\oplus

⊕

Connecting Discrete Mathematics and Computer Science

David Liben-Nowell

 \oplus



preprint_chapters

 \oplus

 \oplus

 \oplus

 \oplus

Connecting Discrete Mathematics and Computer Science

REVISED EDITION

David Liben-Nowell

Department of Computer Science Carleton College



Æ

Page-iv

 \oplus

CAMBRIDGE UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314-321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi - 110025, India

79 Anson Road, #06-04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org

Information on this title: www.cambridge.org/XXX-X-XXX-XXXX-X DOI: 10.1017/XXX-X-XXXXXXX-X

© David Liben-Nowell

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2022 Printed in <country> by <printer>

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

Library of Congress Cataloging-in-Publication Data

ISBN XXX-X-XXX-XXXXX-X Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

 \oplus

Æ

To MDSWM, with never-ending appreciation, and in loving memory of my grandfather, Jay Liben, who brought more joy, curiosity, and kvetching to this world than anyone else I know.



 \oplus

⊕

Contents

 \oplus

Li	st of (Computer Science Connections	page x
Acknowledgements		xiii	
Credits			xvi
1	On	the Point of this Book	1-1
2	Bas	ic Data Types	2-1
	2.1	Why You Might Care	2-2
	2.2	Booleans, Numbers, and Arithmetic	2-4
	Exe	rcises	2-24
	2.3	Sets: Unordered Collections	2-28
	Exe	rcises	2-44
	2.4	Sequences, Vectors, and Matrices: Ordered Collections	2-48
	Exe	rcises	2-65
	2.5	Functions	2-70
	Exe	rcises	2-87
	2.6	Chapter at a Glance	2-90
3	Log	ic	3-1
	3.1	Why You Might Care	3-2
	3.2	An Introduction to Propositional Logic	3-4
	Exe	rcises	3-19
	3.3	Propositional Logic: Some Extensions	3-22
	Exe	rcises	3-36
	3.4	An Introduction to Predicate Logic	3-40
	Exe	rcises	3-60
	3.5	Predicate Logic: Nested Quantifiers	3-63
	Exe	rcises	3-75
	3.6	Chapter at a Glance	3-80

 \oplus

Ĥ

 \oplus

 \oplus

		Contents vii
4	Proofs	4-1
	4.1 Why You Might Care	4-2
	4.2 Error-Correcting Codes	4-4
	Exercises	4-25
	4.3 Proofs and Proof Techniques	4-30
	Exercises	4-50
	4.4 Some Examples of Proofs	4-53
	Exercises	4-72
	4.5 Common Errors in Proofs	4-75
	Exercises	4-84
	4.6 Chapter at a Glance	4-89
5	Mathematical Induction	5-1
	5.1 Why You Might Care	5-2
	5.2 Proofs by Mathematical Induction	5-4
	Exercises	5-24
	5.3 Strong Induction	5-28
	Exercises	5-40
	5.4 Recursively Defined Structures and Structural Induction	5-45
	Exercises	5-58
	5.5 Chapter at a Glance	5-61
6	Analysis of Algorithms	6-1
	6.1 Why You Might Care	6-2
	6.2 Asymptotics	6-4
	Exercises	6-18
	6.3 Asymptotic Analysis of Algorithms	6-22
	Exercises	6-37
	6.4 Recurrence Relations: Analyzing Recursive Algorithms	6-40
	Exercises	6-57
	6.5 An Extension: Recurrence Relations of the Form $T(n) = aT\left(\frac{n}{b}\right) + cn^k$	6-60
	Exercises	6-70
	6.6 Chapter at a Glance	6-72

 \oplus

 \oplus

 \oplus

 \oplus

7	Number Theory	7-1
	7.1 Why You Might Care	7-2
	7.2 Modular Arithmetic	7-4
	Exercises	7-18
	7.3 Primality and Relative Primality	7-21
	Exercises	7-40
	7.4 Multiplicative Inverses	7-43
	Exercises	7-55
	7.5 Cryptography	7-58
	Exercises	7-69
	7.6 Chapter at a Glance	7-72
8	Relations	8-1
	8.1 Why You Might Care	8-2
	8.2 Formal Introduction	8-4
	Exercises	8-21
	8.3 Properties of Relations: Reflexivity, Symmetry, and Transitivity	8-24
	Exercises	8-42
	8.4 Special Relations: Equivalence Relations and Partial/Total Orders	8-45
	Exercises	8-63
	8.5 Chapter at a Glance	8-66
9	Counting	9-1
	9.1 Why You Might Care	9-2
	9.2 Counting Unions and Sequences	9-4
	Exercises	9-28
	9.3 Using Functions to Count	9-33
	Exercises	9-50
	9.4 Combinations and Permutations	9-56
	Exercises	9-77
	9.5 Chapter at a Glance	9-82
10) Probability	10-1
	10.1 Why You Might Care	10-2

Page-ix

 \oplus

 \oplus

 \oplus

	Contents	ix
10.2. Probability. Outcomes. and Events		10-6
Exercises		10-26
10.3 Independence and Conditional Probability		10-30
Exercises		10-52
10.4 Random Variables and Expectation		10-57
Exercises		10-82
10.5 Chapter at a Glance		10-87
11 Graphs and Trees		11-1
11.1 Why You Might Care		11-2
11.2 Formal Introduction		11-4
Exercises		11-30
11.3 Paths, Connectivity, and Distances		11-34
Exercises		11-53
11.4 Trees		11-57
Exercises		11-75
11.5 Weighted Graphs		11-79
Exercises		11-92
11.6 Chapter at a Glance		11-95
12 Looking Forward		12-1
Index		12-5
References		12-15

 \oplus

 \oplus

Æ

 \oplus

List of Computer Science Connections

Chapter 1: On the Point of this Book

Chapter 2: Basic Data Types	
Integers and ints, Reals and floats	2-20
Computing Square Roots, and Not Computing Square Roots	2-22
Set Building in Languages (and MapReduce)	2-40
Clustering Data Sets (and Speech Processing)	2-42
The Vector Space Model	2-61
Rotation Matrices	2-63
Hash Tables and Hash Functions	2-85

Chapter 3: Logic

Natural Language Processing, Ambiguity, and Truth	3-17
Computational Complexity, Satisfiability, and a Million Dollars	3-32
Short-Circuit Evaluation, Optimization, and Modern Compilers	3-34
Game Trees, Logic, and Winning Tic-Tac(-Toe)	3-54
Nonlocal Variables and Lexical vs. Dynamic Scoping	3-56
Gödel's Incompleteness Theorem	3-58
Currying	3-73

Chapter 4: Proofs

Reed–Solomon Codes	4-23
Paul Erdős, "The Book," and Erdős Numbers	4-46
The Four-Color Theorem (and Massive Computer-Generated Proofs)	4-48
Cryptography and the Generation of Prime Numbers	4-68
Other Uncomputable Problems (That You Might Care About)	4-70
The Cost of Missing Proofs: Some Famous Bugs in CS	4-82

Chapter 5: Mathematical Induction

 \oplus

Page-xi

 \oplus

List of Computer Science Connections	xi
Loop Invariants	5-20
Onion Routing, Steganography, and Conversations whose Very Existence is Sensitive	5-22
Triangulation, Computer Graphics, and 3D Surfaces	5-36
Max Heaps	5-38
Grammars, Parsing, and Ambiguity	5-56
Chapter 6: Analysis of Algorithms	
Vacuum Tubes, Transistors, and Moore's Law	6-16
Multitasking, Garbage Collection, and Wall Clocks	6-33
Time, Space, and Complexity	6-35
AVL Trees	6-53
Divide-and-Conquer Algorithms and Matrix Multiplication	6-68
Chapter 7: Number Theory	
Converting Between Bases, Binary Representation, and Generating Strings	7-16
Secret Sharing	7-36
Error Correction with Reed-Solomon Codes	7-38
Miller–Rabin Primality Testing	7-53
Diffie-Hellman Key Exchange	7-67
Chapter 8: Relations	
Relational Databases	8-17
Automating Decisions, Facial Recognition, and Algorithmic Bias	8-19
What's Hard about Designing Voting Systems	8-38
Regular Expressions	8-40
Deterministic Finite Automata (DFAs)	8-59
The Painter's Algorithm and Hidden-Surface Removal	8-61
Chapter 9: Counting	
Running out of IP addresses, and IPv6	9-22
A Lower Bound for Comparison-Based Sorting	9-24
Infinite Cardinalities (and Problems that Can't Be Solved by Any Program)	9-46
Lossy and Lossless Compression	9-48
Brute Force Algorithms and Dynamic Programming	9-73
The Enigma Machine and a First Computer	9-75

 \oplus

 \oplus

11-90

 \oplus

xii List of Computer Science Connections

Chapter 10: Probability	
Using Randomness to Protect Privacy	10-20
Quantum Computing	10-22
Information, Charles Dickens, and the Entropy of English	10-24
Speech Recognition, Bayes' Rule, and Language Models	10-48
Bayesian Modeling and Spam Filtering	10-50
The Monte Carlo Method	10-76
A Randomized Algorithm for Finding Medians	10-78
Chapter 11: Graphs and Trees	
Degree Distributions and the Heavy Tail	11-26
Graph Drawing, Graph Layouts, and the 9/11 Memorial	11-28
The Bowtie Structure of the Web	11-49
Garbage Collection	11-51
Directed Graphs, Cycles, and Kidney Transplants	11-71
Binary Search Trees	11-73

Chapter 12: Looking Forward

Random Walks and Ranking Web Pages

 \oplus

Acknowledgements

Would thou hadst less deserved, That the proportion both of thanks and payment Might have been mine! only I have left to say, More is thy due than more than all can pay.

William Shakespeare (1564–1616) The Scottish Play (c. 1606)

To everyone who has helped, directly and indirectly, with everything over these last years—these words cannot adequately convey my thanks, but at least they're a start: *thank you!*

I owe special thanks to a very long list of generous and warm people—many more than I can mention here—for advice and kindness and support, both technical and emotional, as this book came into being and, slowly, evolved into its present form. For those whom I haven't named by name, please know that it's only because I have gotten such great support from so many people, and I hope that you'll consider this sentence the promise that, whenever we next see each other (however long *that* may take), the first round's on me. While I'm leaving out the names of the many people who have "merely" helped make my life happy and fulfilling while I've been working on this book, I do want to give specific thanks to a few people:

I want to thank my colleagues—near and far, including many who are not just colleagues but also dear friends and beloved family members—for their wisdom and patience, for answering my endlessly annoying questions, and for conversations that led to examples or exercises or bug fixes or the very existence of this entire book (even if you didn't know that's what we were talking about at the time): Katie Ahmann, Eric Alexander, Tanya Amert, Sandra Batista, Tanya Berger-Wolf, Laura Biester, Kelly Connole, Amy Csizmar Dalal, Josh Davis, Corey DeGagne, Doreen Densky, Roger Downs, Laura Effinger-Dean, Eric Egge, Adriana Estill, Andy Exley, Charlotte Foran, Alex Freeman, Sherri Goings, Jack Goldfeather, Daniel Groll, Clara Hardy, Max Harper, Deanna Haunsperger, Pierre Hecker, Maryam Hedayati, Jack Hessel, David Huyck, Sue Jandro, Sarah Jansen, Iris Jastram, Jon Kleinberg, Carissa Knipe, Mark Krusemeyer, Jessica Leiman, Lynn Liben, Doug Marshall, Jadrian Miles, Dave Musicant, Sneha Narayan, Gail Nelson, Rich Nowell, Susan Nowell, Layla Oesper, Kate Olender, Jeff Ondich, Sam Patterson, Anna Rafferty, James Ryan, Alexa Sharp, Asmita Sodhi, Paula Stowe, Julia Strand, Sam Taylor, Mike Tie, Anya Vostinar, Zach Weinersmith, Tom Wexler, Kevin Woods, Jed Yang, Steve Zdancewic, Doug Zimmer, and Chico Zimmerman.



xiv Acknowledgements

I'm grateful to the wonderful folks at Cambridge University Press—Lauren Cowles, Amy He, and especially Katie Leach—for their guidance, honesty, and ability to restore some faith in the entire enterprise. Thanks to Judy Brody, Don Fowley, Bryan Gambrel, Beth Golub, Jessy Moor, Anna Pham, Sondra Scott, and Gladys Soto for their help with a previous incarnation of this material. And my gratitude to the many insightful reviewers of drafts of this material. So many times I got chapter reviews back and put them aside in a huff, only to come back to the reviewers' comments months later and realize that their suggestions were exactly right. (To be clear: blame me, not them, for the errors that I'm sure remain.)

Specific thanks to the Carleton CS 202 students and instructors who worked with early, and buggy, drafts of this book. And thanks to those and many other students at Carleton for their patience, and for sending their comments and suggestions for improvements: Hami Abdi, David Abel, Alexander Auyeung, Andrew Bacon, Kharmen Bharucha, John Blake, Caleb Braun, Macallan Brown, Adam Canady, Noah Carnahan, Yitong Chen, Jinny Cho, Leah Cole, Katja Collier, Lila Conlee, Eric Ewing, Kylie Fournier, Andy Freeland, Emma Freeman, Samuel Greaves, Reilly Hallstrom, Jacob Hamalian, Sylvie Hauser, Jack Hessel, Joy Hill, Matt Javaly, Emily Johnston, Emily Kampa, Carlton Keedy, Henry Keiter, Jonathan Knudson, Julia Kroll, Brennan Kuo, Edward Kwiatkowski, Dimitri Lang, Tristan Leigh, Zach Levonian, Daniel Levy, Rhys Lindmark, Gordon Loery, David Long, Robert Lord, Inara Makhmudova, Elliot Mawby, Javier Moran Lemus, Sean Mullan, Micah Nacht, Justin Norden, Laurel Orr, Raven Pillmann, Josh Pitkofsky, Matthew Pruyne, Nikki Rhodes, Will Schifeling, Colby Seyferth, Alex Simonides, Oscar Smith, Kyung Song, Frederik Stensaeth, Patrick Stephen, Maximiliano Villarreal, Alex Voorhees, Allie Warren, Ben Wedin, Michael Wheatman, Jack Wines, Christopher Winter, and Andrew Yang.

This book would not have been possible without the support of Carleton College, not only for the direct support of this project, but also for providing a wonderfully engaging place to make my professional home. When I started at Carleton, my friends and family back east thought that moving to Minnesota (the frontier!) was nothing less than a sign that I had finally lost it, and I have to admit that I thought they had a point. But it's been a fabulous place to have landed, with great friends and colleagues and students—the kind who don't let you get away with anything, but in a good way.

Some stages of the work on this book occurred while I was visiting the University of Cambridge. Thanks to Churchill College and the Computer Laboratory, and especially to Melissa Hines and Cecilia Mascolo, for their hospitality and support.

And my thanks to the somewhat less formal host institutions that have fueled this writing: Brick Oven Bakery, Cakewalk, Goodbye Blue Monday, Tandem Bagels, The Hideaway (Northfield, MN); Anodyne, Blue Moon, Bull Run, Caffetto, Common Roots, Espresso Royale, Isles Bun & Coffee, Keen Eye, Plan B, Precision Grind, Reverie, Spyhouse, Sebastian Joe's, The Beat, The Nicollet, The Purple Onion, Turtle Bread Company, Uncommon Grounds, Urban Bean (Minneapolis, MN); Ginkgo, Grand Central, Kopplin's (St. Paul, MN); Collegetown Bagels (Ithaca, NY); Slave to the Grind (Bronxville, NY); Bloc Eleven, Diesel

This material will be published by Cambridge University Press as *Connecting Discrete Mathematics and Computer Science* by David Liben-Nowell, and an older edition of the material was published by John Wiley & Sons, Inc as *Discrete Mathematics for Computer Science*. This pre-publication version is free to view and download for personal use only. Not for re-distribution, re-sale,

or use in derivative works. © David Liben-Nowell 2020–2021. This version was posted on October 5, 2021.

Acknowledgements xv

⊕

Cafe (Somerville, MA); Lyndell's (Cambridge, MA); Tryst (Washington, DC); Hot Numbers, Espresso Library (Cambridge, England); and various Starbucks, Caribous, and Dunn Brothers.

The revisions to this book that resulted in the current version occurred during the *annus horribilis* of 2020–2021, which had the secondary effect of precluding even a single visit to any of those various temporary host institutions. My profound gratitude to K. for the kindness, encouragement, and support while I've been toiling away, both at the book and at trying to maintain a semblance of being a human (maybe even one that I recognize), at the dining table that somehow counts as a desk. Here's to many more adventures together (with less toil, maybe?) to come.

And, last but certainly not least, my deepest gratitude to my friends and family for all your help and support while this project has consumed both hours and years. You know who you are, and I hope you also know how much I appreciate you. *Thank you!*

David Liben-Nowell Northfield, MN August 2021

PS: I would be delighted to receive any comments or suggestions. Please don't hesitate to get in touch.

Æ

Page-xvi

⊕

Credits

This book is a revised version of a book first published as *Discrete Mathematics for Computer Science* in 2017 (with a preliminary edition published in 2015) by John Wiley & Sons.

This book was typeset using LAT_EX , and I produced all but a few figures from scratch using TikZ. The other figures are reprinted with permission from their copyright holders:

- *First page of each chapter:* The illustrations that open every chapter were drawn for this book by Carissa Knipe (carissaknipe.com), who was a complete delight to work with—both on these illustrations and when she was a student at Carleton.
- *Figure 2.1:* The photograph of the bear's claws is a National Parks Service photo by Kaiti Critz, taken at the Katmai National Park and Preserve. It is in the public domain.
- *Figure 2.15:* The original (unblurred) image of Ada Lovelace is a section of a portrait by the artist Alfred Edward Chalon (1780–1860), and is in the public domain.
- *Figure 2.49:* The original (unquantized) image of Grace Hopper was taken by David C. MacLean. Official U.S. Navy Photograph, from the collections of the Naval History and Heritage Command. It is in the public domain.
- Figure 4.20: The photograph of Paul Erdős is of him at a student seminar in Budapest in 1992, taken by the Wikipedia user Kmhkmh; it is reproduced via the Creative Commons Attribution 3.0 Unported license creativecommons.org/licenses/by/3.0. The photograph of Chad Jenkins was taken by Joseph Xu of the College of Engineering at the University of Michigan, and is reproduced with permission. The photograph of Bill Gates is by U.S. Department of Energy photographer Ken Shipp, from a 2013 visit to the Department of Energy, and is in the public domain.
- *Figure 4.30:* The poem proving the undecidability of the Halting Problem) is Copyright © 2012 by Geoffrey K. Pullum, and is reproduced with permission from the author.
- *Figure 5.11:* The original image (without any hidden message) is from the National Security Agency photograph "WAVE Demonstrating Bombe" (1944) [Visual Information Record Identification Number 190531-D-IM742-9007.JPG], and is in the public domain.

Credits xvii

 \oplus

- *Figure 5.20:* The images of the Morse–Vail Telegraph Key are derived from a 3D model from the Smithsonian Institution's National Museum of American History, available at https://3d.si.edu, and in the public domain.
- *Figure 5.21:* The images of the rabbit are by Tobias Isenberg; they are printed with permission under CC BY-SA 4.0 https://creativecommons.org/licenses/by-sa/4.0/.
- *Figure 8.9:* The images of the New York State delegation to the U.S. House of Representatives are all official U.S. House of Representatives portraits, and are in the public domain.
- *Figure 9.23:* The original (uncompressed) photograph is "Katherine Johnson At Her Desk at NASA Langley Research Center" by NASA photographer Bob Nye (NASA ID: LRC-1966-B701_P-06717). It is in the public domain.
- *Figure 9.33:* The image is based on a c. 1946 U. S. Army Photo that is in the public domain; it shows two of the earliest-ever computer programmers, Betty Jean Jennings (later known as Jean Bartik) and Frances Bilas (later Frances Spence), running the ENIAC.
- *Figure 9.35:* The image of the Enigma machine is a section of a public-domain photograph from the CIA Museum.
- Quotations that appear at the beginning of section of the book:

The translation of the quotation by Franz Kafka (p. 5-4) is from [67].

The quotation from Mario Andretti (p. 6-4) is printed with permission from Mario Andretti.

The quotation from Vincent van Gogh (p. 6-60) comes from a letter to Theo van Gogh (3 April 1878). The letter can be found in Vincent van Gogh, *The Letters*. Ed. Leo Jansen, Hans Luijten and Nienke Bakker. Amsterdam 2009: www.vangoghletters.org. Reprinted with permission from the Van Gogh Museum.

The quotation from Nelson Mandela (p. 8-2) comes from an interview published by *Reader's Digest*, and it is printed with permission from the Nelson Mandela Foundation and from *Reader's Digest*.

The lyrics from Tom Lehrer's "Poisoning Pigeons in the Park" (p. 9-33) appear with permission from Tom Lehrer, and the Tom Lehrer Trust 2000 (tomlehrersongs.com).

The lines from Emily Dickinson (p. 10-6) appear with permission from Harvard University Press. They appear in *The Poems of Emily Dickinson*, edited by Thomas H. Johnson, Cambridge, Mass.: The Belknap Press of Harvard University Press, Copyright © 1951, 1955 by the President and Fellows of Harvard College. Copyright © renewed 1979, 1983 by the President and Fellows of Harvard College. Copyright © 1914, 1918, 1919, 1924, 1929, 1930, 1932, 1935, 1937, 1942, by Martha Dickinson Bianchi. Copyright © 1952, 1957, 1958, 1963, 1965, by Mary L. Hampson.

The lyrics from John Gorka's "I'm From New Jersey" (p. 10-57) are from the recording *Jack's Crows*, and appear with permission from John Gorka (www.johngorka.com).

 \oplus

 \oplus

xviii Credits

 \oplus

The lyrics from Kris Delmhorst's "North Dakota" (p. 11-34) are excerpted with permission from Kris Delmhorst (www.krisdelmhorst.com).

The remaining quotations that appear at the beginning of each section of the book are in the public domain.