# Foundations of Combinatorics with Applications

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# Preface

Combinatorics, the mathematics of the discrete, has blossomed in this generation. On the theoretical side, a variety of tools, concepts and insights have been developed that allow us to solve previously intractable problems, formulate new problems and connect previously unrelated topics. On the applied side, scientists from physicists to biologists have found combinatorics essential in their research. In all of this, the interaction between computer science and mathematics stands out as a major impetus for theoretical developments and for applications of combinatorics. This text provides an introduction to the mathematical foundations of this interaction and to some of its results.

## Advice to Students

This book does not assume any previous knowledge of combinatorics or discrete mathematics. Except for a few items which can easily be skipped over and some of the material on "generating functions" in Part IV, calculus is not required. What is required is a certain level of ability or "sophistication" in dealing with mathematical concepts. The level of mathematical sophistication that is needed is about the same as that required in a solid beginning calculus course.

You may have noticed similarities and differences in how you think about various fields of mathematics such as algebra and geometry. In fact, you may have found some areas more interesting or more difficult than others partially because of the different thought patterns required. The field of combinatorics will also require you to develop some new thought patterns. This can sometimes be a difficult and frustrating process. Here is where patience, mathematical sophistication and a willingness to ask "stupid questions" can all be helpful.

Combinatorics differs as much from mathematics you are likely to have studied previously as algebra differs from geometry. Some people find this disorienting and others find it fascinating. The introductions to the parts and to the chapters can help you orient yourself as you learn about combinatorics. Don't skip them.

Because of the newness of much of combinatorics, a significant portion of the material in this text was only discovered in this generation. Some of the material is closely related to current research. In contrast, the other mathematics courses you have had so far probably contained little if anything that was not known in the Nineteenth Century. Welcome to the frontiers!

## The Material in this Book

Combinatorics is too big a subject to be done justice in a single text. The selection of material in this text is based on the need to provide a solid introductory course for our students in pure mathematics and in mathematical computer science. Naturally, the material is also heavily influenced by our own interests and prejudices.

Parts I and II deal with two fundamental aspects of combinatorics: enumeration and graph theory. "Enumeration" can mean either counting or listing things. Mathematicians have generally limited their attention to counting, but listing plays an important role in computer science, so we discuss both aspects. After introducing the basic concepts of "graph theory" in Part II, we present a variety of applications of interest in computer science and mathematics. Induction and recursion play a fundamental role in mathematics. The usefulness of recursion in computer science and in its interaction with combinatorics is the subject of Part III. In Part IV we look at "generating functions," a powerful tool for studying counting problems. We have included a variety of material not usually found in introductory texts:

- Trees play an important role. Chapter 3 discusses decision trees with emphasis on ranking and unranking. Chapter 9 is devoted to the theory and application of rooted plane trees. Trees have many practical applications, have an interesting and accessible theory and provide solid examples of inductive proofs and recursive algorithms.
- Software and network sorts are discussed in Chapter 8. We have attempted to provide the overview and theory that is often lacking elsewhere.
- Part IV is devoted to the important topic of generating functions. We could not, in good conscience, deny our students access to the more combinatorial approaches to generating functions that have emerged in recent years. This necessitated a longer treatment than a quick ad hoc treatment would require. Asymptotic analysis of generating functions presented a dilemma. On the one hand, it is very useful; while on the other hand, it cannot be done justice without an introductory course in complex analysis. We chose a somewhat uneasy course: In the last section we presented some rules for analysis that usually work and can be understood without a knowledge of complex variables.

## Planning a Course

A variety of courses can be based on this text. Depending on the material covered, the pace at which it is done and the level of rigor required of the students, this book could be used in a challenging lower division course, in an upper division course for engineering, science or mathematics students, or in a beginning graduate course. There are a number of possibilities for choosing material suitable for each of these classes. A graduate course could cover the entire text at a leisurely pace in a year or at a very fast pace in a semester. Here are some possibilities for courses with a length of one semester to two quarters, depending on how much parenthesized optional material is included. Parts of an optional chapter can also be used instead of the entire chapter.

- A lower division course: 1, 2.1–2.3, (2.4), 3.1, (4.1), 5.1, (5.2), 5.3–5.5, (6), 7.1, 7.2, (7.3), (8), 9.1, (9.2).
- An upper division or beginning graduate course emphasizing mathematics: 1–3, 4.1, (4.2), 4.3, 5, 6.1, (6.2–6.4), 7, (8) 9.1, (9.2–9.3), 10, (11).
- An upper division or beginning graduate course emphasizing computer science: 1–3, 4.1, 5, 6.1, 6.3, (6.4), (6.5), 7, 8, (9.1), 9.2, 9.3, 10, (11.4).

Asterisks, or stars, (*) appear before various parts of the text to help in course design. Starred exercises are either more difficult than other exercises in that section or depend on starred material. Starred examples are generally more difficult than other material in the chapter. A section or chapter that is not as central as the rest of the material is also starred. The material in Part IV, especially parts of Chapter 11, is more difficult than the rest of the text.

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