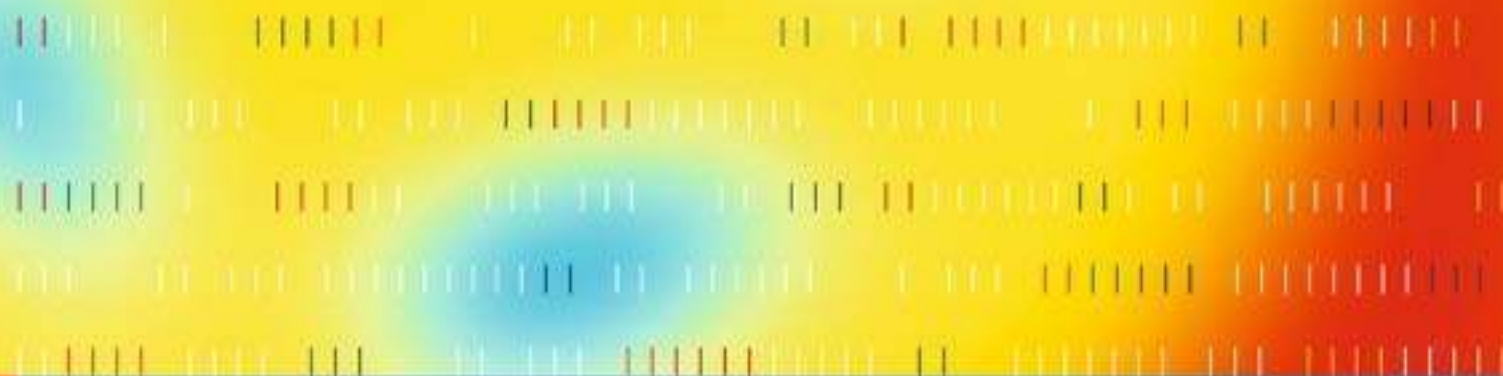


Sergey Kitaev



Patterns in Permutations and Words

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Patterns in Permutations and Words

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Foreword

The study of patterns in permutations and words has a long history. For example, starting in the 1880s, MacMahon began his study of combinatorial objects. In particular, he gave generating functions for the distribution of inversions in permutations and words which in modern day terminology correspond to occurrences of the pattern 21. The study of descents or consecutive occurrences of the pattern 21 goes back even further in that Leonhard Euler in 1749 introduced polynomials of the form $\sum_{k=0}^n (k+1)^n t^k = \frac{A_n(t)}{(1-t)^{n+1}}$ to help in the evaluation of the Dirichlet η -function $\eta(s) = \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n^s}$. The polynomial $A_n(t)$, which is now known as the Eulerian polynomial, is the generating function of the number of descents over the symmetric group S_n , i.e. $A_n(t) = \sum_{\sigma \in S_n} x^{\text{des}(\sigma)}$. The Eulerian polynomials were studied from a combinatorial point of view by Foata and Schützenberger in 1970. The study of permutations and words that have regular patterns also has a long history. For example, André in 1879 showed that the exponential generating function of up-down permutations is $\sec(x) + \tan(x)$ and Carlitz in 1973 found the generating functions for up-down words. These and other works led to the study of permutation statistics which became an active area of research starting in the 1970s and remains an active area of research up to this day.

The origin of the modern day study of patterns in words can be traced back to papers by Rotem, Rogers, and Knuth in the 1970s and early 1980s. The first systematic study of permutation patterns was not undertaken until the paper by Simion and Schmidt which appeared in 1985. Today the study of patterns in permutations and words is a very active field as is evidenced by the exceedingly long bibliography for this volume. At this point, there is a rich collection of tools that has been developed to study a variety of problems such as how to count the number of permutations and words that avoid a given pattern or collection of patterns or how to find the generating function for the number of occurrences of a pattern or collection of patterns. The notion of patterns in permutations and words has proved to be a useful language in a variety of seemingly unrelated problems including the theory of Kazhdan-Lusztig polynomials, singularities of Schubert varieties, Chebyshev polynomials, rook polynomials for Ferrers boards, and various sorting algorithms

including sorting stacks and sortable permutations. In addition, the study of patterns in permutations and words also arises in computational biology and theoretical physics.

The present book is a welcome addition to the literature on permutation patterns. In this book, Sergey Kitaev not only systematizes and organizes a vast number of results on patterns in permutations and words that have appeared in the literature, but he also describes the connections of the study of patterns in permutations and words with the various fields mentioned in the previous paragraph. The study of patterns in permutations and words also leads to a large number of interesting questions in bijective combinatorics. For example, we say that two permutations σ and τ are Wilf-equivalent if for all n , the number of permutations of S_n which avoid σ , i.e. which have no occurrences of the pattern σ , is the same as the number of permutations of S_n which avoid τ . There is a vast literature on classifying which pairs of permutations are Wilf-equivalent and such a classification naturally leads to questions of how to find bijective proofs of such equivalences. Similarly, there is a large literature which shows that various other combinatorial objects such as partially ordered sets, lattice paths, planar maps, and labeled trees are equinumerous with certain classes of permutations which avoid a given pattern. This book provides a valuable introduction to the study of bijective questions that arise in the study of patterns in permutations and words. Another novel feature of this book is that Kitaev puts particular emphasis on various generalizations of classical patterns in permutations and words such as partially ordered patterns, barred patterns, vincular patterns, bivariate patterns, and place-difference-value patterns. This is the first book that provides a comprehensive look at such generalizations of classical patterns. Thus, this book provides a welcome and valuable addition to the study of patterns in permutations and words. I believe that it will provide a valuable introduction for graduate students and researchers who want to pursue research in the study of patterns in permutations and words as well as a valuable reference for experts in the field.

Jeffrey B. Remmel
San Diego, February 20, 2011

Preface

This book deals with occurrences of patterns in permutations and, more generally, in words with repeated letters. An occurrence of a pattern in a word is a subsequence of the word whose letters appear in the same order of size as the letters in the pattern. As a simple example, an occurrence of the pattern 321 is simply a decreasing subsequence of length 3, such as the one formed by the letters 632 in the permutation 4631725.

The patterns we deal with have been studied sporadically, often implicitly, for over a century, but in the last 20 years or so, the area has grown dramatically, resulting in many hundreds of published papers and in the annual conference “Permutation Patterns” organized for the first time at the University of Otago in Dunedin, New Zealand, in 2003. The introduction of the area of (permutation) patterns is traditionally attributed to Donald Knuth and in particular to exercises on pages 242–243 in his first volume of “The Art of Computer Programming” [540] in 1968, while the first systematic study of pattern avoidance was done by Rodica Simion and Frank W. Schmidt [721] in 1985.

There are several survey papers on this subject [136, 183, 515, 512, 352, 749, 751, 805] and the entire Volume 9 (2) of the *Electronic Journal of Combinatorics* is devoted to it. Moreover, there are proceedings of the Permutation Patterns 2007 conference, edited by Steve Linton, Nik Ruškuc and Vincent Vatter, and published in the London Mathematical Society Lecture Note Series, Cambridge University Press (vol. 376). The book “A walk through combinatorics” [141] by Miklós Bóna contains material on permutation patterns, while the book “Combinatorics of permutations” [137] by the same author provides a comprehensive and accessible introduction to so-called *classical permutation patterns*. Finally, there is the book “Combinatorics of compositions and words” [461] by Silvia Heubach and Toufik Mansour directly related to the subject.

However, the area has grown far beyond the content of the books mentioned above. The notion of a “pattern” has been extended in many different ways, often bringing new connections to other disciplines. Even such an important and relatively well-studied class of patterns as “generalized patterns” (called “vincular patterns”

in this book) introduced by Eric Babson and Einar Steingrímsson in 2000, received almost no attention in the books by Bóna and was not considered for permutations in the book by Heubach and Mansour. One of the goals of this book is to introduce a new notation for vincular patterns, because it has been somewhat confusing so far.

The two main objectives of this book are the following:

1. **To provide a motivation** to study patterns by demonstrating as many links to other areas of research as possible — Chapters 2 and 3 are entirely dedicated to this, and many other parts of the book contain such motivating material. These links provide connections to different combinatorial structures appearing in the literature, but also references to computer science (*sorting, generating, and complexity issues*), statistical mechanics (*Partially Asymmetric Simple Exclusion Process*), and computational biology (*whole genome duplication-random loss model*).
2. **To be comprehensive** in mentioning existing publications, and in sketching new research directions and trends in the field. In particular, we hope to have gathered, in our bibliography, almost all published papers related to the area (the book contains more than 800 references). Of course, there is a price to pay for being comprehensive, while keeping the size of the book within reasonable limits — we give very few proofs and there are no exercises. However, references are given to all results mentioned, so that the interested reader should have no problems finding the details.

While the book mentions several original results from papers in preparation, a couple of important topics were not covered the way they deserve to be. These topics include, but are not limited to, the intensively studied theory of *pattern classes* (see Remark 6.1.65 for a collection of references on it) and *enumeration schemes* (see [662, 663, 781, 816]). Moreover, we do not discuss at all a couple of research directions, for example, the results on the Möbius function on posets defined by different notions of pattern containment (see [107, 122, 202, 513, 708, 752]). Except for that, the book is a comprehensive collection of up-to-date results on patterns, most of which will be accessible to a broad audience, from undergraduate students to active researchers in the area of patterns in words and permutations, or adjacent fields.

The book is organized as follows.

- In Chapter 1 we introduce the main classes of patterns of interest in this book (classical patterns, barred patterns, vincular patterns, bivincular patterns, and

partially ordered patterns) and also provide examples of typical problems on these patterns. Moreover, we list a bibliography related to each of the pattern classes.

- In Chapters 2 and 3 we provide motivation points to study patterns in words and permutations. They include links to theoretical computer science through several sorting devices, planar maps and relevant objects, Schubert varieties and Kazhdan-Lusztig polynomials, computational biology through the tandem duplication-random loss model, statistical mechanics through the Partially Asymmetric Simple Exclusion Process, the theory of partially ordered sets, classification of Mahonian statistics, bijective combinatorics through encoding combinatorial objects by pattern-restricted permutations, and more.
- In Chapter 4 we present the more than thirty year history of bijections between permutations avoiding any classical pattern trivially equivalent to 321 and any pattern trivially equivalent to 132. We discuss a recent classification of these bijections and a philosophical question on what is a “good” bijection from the point of view of bijective combinatorics. Additionally, this chapter provides a collection of approaches to deal with classical patterns, along with general theorems about Wilf-equivalence of certain classical patterns.
- Chapter 5 contains an overview of results on consecutive patterns, and various approaches to studying them. For example, in this chapter we discuss the symbolic method, the symmetric functions approach, and the cluster and chain methods.
- In Chapters 6 and 7 we collect known (mostly enumerative) results on various patterns other than consecutive ones.
- In Chapter 8 we discuss several topics without a common thread. These topics include simple permutations, pattern matching problems, Gray codes, packing patterns, a link to combinatorics on words, universal cycles, simsun permutations, and games on patterns in permutations.
- In Chapter 9 we present several extensions and generalizations of the study of patterns discussed in the previous chapters.
- Appendix A serves as an easy access to the definitions for most of the permutation/word statistics and number sequences appearing in this book, while in Appendix B we provide a couple of basic algebraic facts, including the notion of Chebyshev polynomials of the second kind.

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Sergey Kitaev
Reykjavík, March 11, 2011

Notation

| | |
|------------------------------------------|-------------------------------------------------------------|
| $ A $ | the number of elements in a set A |
| $\text{asc}(\pi)$ | the number of ascents in π |
| $\text{Av}(P)$ | the set of all permutations avoiding each pattern in P |
| $\text{Av}_\ell(P)$ | the set $\cup_{n \geq 0} W_{n,\ell}(P)$ |
| b.g.f. | bivariate generating function |
| BP | barred pattern |
| BVP | bivincular pattern |
| C_n | the n -th Catalan number |
| $C(x)$ | the g.f. $\frac{1-\sqrt{1-4x}}{2x}$ for the Catalan numbers |
| $c(\pi)$ | the complement of a permutation π |
| \mathcal{D}_n | the set of all Dyck paths on $2n$ steps |
| $\text{des}(\pi)$ | the number of descents in π |
| \mathbb{E} | the set of even numbers $\{0, 2, 4, \dots\}$ |
| e.g.f. | exponential generating function |
| F_n | the n -th Fibonacci number |
| $f.g(\pi)$ | the composition $f(g(\pi))$ |
| g.f. | generating function |
| $i(\pi)$ | the inverse of a permutation π |
| $\text{inv}(\pi)$ | the number of inversions in a permutation π |
| $[\ell]$ | the set $\{1, 2, \dots, \ell\}$ |
| $[\ell]^n$ | the set of all words of length n over $[\ell]$ |
| $[\ell]^*$ | the set $\cup_{n \geq 0} [\ell]^n$ |
| M_n | the n -th Motzkin number |
| \mathbb{N} | the set of natural numbers $\{0, 1, 2, \dots\}$ |
| n -permutation | permutation of length n |
| $[n]_q$ | $1 + q + q^2 + \dots + q^{n-1} = \frac{1-q^n}{1-q}$ |
| $[n]_{p,q}$ | $\frac{p^n - q^n}{p - q}$ |
| $[n]_q! = [n]!$ | $[n]_q [n-1]_q \dots [1]_q$ |
| $[n]_{p,q}!$ | $[n]_{p,q} [n-1]_{p,q} \dots [1]_{p,q}$ |
| $\begin{bmatrix} n \\ k \end{bmatrix}_q$ | $\frac{[n]_q!}{[k]_q! [n-k]_q!}$ |

| | |
|-----------------------------------------------|--------------------------------------------------------------------------------------------|
| \mathbb{O} | the set of odd numbers $\{1, 3, 5, \dots\}$ |
| \mathbb{P} | the set of positive integers |
| POP | partially ordered pattern |
| \mathbb{Q} | the set of rational numbers |
| \mathbb{R} | the set of real numbers |
| $r(\pi)$ | the reverse of a permutation/word π |
| $\text{red}(\pi)$ | the reduced form of a permutation π |
| \mathcal{S}_n | the set of all permutations of length n |
| S_n | the n -th (large) Schröder number |
| $\mathcal{S}_n(P)$ | the set of all n -permutations avoiding each pattern in P |
| $\mathcal{S}_n^k(P)$ | the set of all n -permutations containing k occurrences of patterns in P |
| \mathcal{S}_∞ | the set $\cup_{n \geq 0} \mathcal{S}_n$ |
| $s_n(P)$ | $ \mathcal{S}_n(P) $ |
| $s_n^k(P)$ | $ \mathcal{S}_n^k(P) $ |
| $S(n, k)$ | Stirling number of the second kind |
| $U_n(x)$ | the n -th Chebyshev polynomial of the second kind |
| VP | vincular pattern |
| $W_{n,\ell}(P)$ | the set of all words in $[\ell]^n$ that avoid each pattern in P |
| $W_{n,\ell}^k(P)$ | the set of all words in $[\ell]^n$ that contain exactly k occurrences of patterns in P |
| $w_{n,\ell}(P)$ | $ W_{n,\ell}(P) $ |
| $w_{n,\ell}^k(P)$ | $ W_{n,\ell}^k(P) $ |
| \mathbb{Z} | the set of integers |
| $\alpha_1 \oplus \alpha_2$ | $12[\alpha_1, \alpha_2]$ |
| $\alpha_1 \ominus \alpha_2$ | $21[\alpha_1, \alpha_2]$ |
| ε | the empty word/permutation |
| $p_1 \sim p_2$ | p_1 and p_2 are Wilf-equivalent |
| $p_1 \sim_k p_2$ | p_1 and p_2 are k -Wilf-equivalent |
| $p_1 \sim_* p_2$ | p_1 and p_2 are strongly Wilf-equivalent |
| $\sigma[\alpha_1, \alpha_2, \dots, \alpha_m]$ | the inflation of σ by $\alpha_1, \alpha_2, \dots, \alpha_m$ |

Contents

| | | |
|----------|--------------------------------------------------------------|-----------|
| 1 | What is a pattern in a permutation or a word? | 1 |
| 1.1 | Classical patterns in permutations | 8 |
| 1.2 | Barred patterns (BPs) in permutations | 9 |
| 1.3 | Vincular patterns (VPs) in permutations | 10 |
| 1.4 | Bivincular patterns (BVPs) in permutations | 13 |
| 1.5 | Partially ordered patterns | 16 |
| 1.6 | Patterns in words | 19 |
| 1.7 | Some typical problems related to patterns | 21 |
| 1.8 | Bibliography related to the introduced patterns | 26 |
| | | |
| 2 | Why such patterns? A few motivation points | 29 |
| 2.1 | Sorting permutations with stacks and other devices | 29 |
| 2.1.1 | Sorting with k stacks in series | 30 |
| 2.1.2 | Sorting with k stacks in parallel | 35 |
| 2.1.3 | Input-restricted and output-restricted dequeues | 35 |
| 2.1.4 | Sorting with pop-stacks | 37 |
| 2.1.5 | A generalization of stack sorting permutations | 39 |
| 2.2 | Planar maps, trees, bipolar orientations | 40 |
| 2.2.1 | Planar maps and plane bipolar orientations | 41 |
| 2.2.2 | Description trees and skew ternary trees | 43 |
| 2.2.3 | Relevant pattern-avoidance | 47 |
| 2.2.4 | Baxter permutations | 52 |

| | | |
|----------|-----------------------------------------------------------------------------------|-----------|
| 2.2.5 | Separable permutations | 57 |
| 2.2.6 | Schröder permutations | 66 |
| 2.2.7 | A hierarchy of permutation classes | 70 |
| 2.3 | Schubert varieties and Kazhdan-Lusztig polynomials | 71 |
| 2.3.1 | Schubert varieties | 73 |
| 2.3.2 | Kazhdan-Lusztig polynomials | 76 |
| 2.4 | A link to computational biology | 77 |
| 2.4.1 | Duplication-loss steps of bounded width | 79 |
| 2.4.2 | The whole genome duplication-random loss model | 79 |
| 3 | More motivation points | 81 |
| 3.1 | Applications to statistical mechanics | 81 |
| 3.1.1 | PASEP | 81 |
| 3.1.2 | Permutation tableaux | 84 |
| 3.1.3 | PASEP and pattern-avoidance | 86 |
| 3.2 | Posets, diagrams, and matrices | 89 |
| 3.2.1 | Unlabeled (2+2)-free posets | 90 |
| 3.2.2 | Ascent sequences | 93 |
| 3.2.3 | Stoimenow's diagrams | 96 |
| 3.2.4 | Upper triangular matrices | 98 |
| 3.2.5 | Connections between the objects and pattern-avoidance | 99 |
| 3.2.6 | Enumeration and solving two conjectures | 103 |
| 3.3 | A classification of the Mahonian statistics | 107 |
| 3.3.1 | Mahonian statistics in the literature | 108 |
| 3.3.2 | A Mahonian statistic | 110 |
| 3.3.3 | Mahonian statistics and combinations of patterns of arbitrary length | 111 |
| 3.4 | Encoding combinatorial structures | 113 |
| 3.4.1 | Objects of interest and the table with connections | 113 |
| 3.4.2 | Examples of bijections involved in Table 3.2 | 117 |

| | | |
|----------|-----------------------------------------------------------------------------------|------------|
| 3.5 | Several structures under one roof | 120 |
| 3.5.1 | Co-unimodal patterns | 121 |
| 3.5.2 | Peaks and valleys in permutations | 122 |
| 3.5.3 | Patterns containing the \square symbol | 124 |
| 3.5.4 | Avoiding non-consecutive occurrences of patterns | 125 |
| 3.5.5 | V- and Λ -patterns | 127 |
| 3.5.6 | Encoding combinatorial objects by POPs | 130 |
| 3.6 | Proving identities combinatorially | 136 |
| 4 | Bijections between 321- and 132-avoiding permutations | 141 |
| 4.1 | Bijections between $\text{Av}(321)$ and $\text{Av}(132)$ | 144 |
| 4.1.1 | Knuth's bijection, 1973 | 145 |
| 4.1.2 | Knuth-Rotem's bijection, 1975 | 147 |
| 4.1.3 | Simion-Schmidt's bijection, 1985 | 148 |
| 4.1.4 | Knuth-Richards's bijection, 1988 | 148 |
| 4.1.5 | West's bijection, 1995 | 151 |
| 4.1.6 | Krattenthaler's bijection, 2001 | 152 |
| 4.1.7 | Billey-Jockusch-Stanley-Reifegerste's bijection, 2002 | 153 |
| 4.1.8 | Elizalde-Deutsch's bijection, 2003 | 154 |
| 4.1.9 | Mansour-Deng-Du's bijection, 2006 | 155 |
| 4.2 | Classification of bijections between 321- and 132-avoiding permutations | 158 |
| 5 | Consecutive patterns | 165 |
| 5.1 | The symbolic method | 165 |
| 5.1.1 | A direct approach | 166 |
| 5.1.2 | Increasing binary trees | 169 |
| 5.2 | An inclusion-exclusion approach | 173 |
| 5.3 | The symmetric functions approach | 177 |
| 5.3.1 | Symmetric functions | 177 |
| 5.3.2 | Brick tabloids | 178 |

| | | |
|----------|-------------------------------------------------------------------|------------|
| 5.3.3 | Results obtained by using symmetric functions | 182 |
| 5.4 | The cluster and chain methods | 185 |
| 5.4.1 | Applications of the methods | 188 |
| 5.4.2 | Patterns without self-overlaps | 190 |
| 5.5 | Applications of Fédou's bijection | 191 |
| 5.6 | Walks in graphs of overlapping patterns | 192 |
| 5.7 | Asymptotic enumeration | 194 |
| 5.7.1 | A complex analysis result | 196 |
| 5.7.2 | A spectral approach | 197 |
| 5.8 | Multi-avoidance of consecutive patterns | 203 |
| 5.8.1 | Avoidance with prescribed beginning | 205 |
| 5.8.2 | Avoidance with prescribed beginning and ending | 208 |
| 5.9 | Consecutive patterns and 312-avoiding permutations | 209 |
| 5.10 | Consecutive patterns in words | 211 |
| 5.11 | Non-overlapping consecutive patterns | 214 |
| 5.12 | A hierarchy of consecutive pattern enumeration problems | 217 |
| 5.12.1 | Fédou's insertion shift bijection | 218 |
| 5.13 | More results on consecutive patterns | 220 |
| 6 | Classical patterns and POPs | 223 |
| 6.1 | Classical patterns in permutations | 223 |
| 6.1.1 | Patterns of length at most 4 | 223 |
| 6.1.2 | Containing occurrences of patterns | 233 |
| 6.1.3 | Larger patterns | 237 |
| 6.1.4 | Asymptotics | 238 |
| 6.1.5 | Avoiding a 3-pattern with extra restrictions | 244 |
| 6.1.6 | More results on classical patterns | 257 |
| 6.1.7 | Classical patterns and involutions | 259 |
| 6.1.8 | Classical patterns and alternating permutations | 271 |
| 6.1.9 | Classical patterns and Dumont permutations | 274 |

| | | |
|----------|------------------------------------------------------------|------------|
| 6.1.10 | Classical patterns and even/odd permutations | 277 |
| 6.2 | Classical patterns in words | 280 |
| 6.2.1 | Wilf-equivalence | 280 |
| 6.2.2 | Enumeration | 282 |
| 6.2.3 | An asymptotic result | 285 |
| 6.2.4 | Longest alternating subsequences | 285 |
| 6.3 | Partially ordered patterns in permutations | 286 |
| 6.3.1 | Multi-patterns | 287 |
| 6.3.2 | Shuffle patterns | 287 |
| 6.4 | Partially ordered patterns in words | 289 |
| 7 | VPs, BVPs and BPs | 291 |
| 7.1 | Vincular patterns in permutations | 291 |
| 7.1.1 | Avoidance of a vincular 3- or 4-pattern | 293 |
| 7.1.2 | Containing occurrences of vincular patterns | 295 |
| 7.1.3 | Asymptotic results for vincular patterns | 297 |
| 7.1.4 | VPs and a classical 3-pattern | 299 |
| 7.1.5 | More results on vincular patterns | 302 |
| 7.1.6 | VPs and alternating permutations | 303 |
| 7.1.7 | VPs and Dumont permutations | 304 |
| 7.2 | Vincular patterns in words | 305 |
| 7.3 | Bivincular patterns in permutations | 307 |
| 7.4 | Barred patterns in permutations | 308 |
| 7.4.1 | A systematic enumeration for BPs avoidance | 311 |
| 7.4.2 | Barred vincular patterns | 313 |
| 8 | Miscellaneous on patterns in permutations and words | 317 |
| 8.1 | Simple permutations | 317 |
| 8.1.1 | Enumeration of simple permutations | 319 |
| 8.1.2 | Exceptional simple permutations | 319 |

| | | |
|-------|--------------------------------------------------------------|-----|
| 8.1.3 | Simple extensions | 321 |
| 8.1.4 | Substitution closures | 321 |
| 8.1.5 | Algebraic generating functions | 322 |
| 8.1.6 | Finite basis and three more theorems | 323 |
| 8.1.7 | Permutation classes with two restrictions | 324 |
| 8.2 | Some algorithmic aspects of patterns | 325 |
| 8.2.1 | Pattern matching problems | 325 |
| 8.2.2 | Gray codes | 326 |
| 8.3 | Packing patterns | 330 |
| 8.3.1 | Pattern densities | 332 |
| 8.3.2 | Packing sets of patterns | 335 |
| 8.3.3 | Packing patterns in words | 336 |
| 8.4 | Several approaches to study patterns | 339 |
| 8.4.1 | Transfer matrices | 339 |
| 8.4.2 | Generating trees | 339 |
| 8.4.3 | ECO method | 341 |
| 8.4.4 | The insertion encoding | 341 |
| 8.4.5 | Block decompositions | 342 |
| 8.5 | A bridge to combinatorics on words | 343 |
| 8.5.1 | Morphisms and square-free words | 344 |
| 8.5.2 | Patterns in combinatorics on words | 345 |
| 8.5.3 | Powers and sesquipowers | 346 |
| 8.5.4 | Avoidability on a fixed alphabet | 347 |
| 8.5.5 | Crucial and maximal words for sets of prohibitions | 348 |
| 8.5.6 | Square-free permutations | 350 |
| 8.6 | Universal cycles | 351 |
| 8.7 | Simsun permutations | 355 |
| 8.8 | An involution on Catalan objects | 357 |
| 8.9 | Permutation avoidance games | 358 |

| | | |
|----------|----------------------------------------------------------------------------------|------------|
| 9 | Extending research on patterns in permutations and words to other domains | 361 |
| 9.1 | Refining patterns/statistics | 361 |
| 9.1.1 | More on descents and ascents relative to equivalence classes mod k | 364 |
| 9.1.2 | k -descents and k -excedences in permutations | 365 |
| 9.1.3 | Descent pairs with prescribed tops and bottoms | 365 |
| 9.2 | Place-difference-value patterns | 367 |
| 9.3 | Pattern-avoidance in multisets | 369 |
| 9.4 | Patterns in finite approximations of sequences | 370 |
| 9.4.1 | The Peano curve | 370 |
| 9.4.2 | The Dragon curve sequence and the σ -sequence | 371 |
| 9.4.3 | General study related to words generated by morphisms and patterns | 373 |
| 9.5 | Pattern-avoidance on partial permutations | 375 |
| 9.6 | Signed and colored permutations and patterns | 377 |
| 9.7 | Generalized factor order | 381 |
| 9.8 | Miscellaneous | 382 |
| 9.8.1 | Pattern-avoiding set partitions | 383 |
| 9.8.2 | Pattern-avoidance in matrices | 383 |
| 9.8.3 | Pattern-avoidance in n -dimensional objects | 383 |
| 9.8.4 | Cyclically closed pattern classes of permutations | 384 |
| 9.8.5 | Pattern-matching in the cycle structure of permutations | 384 |
| 9.8.6 | Equivalence classes of permutations avoiding a pattern | 385 |
| 9.8.7 | Extended pattern-avoidance | 385 |
| A | Useful notions and facts | 387 |
| A.1 | Statistics on permutations and words | 387 |
| A.2 | Numbers and lattice paths of interest | 389 |
| A.2.1 | Numbers involved | 390 |
| A.2.2 | Lattice paths involved | 396 |

| | | |
|----------|----------------------------------------------------|------------|
| A.3 | Pattern-avoiding permutations | 398 |
| B | Some algebraic background | 401 |
| B.1 | The ring of formal power series | 401 |
| B.2 | Chebyshev polynomials of the second kind | 403 |
| | Bibliography | 405 |
| | Index | 465 |

Chapter 1

What is a pattern in a permutation or a word?

We begin with some basic definitions.

Definition 1.0.1. A *word* is a sequence whose symbols (or *letters*) come from a set called an *alphabet*. Alphabets in this book are finite, and the most typical alphabet here is of the form $[\ell] = \{1, 2, \dots, \ell\}$. Most of the words we deal with in this book are finite as well. We let $[\ell]^n$ denote the set of all words of length n over $[\ell]$ and $[\ell]^* = \cup_{n \geq 0} [\ell]^n$. A word from an ℓ -letter alphabet is often referred to as an “ ℓ -ary word”.

Example 1.0.2. 2411121 and 25554 are words over the alphabet $[5] = \{1, 2, 3, 4, 5\}$, while *abbacca* is a word over the alphabet $\{a, b, c\}$.

$$[3]^2 = \{11, 12, 13, 21, 22, 23, 31, 32, 33\}.$$

It is easy to show that there are k^n different words of length n over a k -letter alphabet.

Definition 1.0.3. A *permutation* of length n (also referred to as an n -permutation) is a one-to-one function from an n -element set to itself. We write permutations as words $\sigma = \sigma_1 \sigma_2 \cdots \sigma_n$, whose letters are distinct and usually consist of the integers $1, 2, \dots, n$ (where σ_i is the image of i under σ). This way of writing permutations is often referred to as *one-line notation*. We let \mathcal{S}_n denote the set of all permutations of length n , and $\mathcal{S}_\infty = \cup_{n \geq 0} \mathcal{S}_n$.

Example 1.0.4. 413265 is a 6-permutation, whereas 265, *bca*, and 132 are permutations of length 3. $\mathcal{S}_1 = \{1\}$, $\mathcal{S}_2 = \{12, 21\}$, $\mathcal{S}_3 = \{123, 132, 213, 231, 312, 321\}$, etc.

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