DAVID LIBEN-NOWELL

DEPARTMENT OF COMPUTER SCIENCE

CARLETON COLLEGE

# DISCRETE MATHEMATICS FOR COMPUTER SCIENCE

OR

# (A Bit of) The Math that Computer Scientists Need to Know

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.

A revised version of this material has been / 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 April 5, 2021.

### Contents

### 1 On the Point of this Book 101

### 2 Basic Data Types 201

- 2.1 Why You Might Care 202
- 2.2 Booleans, Numbers, and Arithmetic 203
- 2.3 Sets: Unordered Collections 222
- 2.4 Sequences, Vectors, and Matrices: Ordered Collections 237
- 2.5 Functions 253
- 2.6 *Chapter at a Glance* 270

### 3 Logic 301

- 3.1 Why You Might Care 302
- 3.2 An Introduction to Propositional Logic 303
- 3.3 Propositional Logic: Some Extensions 317
- 3.4 An Introduction to Predicate Logic 331
- 3.5 Predicate Logic: Nested Quantifiers 349
- 3.6 Chapter at a Glance 362

- 4 *Proofs* 401
  - 4.1 Why You Might Care 402
  - 4.2 Error-Correcting Codes 403
  - 4.3 Proofs and Proof Techniques 423
  - 4.4 Some Examples of Proofs 441
  - 4.5 Common Errors in Proofs 458
  - 4.6 Chapter at a Glance 469
- 5 Mathematical Induction 501
  - 5.1 Why You Might Care 502
  - 5.2 Proofs by Mathematical Induction 503
  - 5.3 Strong Induction 521
  - 5.4 *Recursively Defined Structures and Structural Induction* 533
  - 5.5 Chapter at a Glance 546
- 6 Analysis of Algorithms 601
  - 6.1 Why You Might Care 602
  - 6.2 Asymptotics 603
  - 6.3 Asymptotic Analysis of Algorithms 617
  - 6.4 Recurrence Relations: Analyzing Recursive Algorithms 631
  - 6.5 Recurrence Relations: The Master Method 647
  - 6.6 *Chapter at a Glance* 657
- 7 Number Theory 701
  - 7.1 Why You Might Care 702
  - 7.2 Modular Arithmetic 703
  - 7.3 *Primality and Relative Primality* 717
  - 7.4 Multiplicative Inverses 734
  - 7.5 Cryptography 745
  - 7.6 *Chapter at a Glance* 756

#### *8 Relations* 801

8.1 Why You Might Care 802

8.2 Formal Introduction 803

8.3 Properties of Relations: Reflexivity, Symmetry, and Transitivity 818

8.4 Special Relations: Equivalence Relations and Partial/Total Orders 833

- 8.5 Chapter at a Glance 850
- 9 Counting 901
  - 9.1 Why You Might Care 902
  - 9.2 Counting Unions and Sequences 903
  - 9.3 Using Functions to Count 926
  - 9.4 Combinations and Permutations 944
  - 9.5 Chapter at a Glance 965

### 10 Probability 1001

- 10.1 Why You Might Care 1002
- 10.2 Probability, Outcomes, and Events 1005
- 10.3 Independence and Conditional Probability 1021
- 10.4 Random Variables and Expectation 1041
- 10.5 Chapter at a Glance 1067
- *11 Graphs and Trees* 1101
  - 11.1 Why You Might Care 1102
  - 11.2 Formal Introduction 1103
  - 11.3 Paths, Connectivity, and Distances 1129
  - 11.4 Trees 1147
  - 11.5 Weighted Graphs 1164
  - 11.6 Chapter at a Glance 1177

12 Index 1201

# List of Computer Science Connections

Chapter 2: Basic Data Types

Integers and ints, Reals and floats 217 Computing Square Roots, and Not Computing Square Roots 218 Set Building in Languages 233 Clustering 234 The Vector Space Model 248 Rotation Matrices 249 Hash Tables and Hash Functions 267

Chapter 3: Logic

Natural Language Processing, Ambiguity, and Truth314Computational Complexity, Satisfiability, and \$1,000,000326Short-Circuit Evaluation, Optimization, and Modern Compilers327Game Trees, Logic, and Winning Tic-Tac(-Toe)344Nonlocal Variables and Lexical vs. Dynamic Scoping345Gödel's Incompleteness Theorem346Currying357

Chapter 4: Proofs

Reed–Solomon Codes418Are Massive Computer-Generated Proofs Proofs?437Paul Erdős, "The Book," and Erdős Numbers438Cryptography and the Generation of Prime Numbers454Other Uncomputable Problems (That You Might Care About)455The Cost of Missing Proofs: Some Famous Bugs in CS464

### Chapter 5: Mathematical Induction

Loop Invariants	517		
Triangulation, Cor	nputer Graphics, and	3D Surfaces	528
Max Heaps 52	9		
Grammars, Parsin	g, and Ambiguity	543	

### Chapter 6: Analysis of Algorithms

Moore's Law	613			
Multitasking, C	Garbage Collection	, and Wall Clocks	627	
Time, Space, an	d Complexity	628		
AVL Trees	643			
Divide-and-Conquer Algorithms and Matrix Multiplication				655

### Chapter 7: Number Theory

Converting Between Bases, Binary Representation, and Generating Strings714Secret Sharing730Error Correction with Reed–Solomon Codes731Miller–Rabin Primality Test742Diffie–Hellman Key Exchange753

*Chapter 8: Relations* 

Relational Databases815Regular Expressions830Deterministic Finite Automata (DFAs)846The Painter's Algorithm and Hidden-Surface Removal847

### Chapter 9: Counting

Running out of IP addresses, and IPv6919A Lower Bound for Comparison-Based Sorting920Infinite Cardinalities (and Problems that Can't Be Solved by Any Program)937Lossy and Lossless Compression938Brute Force Algorithms and Dynamic Programming959The Enigma Machine and the First Computer960

### Chapter 10: Probability

Quantum Computing1016Information, Charles Dickens, and the Entropy of English1017Speech Recognition, Bayes' Rule, and Language Models1036Bayesian Modeling and Spam Filtering1037A Randomized Algorithm for Finding Medians1060The Monte Carlo Method1062

Chapter 11: Graphs and Trees

Degree Distributions and the Heavy Tail1123Graph Drawing, Graph Layouts, and the 9/11 Memorial1124The Bowtie Structure of the Web1142Garbage Collection1143Directed Graphs, Cycles, and Kidney Transplants1159Binary Search Trees1160Random Walks and Ranking Web Pages1174

## 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

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. 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, when we next see each other, the first round's on me. While I'm leaving out the names of the many people who have 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): Eric Alexander, Tanya Berger-Wolf, Kelly Connole, Amy Csizmar Dalal, Josh Davis, Roger Downs, Laura Effinger-Dean, Eric Egge, Adriana Estill, Andy Exley, Alex Freeman, Sherri Goings, Jack Goldfeather, Deanna Haunsperger, Pierre Hecker, David Huyck, Sue Jandro, Sarah Jansen, Iris Jastram, Jon Kleinberg, Carissa Knipe, Mark Krusemeyer, Jessica Leiman, Lynn Liben, Jadrian Miles, Dave Musicant, Gail Nelson, Rich Nowell, Layla Oesper, Jeff Ondich, Sam Patterson, Anna Rafferty, Alexa Sharp, Julia Strand, Mike Tie, Zach Weinersmith, Tom Wexler, Kevin Woods, Jed Yang, and Steve Zdancewic.

I also owe my appreciation to Don Fowley, Bryan Gambrel, Beth Golub, Jessy Moor, Anna Pham, Sondra Scott, and Gladys Soto at Wiley. Thanks to Judy Brody for relentless and efficient pursuit of permissions (from many different people and publishers)

to use the quotes that appear as epigraphs throughout the book. And thanks as well to the many insightful reviewers of previous 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. (And, to be clear: blame me, not them, for the errors that I'm sure remain.)

I specifically want to thank Eric Alexander, Laura Biester, Josh Davis, Charlotte Foran, Jadrian Miles, Dave Musicant, Layla Oesper, Anna Rafferty, Jed Yang, and the Carleton CS 202 students from 2013–2017 for their willingness to work 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-in particular: 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, Greg 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 of the late 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, Spy-house, 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 Cafe (Somerville, MA); Lyndell's (Cambridge, MA); Tryst (Washington, DC); Hot Numbers, Espresso Library (Cambridge, England); and various Starbucks, Caribous, and Dunn Brothers.

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 May 2017

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

## Credits

This book was typeset using LATEX, and I produced all but a few figures from scratch using a combination of PSTricks and TikZ. The other figures are reprinted with permission from their copyright holders. The illustrations that open every chapter were drawn by Carissa Knipe (http://carissaknipe.com), who was a complete delight to work with—both on these illustrations and when she was a student at Carleton. I took the photograph of a house in Figure 2.48 myself. Figure 4.5 (the Therac-25 diagram) is reproduced from Nancy Leveson's book *Safeware: System Safety and Computers* with permission from Pearson Education. Figure 4.27 (a poem proving the undecidability of the Halting Problem) is reproduced with permission from Geoffrey K. Pullum. Figure 5.22 (triangulations of a rabbit) is reproduced from a paper by Tobias Isenberg, Knut Hartmann, and Henry König with permission from the Society for Modeling and Simulation International (SCS). Figure 11.15 (a map of some European train routes) is reproduced with permission from RGBAlpha/Getty Images.<sup>1</sup>

For their kind permission to use quotes that appear as epigraphs in sections throughout the book, thanks to:

- *Kurt Vonnegut, p. 102.* Excerpt from *Hocus Pocus* by Kurt Vonnegut, copyright ©1990 by Kurt Vonnegut. Used by permission of G. P. Putnam's Sons, an imprint of Penguin Publishing Group, a division of Penguin Random House LLC. All rights reserved. Any third party use of this material, outside of this publication, is prohibited. Interested parties must apply directly to Penguin Random House LLC for permission.
- *Pablo Picasso, p. 203.* ©2017 Estate of Pablo Picasso / Artists Rights Society (ARS), New York. Reprinted with permission.
- Laurence J. Peter, p. 317. Reprinted with permission of the estate of Laurence J. Peter.
- *Carl Sagan, p. 331.* From *Broca's Brain: Reflections on the Romance of Science,* ©1979 Carl Sagan. Reprinted with permission from Democritus Properties, LLC.
- *Peter De Vries, p. 349.* Copyright ©1967 by Peter De Vries. Reprinted by permission of Curtis Brown, Ltd. All rights reserved.

<sup>1</sup> Nancy Leveson. Safeware: System Safety and Computers. Pearson Education, Inc., New York, 1995; Tobias Isenberg, Knut Hartmann, and Henry König. Interest value driven adaptive subdivision. In Simulation and Visualisation (SimVis), pages 139-149. SCS European Publishing House, 2003; and Geoffrey K. Pullum. Scooping the loop snooper: A proof that the halting problem is undecidable. Mathematics Magazine, 73(4):319-320, 2000. Used by permission of Geoffrey K. Pullum.

- *Edna St. Vincent Millay, p. 521.* Edna St. Vincent Millay, excerpt from a letter to Arthur Davidson Ficke (October 24, 1930) from *Letters of Edna St. Vincent Millay*, edited by Allan Ross Macdougall, ©1952 by Norma Millay Ellis. Reprinted with the permission of The Permissions Company, Inc., on behalf of Holly Peppe, Literary Executor, The Millay Society, www.millay.org.
- *George C. Marshall, p. 533.* Reprinted with permission of the George C. Marshall Foundation.
- *Peter Drucker, p. 602.* Reprinted with permission of the Drucker 1996 Literary Works Trust.
- Bob Dylan, p. 603. Lyrics from Bob Dylan's "Don't Think Twice, It's All Right" (1963). Copyright ©1963 by Warner Bros. Inc.; renewed 1991 by Special Rider Music. All rights reserved. International copyright secured. Reprinted by permission.
- Mario Andretti, p. 617. Printed with permission of Sports Management Network, Inc.
- *E. B. White*, *p.* 631. E. B. White / *The New Yorker*; ©Conde Nast. The quote originally appeared in the *Notes and Comment* section of the July 3, 1943 issue of *The New Yorker*, "The 40s: The Story of a Decade." Reprinted with permission.

Charles de Gaulle, p. 647. © Editions Plon. Reprinted with permission.

- W. H. Auden, p. 703. "Notes on the Comic" from *The Dyer's Hand and Other Essays* by W. H. Auden, copyright ©1948, 1950, 1952, 1953, 1954, 1956, 1957, 1958, 1960, 1962 by W. H. Auden. Used by permission of Random House, an imprint and division of Penguin Random House LLC. All rights reserved. Any third party use of this material, outside of this publication, is prohibited. Interested parties must apply directly to Penguin Random House LLC for permission.
- *Bill Watterson, p. 833.* Quote from a *Calvin & Hobbes* cartoon; reprinted with permission from Universal Uclick.
- *Tom Lehrer, p. 926.* Lyrics from "Poisoning Pigeons In The Park" reprinted with permission from Maelstrom Music/ Tom Lehrer.
- Dick Cavett, p. 1021. Reprinted with permission from Dick Cavett.
- *Tom Stoppard*, *p.* 1108. Excerpts from *Rosencrantz and Guildenstern Are Dead*, copyright © 1967 by Tom Stoppard. Used by permission of Grove/Atlantic, Inc. Any third party use of this material, outside of this publication, is prohibited.
- Marshall Dodge and Robert Bryan, p. 1129. From "Which Way to Millinocket?," Bert and I (1958). Reprinted with permission from Islandport Press, Inc.