of this AI-based research offers interesting opportunities for articulating concerns about particular designs and about the field of design itself. That is, recent attempts to use symbolic representation to make design computable have perforce led to an articulation of the design process that should be quite useful to the engineering community in its ongoing examination of design in education, practice, and research.

Thus, we have directed this monograph toward synthesizing an operational definition of engineering design to better articulate what we mean by engineering design, how we can discuss both the design of artifacts and the process of design, and which areas are most amenable to – and perhaps most require – formal research approaches. The central theme of our discussion, that representation is the key element in design, parallels the polymathic vision of Simon, who listed representation as one of the seven subjects in the ideal engineering design curriculum. In addition, akin to the quotation (p. vi) from Knuth, we argue that recent research in AI aimed at rendering design computable has provided new techniques for design representation that enable us to better explicate design concepts and processes. These developments have at the same time given us computer-aided design tools of unparalleled power and flexibility. Another consequence of these recent developments is that we now have available new ways of designing our design knowledge (cf. Stefik and Conway, as quoted on p. vi) and corresponding problem-solving paradigms that should be incorporated into the *weltanschauung* of engineers and designers.

However, although much of this discussion has been motivated by current research aimed at making design (and other cognitive processes) computable in

some sense, we most emphatically do not argue that all design should be automated or even made computable. Design activities encompass a spectrum from *routine* design of familiar parts and devices, through *variant* design that requires some modification in form or function, to truly *creative* design of new artifacts. It is difficult to argue that we can at present model truly creative design. However, although we may not be able to model – and thus describe and teach – creativity, we must recognize that the spectrum of design concerns does include many processes that are susceptible to thoughtful analysis – in other words, that are cognitive processes. Traditional designers and teachers of design might well complain about the characterization of design as a cognitive process, but we would respond that this is due to confusion about where creativity and thoughtful process interact and overlap, on the one hand, and where they are distinct, on the other. The boundary between creativity and what we recognize as a cognitive process is a moving one, especially in terms of our understanding, so we must be careful not to develop a new orthodoxy about design that prejudges where that boundary is and where, as a result, we preclude what we can learn and teach about design.

We also do not claim that AI has all the answers. Rather, we believe that AI-based efforts aimed at increasing the options for representing designed artifacts and the design process are helping produce a deeper awareness of what is involved in design as well as a vocabulary for discussing design. It is this awareness and its articulation that is worth exploring and adapting in order to improve the art of engineering. And because design tasks vary from the routine to the creative (or from adaptive through variant to original), we suggest that the focus of research in computer-aided design should not be to simply automate design. Rather, we believe that such research could be viewed as having both a "science" component and an "engineering" component, the former being perhaps more basic than the latter. The goals of the more basic research would include developing better representations, languages, and problem-solving methods as well as a deeper understanding of the kind of knowledge used to solve engineering design (and analysis) problems. The goal of engineering-oriented research could be said to be the creation of *designer's assistants* that support and facilitate the exploration of design alternatives or (perhaps radically) different designs. In this respect, we also point out that such designer's assistants have produced some very tangible gains in product design (cf. Section 1.2).

This book is organized as follows. In Chapter 1, we frame the basic issues in greater detail. In Chapter 2, we review some definitions of design, both in engineering and in other domains, and we present a working definition of engineering design that is sufficiently abstract to acknowledge design both for the production of plans for making artifacts and as a process in itself. We devote the next two chapters to defining and characterizing the design process as a thought process, and we pay special attention to embedding some of the newer ideas into traditional views of design. In Chapter 3, we outline some traditional views of the design process, both descriptive and prescriptive, and then we present some more recent descriptions that reflect some of the research we just mentioned. We then proceed to taxonomies of design (Chapter 4); that is, we try to characterize design tasks and refine them in

some detail. Such formalization of the design process has been done only relatively recently, and so we will probably raise more questions about such taxonomies than we will provide answers. An extended discussion of artifact representation is given next (Chapter 5), with particular emphasis on representations used in engineering and buttressed by examples drawn from recent engineering design research results. Chapter 5 also raises questions about communicating design requirements and ideas, particularly in the context of representing design attributes in shared, transmittable ways.

In Chapter 6, we turn to the next logical step, the representation of the design process. We start with a look at some key AI-based problem-solving methods and then review briefly some classical design aids. We do this to introduce some of the vocabulary (and the underlying ideas) used to describe design as a process of articulating and solving engineering problems. Then, having identified a language suitable for discourse about the discipline of design, we provide illustrations of new representations of design knowledge and how these representations help us apply that knowledge in design processes. In Chapter 7, we review some of the current research in engineering design representation with an eye toward identifying future trends. In this final chapter, we also look at the roles that symbolic representation and knowledge-based (expert) systems can play in engineering design, in both practice and education.

In Chapters 5 and 6, especially, we cast many examples in the style of object-oriented programming. In the research and applications literature, these illustrations are presented in pseudocode. Although there are some common approaches (e.g., object names, attributes, values, and procedures are typically written in a sans serif type such as Helvetica), there is also a wide variety of practices that depend on the preferences of individual researchers (or, perhaps more accurately, the capabilities of their software package!). We adopted Helvetica as the preferred font for all such examples, but we follow the preferences of the cited authors when it comes to capitalization, underscores, and so on. Thus, it may appear at first glance that we are being somewhat inconsistent in our presentation. In fact, however, we are striving for consistency with the typeface and the intentions of the works cited.

Finally, a note on referencing the many works whose ideas we build on in this rather personal view of design. In order to not distract you, the reader, with numerous citations in the text, the "bibliographic notes" appear at the end of each chapter. The notes outline particular concepts and ideas, along with their appropriate citations, in what is often called the "social science" style (i.e., author(s) (date)). The notes are organized by chapter sections, and the citations are keyed to the reference list found at the end of the book. We worked very hard to be both complete and fair as we compiled these notes and citations. However, perhaps flaunting our humanity, we apologize in advance for any errors in this regard and ask for a divine response from those who have been inadvertently forgotten or improperly cited!

Acknowledgments

From the First Edition

Steven J. Fenves (Carnegie Mellon University) provided an encouraging ear as I talked my way through a very early vision of this book, and he has maintained a friendly interest ever since.

Daniel R. Rehak (Carnegie Mellon University) exercised his unique critical skills intelligently and perceptively over much of the life of the project. He did his best to keep me intellectually honest. What more could one ask of a critic?

Dr. Conrad Guettler and Ms. Florence Padgett of Cambridge University Press have also earned large measures of gratitude. For some years, Conrad gently but persistently encouraged me to write this monograph, and Florence provided cheerful and unflagging editorial support during my life as a Press author.

Erik K. Antonsson (California Institute of Technology) and David M. Steier (Price Waterhouse) provided helpful comments on some of the early chapters of the book. So did my biking buddy, Alicia Ross of Claremont, who listened to me ramble as we cycled around the Inland Empire.

Several publishers, corporations, and individuals have kindly granted me permission to reproduce or replicate figures that have originally appeared elsewhere. The citations for the particular works from which figures have been taken or adpated are given in the respective figure captions. Thus, my sincere thanks to Addison-Wesley (5.11–5.14); American Society of Civil Engineers (5.18–5.21); American Society of Mechanical Engineers (4.1, 4.2, 5.4, 6.12); Butterworth-Heinemann (5.9, 5.15–5.17); John R. Dixon (5.5, 5.6); Steven J. Fenves (1.1); James H. Garrett, Jr. (5.22); R. Gronewold, C. White, C. Nichols, M. Shane, and K. Wong (6.1); B. Hartmann, B. Hulse, S. Jayaweera, A. Lamb, B. Massey, and R. Minneman (6.2, 6.3, 6.6); Institute of Electrical and Electronics Engineers (6.11, 6.15, 6.18, 6.19); International Federation for Information Processing (5.3, 6.13, 6.14); Macmillan (3.1); McGraw-Hill (6.7–6.10); Pergamon Press (3.4, 5.2); Southern California Edison (5.1, 5.10); Springer-Verlag (3.2, 4.3–4.8); John Wiley (3.3, 6.4, 6.5); and Xerox Corporation (5.7, 5.8, 6.16, 6.20).

For the Second Edition

Clive wants to thank Joan Dym for her patience, understanding, and support as he worked to complete yet another book, and Dave wants to thank his family, friends, and coworkers. We both would like to thank our editor, Peter Gordon, for his encouragement and optimism.