Elements of Information Theory
Thomas M. Cover, Joy A. Thomas

Print ISBN 0-471-06259-6 Online ISBN 0-471-20061-1

Elements of Information Theory

Elements of Information Theory
Thomas M. Cover, Joy A. Thomas

Print ISBN 0-471-06259-6 Online ISBN 0-471-20061-1

WILEY SERIES IN TELECOMMUNICATIONS

Donald L. Schilling, Editor
City College of New York

Digital Telephony, 2nd Edition
John Bellamy

Elements of Information Theory
Thomas M. Cover and Joy A. Thomas

Telecommunication System Engineering, 2nd Edition
Roger L. Freeman

Telecommunication Transmission Handbook, 3rd Edition
Roger L. Freeman

Introduction to Communications Engineering, 2nd Edition
Robert M. Gagliardi

Expert System Applications to Telecommunications
Jay Liebowitz

Synchronization in Digital Communications, Volume 1
Heinrich Meyr and Gerd Ascheid

Synchronization in Digital Communications, Volume 2
Heinrich Meyr and Gerd Ascheid (in preparation)

Computational Methods of Signal Recovery and Recognition
Richard J. Mammone (in preparation)

Business Earth Stations for Telecommunications
Walter L. Morgan and Denis Rouffet

Satellite Communications: The First Quarter Century of Service
David W. E. Rees

Worldwide Telecommunications Guide for the Business Manager
Walter L. Vignault

Elements of Information Theory

THOMAS M. COVER

Stanford University
Stanford, California

JOY A. THOMAS

IBM T. J. Watson Research Center
Yorktown Heights, New York

A Wiley-Interscience Publication
JOHN WILEY & SONS, INC.
New York / Chichester / Brisbane / Toronto / Singapore

ISBN 0-471-20061-1.

This title is also available in print as ISBN 0-471-06259-6

For more information about Wiley products, visit our web site at www.Wiley.com.

Library of Congress Cataloging in Publication Data:

Cover, T. M., 1938—
Elements of Information theory / Thomas M. Cover, Joy A. Thomas.
p. cm.—(Wiley series in telecommunications)
"A Wiley-Interscience publication."
Includes bibliographical references and index.
ISBN 0-471-06259-6
1. Information theory. I. Thomas, Joy A. II. Title.
III. Series.
Q360.C68 1991
003′.54—dc20 90-45484
CIP

Printed in the United States of America

20 19 18 17 16 15 14 13

To my father
Tom Cover

To my parents
Joy Thomas

Preface

This is intended to be a simple and accessible book on information theory. As Einstein said, *"Everything should be made as simple as possible, but no simpler."* Although we have not verified the quote (first found in a fortune cookie), this point of view drives our development throughout the book. There are a few key ideas and techniques that, when mastered, make the subject appear simple and provide great intuition on new questions.

This book has arisen from over ten years of lectures in a two-quarter sequence of a senior and first-year graduate level course in information theory, and is intended as an introduction to information theory for students of communication theory, computer science and statistics.

There are two points to be made about the simplicities inherent in information theory. First, certain quantities like entropy and mutual information arise as the answers to fundamental questions. For example, entropy is the minimum descriptive complexity of a random variable, and mutual information is the communication rate in the presence of noise. Also, as we shall point out, mutual information corresponds to the increase in the doubling rate of wealth given side information. Second, the answers to information theoretic questions have a natural algebraic structure. For example, there is a chain rule for entropies, and entropy and mutual information are related. Thus the answers to problems in data compression and communication admit extensive interpretation. We all know the feeling that follows when one investigates a problem, goes through a large amount of algebra and finally investigates the answer to find that the entire problem is illuminated, not by the analysis, but by the inspection of the answer. Perhaps the outstanding examples of this in physics are Newton's laws and

Schrodinger's wave equation. Who could have foreseen the awesome philosophical interpretations of Schrödinger's wave equation?

In the text we often investigate properties of the answer before we look at the question. For example, in Chapter 2, we define entropy, relative entropy and mutual information and study the relationships and a few interpretations of them, showing how the answers fit together in various ways. Along the way we speculate on the meaning of the second law of thermodynamics. Does entropy always increase? The answer is yes and no. This is the sort of result that should please experts in the area but might be overlooked as standard by the novice.

In fact, that brings up a point that often occurs in teaching. It is fun to find new proofs or slightly new results that no one else knows. When one presents these ideas along with the established material in class, the response is "sure, sure, sure." But the excitement of teaching the material is greatly enhanced. Thus we have derived great pleasure from investigating a number of new ideas in this text book.

Examples of some of the new material in this text include the chapter on the relationship of information theory to gambling, the work on the universality of the second law of thermodynamics in the context of Markov chains, the joint typicality proofs of the channel capacity theorem, the competitive optimality of Huffman codes and the proof of Burg's theorem on maximum entropy spectral density estimation. Also the chapter on Kolmogorov complexity has no counterpart in other information theory texts. We have also taken delight in relating Fisher information, mutual information, and the Brunn-Minkowski and entropy power inequalities. To our surprise, many of the classical results on determinant inequalities are most easily proved using information theory.

Even though the field of information theory has grown considerably since Shannon's original paper, we have strived to emphasize its coherence. While it is clear that Shannon was motivated by problems in communication theory when he developed information theory, we treat information theory as a field of its own with applications to communication theory and statistics.

We were drawn to the field of information theory from backgrounds in communication theory, probability theory and statistics, because of the apparent impossibility of capturing the intangible concept of information.

Since most of the results in the book are given as theorems and proofs, we expect the elegance of the results to speak for themselves. In many cases we actually describe the properties of the solutions before introducing the problems. Again, the properties are interesting in themselves and provide a natural rhythm for the proofs that follow.

One innovation in the presentation is our use of long chains of inequalities, with no intervening text, followed immediately by the

explanations. By the time the reader comes to many of these proofs, we expect that he or she will be able to follow most of these steps without any explanation and will be able to pick out the needed explanations. These chains of inequalities serve as pop quizzes in which the reader can be reassured of having the knowledge needed to prove some important theorems. The natural flow of these proofs is so compelling that it prompted us to flout one of the cardinal rules of technical writing. And the absence of verbiage makes the logical necessity of the ideas evident and the key ideas perspicuous. We hope that by the end of the book the reader will share our appreciation of the elegance, simplicity and naturalness of information theory.

Throughout the book we use the method of weakly typical sequences, which has its origins in Shannon's original 1948 work but was formally developed in the early 1970s. The key idea here is the so-called asymptotic equipartition property, which can be roughly paraphrased as "Almost everything is almost equally probable."

Chapter 2, which is the true first chapter of the subject, includes the basic algebraic relationships of entropy, relative entropy and mutual information as well as a discussion of the second law of thermodynamics and sufficient statistics. The asymptotic equipartition property (AEP) is given central prominence in Chapter 3. This leads us to discuss the entropy rates of stochastic processes and data compression in Chapters 4 and 5. A gambling sojourn is taken in Chapter 6, where the duality of data compression and the growth rate of wealth is developed.

The fundamental idea of Kolmogorov complexity as an intellectual foundation for information theory is explored in Chapter 7. Here we replace the goal of finding a description that is good on the average with the goal of finding the universally shortest description. There is indeed a universal notion of the descriptive complexity of an object. Here also the wonderful number Ω is investigated. This number, which is the binary expansion of the probability that a Turing machine will halt, reveals many of the secrets of mathematics.

Channel capacity, which is the fundamental theorem in information theory, is established in Chapter 8. The necessary material on differential entropy is developed in Chapter 9, laying the groundwork for the extension of previous capacity theorems to continuous noise channels. The capacity of the fundamental Gaussian channel is investigated in Chapter 10.

The relationship between information theory and statistics, first studied by Kullback in the early 1950s, and relatively neglected since, is developed in Chapter 12. Rate distortion theory requires a little more background than its noiseless data compression counterpart, which accounts for its placement as late as Chapter 13 in the text.

The huge subject of network information theory, which is the study of the simultaneously achievable flows of information in the presence of

noise and interference, is developed in Chapter 14. Many new ideas come into play in network information theory. The primary new ingredients are interference and feedback. Chapter 15 considers the stock market, which is the generalization of the gambling processes considered in Chapter 6, and shows again the close correspondence of information theory and gambling.

Chapter 16, on inequalities in information theory, gives us a chance to recapitulate the interesting inequalities strewn throughout the book, put them in a new framework and then add some interesting new inequalities on the entropy rates of randomly drawn subsets. The beautiful relationship of the Brunn-Minkowski inequality for volumes of set sums, the entropy power inequality for the effective variance of the sum of independent random variables and the Fisher information inequalities are made explicit here.

We have made an attempt to keep the theory at a consistent level. The mathematical level is a reasonably high one, probably senior year or first-year graduate level, with a background of at least one good semester course in probability and a solid background in mathematics. We have, however, been able to avoid the use of measure theory. Measure theory comes up only briefly in the proof of the AEP for ergodic processes in Chapter 15. This fits in with our belief that the fundamentals of information theory are orthogonal to the techniques required to bring them to their full generalization.

Each chapter ends with a brief telegraphic summary of the key results. These summaries, in equation form, do not include the qualifying conditions. At the end of each we have included a variety of problems followed by brief historical notes describing the origins of the main results. The bibliography at the end of the book includes many of the key papers in the area and pointers to other books and survey papers on the subject.

The essential vitamins are contained in Chapters 2, 3, 4, 5, 8, 9, 10, 12, 13 and 14. This subset of chapters can be read without reference to the others and makes a good core of understanding. In our opinion, Chapter 7 on Kolmogorov complexity is also essential for a deep understanding of information theory. The rest, ranging from gambling to inequalities, is part of the terrain illuminated by this coherent and beautiful subject.

Every course has its first lecture, in which a sneak preview and overview of ideas is presented. Chapter 1 plays this role.

TOM COVER
JOY THOMAS

Palo Alto, June 1991

Acknowledgments

We wish to thank everyone who helped make this book what it is. In particular, Toby Berger, Masoud Salehi, Alon Orlitsky, Jim Mazo and Andrew Barron have made detailed comments on various drafts of the book which guided us in our final choice of content. We would like to thank Bob Gallager for an initial reading of the manuscript and his encouragement to publish it. We were pleased to use twelve of his problems in the text. Aaron Wyner donated his new proof with Ziv on the convergence of the Lempel-Ziv algorithm. We would also like to thank Norman Abramson, Ed van der Meulen, Jack Salz and Raymond Yeung for their suggestions.

Certain key visitors and research associates contributed as well, including Amir Dembo, Paul Algoet, Hirosuke Yamamoto, Ben Kawabata, Makoto Shimizu and Yoichiro Watanabe. We benefited from the advice of John Gill when he used this text in his class. Abbas El Gamal made invaluable contributions and helped begin this book years ago when we planned to write a research monograph on multiple user information theory. We would also like to thank the Ph.D. students in information theory as the book was being written: Laura Ekroot, Will Equitz, Don Kimber, Mitchell Trott, Andrew Nobel, Jim Roche, Erik Ordentlich, Elza Erkip and Vittorio Castelli. Also Mitchell Oslick, Chien-Wen Tseng and Michael Morrell were among the most active students in contributing questions and suggestions to the text. Marc Goldberg and Anil Kaul helped us produce some of the figures. Finally we would like to thank Kirsten Goodell and Kathy Adams for their support and help in some of the aspects of the preparation of the manuscript.

Joy Thomas would also like to thank Peter Franaszek, Steve Lavenberg, Fred Jelinek, David Nahamoo and Lalit Bahl for their encouragement and support during the final stages of production of this book.

TOM COVER
JOY THOMAS

Contents

List of Figures

Elements of Information Theory

Elements of Information Theory
Thomas M. Cover, Joy A. Thomas

Print ISBN 0-471-06259-6 Online ISBN 0-471-20061-1

Index

Page numbers set in **boldface** indicate the primary references.