

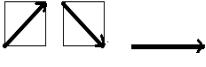
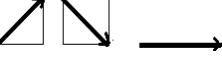
Table of Contents

General Introduction	xxiii
Chapter 1. Some Historical Elements	1
1.1. Yi King	1
1.2. Flavor combinations in India	2
1.3. Sand drawings in Africa	3
1.4. Galileo's problem	4
1.5. Pascal's triangle	7
1.6. The combinatorial explosion: Abu Kamil's problem, the palm grove problem and the Sudoku grid	9
1.6.1. Solution to Abu Kamil's problem	11
1.6.2. Palm Grove problem, where $N = 4$	12
1.6.3. Complete Sudoku grids	14
PART 1. COMBINATORICS	17
Part 1. Introduction	19
Chapter 2. Arrangements and Combinations	21
2.1. The three formulae	21
2.2. Calculation of C_n^p , Pascal's triangle and binomial formula	25
2.3. Exercises	27
2.3.1. Demonstrating formulae	27
2.3.2. Placing rooks on a chessboard	28
2.3.3. Placing pieces on a chessboard	29
2.3.4. Pascal's triangle modulo k	30
2.3.5. Words classified based on their blocks of letters	31
2.3.6. Diagonals of a polygon	33

2.3.7. Number of times a number is present in a list of numbers	35
2.3.8. Words of length n based on 0 and 1 without any block of 1s repeated	37
2.3.9. Programming: classification of applications of a set with n elements in itself following the form of their graph	39
2.3.10. Individuals grouped 2×2	42
Chapter 3. Enumerations in Alphabetical Order	43
3.1. Principle of enumeration of words in alphabetical order	43
3.2. Permutations	44
3.3. Writing binary numbers	46
3.3.1. Programming	46
3.3.2. Generalization to expression in some base B	46
3.4. Words in which each letter is less than or equal to the position	47
3.4.1. Number of these words	47
3.4.2. Program	47
3.5. Enumeration of combinations	47
3.6. Combinations with repetitions	49
3.7. Purchase of P objects out of N types of objects	49
3.8. Another enumeration of permutations	50
3.9. Complementary exercises	52
3.9.1. Exercise 1: words with different successive letters	52
3.9.2. Exercise 2: repeated purchases with a given sum of money	56
3.10. Return to permutations	58
3.11. Gray code	60
Chapter 4. Enumeration by Tree Structures	63
4.1. Words of length n , based on N letters $1, 2, 3, \dots, N$, where each letter is followed by a higher or equal letter	63
4.2. Permutations enumeration	66
4.3. Derangements	67
4.4. The queens problem	69
4.5. Filling up containers	72
4.6. Stack of coins	76
4.7. Domino tiling a chessboard	79
Chapter 5. Languages, Generating Functions and Recurrences	85
5.1. The language of words based on two letters	85
5.2. Domino tiling a $2 \times n$ chessboard	88
5.3. Generating function associated with a sequence	89

5.4. Rational generating function and linear recurrence	91
5.5. Example: routes in a square grid with rising shapes without entanglement.	92
5.6. Exercises on recurrences	94
5.6.1. Three types of purchases each day with a sum of N dollars	94
5.6.2. Word building	96
5.7. Examples of languages	98
5.7.1. Language of parts of an element set $\{a, b, c, d, \dots\}$	98
5.7.2. Language of parts of a multi-set based on n elements a, b, c , etc., where these elements can be repeated as much as we want	99
5.7.3. Language of words made from arrangements taken from n distinct and non-repeated letters a, b, c , etc., where these words are shorter than or equal to n	99
5.7.4. Language of words based on an alphabet of n letters	100
5.8. The exponential generating function	101
5.8.1. Exercise 1: words based on three letters a, b and c , with the letter a at least twice.	101
5.8.2. Exercise 2: sending n people to three countries, with at least one person per country	103
Chapter 6. Routes in a Square Grid	105
6.1. Shortest paths from one point to another.	105
6.2. n -length paths using two (perpendicular) directions of the square grid	108
6.3. Paths from O to $B(n, x)$ neither touching nor crossing the horizontal axis and located above it	109
6.4. Number of n -length paths that neither touch nor cross the axis of the adscissae until and including the final point	110
6.5. Number of n -length paths above the horizontal axis that can touch but not cross the horizontal axis	111
6.6. Exercises	112
6.6.1. Exercise 1: show that $C_{2n}^n = \sum_{k=0}^n (C_n^k)^2$	112
6.6.2. Exercise 2: show that $\sum_{k=0}^P C_{N-1+k}^k = C_{N+P}^P$	113
6.6.3. Exercise 3: show that $\sum_{k=1}^{n'} 2k C_{2n'}^{n'+k} = n' C_{2n'}^{n'}$	113
6.6.4. Exercise 4: a geometrico-linguistic method	114
6.6.5. Exercise 5: paths of a given length that never intersect each other and where the four directions are allowed in the square grid	115

Chapter 7. Arrangements and Combinations with Repetitions	119
7.1. Anagrams	119
7.2. Combinations with repetitions	121
7.2.1. Routes in a square grid.	121
7.2.2. Distributing (indiscernible) circulars in personalized letter boxes .	121
7.2.3. Choosing I objects out of N categories of object	121
7.2.4. Number of positive or nul integer solutions to the equation $x_0 + x_1 + \dots + x_{n-1} = P$	122
7.3. Exercises	125
7.3.1. Exercise 1: number of ways of choosing six objects out of three categories, with the corresponding prices	125
7.3.2. Exercise 2: word counting.	125
7.3.3. Exercise 3: number of words of P characters based on an alphabet of N letters and subject to order constraints	127
7.3.4. Exercise 4: choice of objects out of several categories taking at least one object from each category	128
7.3.5. Exercise 5: choice of P objects out of N categories when the stock is limited	128
7.3.6. Exercise 6: generating functions associated with the number of integer solutions to an equation with n unknowns	129
7.3.7. Exercise 7: number of solutions to the equation $x + y + z = k$, where k is a given natural integer and $0 \leq x \leq y \leq z$	130
7.3.8. Exercise 8: other applications of the method using generating functions	131
7.3.9. Exercise 9: integer-sided triangles	132
7.3.10. Revision exercise: sending postcards	133
7.4. Algorithms and programs	135
7.4.1. Anagram program	135
7.4.2. Combinations with repetition program	136
Chapter 8. Sieve Formula	137
8.1. Sieve formula on sets	138
8.2. Sieve formula in combinatorics	142
8.3. Examples	142
8.3.1. Example 1: filling up boxes with objects, with at least one box remaining empty	142
8.3.2. Example 2: derangements	144
8.3.3. Example 3: formula giving the Euler number $\varphi(n)$	145
8.3.4. Example 4: houses to be painted	146
8.3.5. Example 5: multiletter words	148
8.3.6. Example 6: coloring the vertices of a graph	150

8.4. Exercises	153
8.4.1. Exercise 1: sending nine diplomats, 1, 2, 3, ..., 9, to three countries A, B, C	153
8.4.2. Exercise 2: painting a room	153
8.4.3. Exercise 3: rooks on a chessboard	155
8.5. Extension of sieve formula.	158
8.5.1. Permutations that have k fixed points	159
8.5.2. Permutations with q disjoint cycles that are k long	160
8.5.3. Terminal nodes of trees with n numbered nodes.	161
8.5.4. Revision exercise about a word: intelligent.	163
Chapter 9. Mountain Ranges or Parenthesis Words: Catalan Numbers	165
9.1. Number $c(n)$ of mountain ranges $2n$ long	166
9.2. Mountains or primitive words	167
9.3. Enumeration of mountain ranges	168
9.4. The language of mountain ranges.	169
9.5. Generating function of the C_{2n}^n and Catalan numbers	171
9.6. Left factors of mountain ranges	173
9.6.1. Algorithm for obtaining the numbers of these left factors $a(N, X)$.	175
9.6.2. Calculation following the lines of Catalan's triangle	176
9.6.3. Calculations based on the columns of the Catalan triangle	177
9.6.4. Average value of the height reached by left factors.	178
9.6.5. Calculations based on the second bisector of the Catalan triangle .	180
9.6.6. Average number of mountains for mountain ranges	183
9.7. Number of peaks of mountain ranges	184
9.8. The Catalan mountain range, its area and height	187
9.8.1. Number of mountain ranges $2n$ long passing through a given point on the square grid.	187
9.8.2. Sum of the elements of lines in triangle $OO'B$ of mountain ranges $2n$ long.	188
9.8.3. Sum of numbers in triangle $OO'B$	189
9.8.4. Average area of a mountain $2n$ long.	190
9.8.5. Shape of the average mountain range	192
9.8.6. Height of the Catalan mountain range.	194
Chapter 10. Other Mountain Ranges	197
10.1. Mountain ranges based on three lines 	197
10.2. Words based on three lines  with as many rising lines as falling lines	198

10.2.1. Explicit formula $v(n)$	199
10.2.2. Return to $u(n)$ number of mountain ranges based on three letters a, b, c and a link with $v(n)$	200
10.3. Example 1: domino tiling of an enlarged Aztec diamond	200
10.4. Example 2: domino tiling of half an Aztec diamond	204
10.4.1. Link between Schröder numbers and Catalan numbers	207
10.4.2. Link with Narayana numbers	207
10.4.3. Another way of programming three-line mountain ranges	208
10.5. Mountain ranges based on three types of lines 	210
10.6. Example 3: movement of the king on a chessboard	213
Chapter 11. Some Applications of Catalan Numbers and Parenthesis Words	215
11.1. The number of ways of placing n chords not intersecting each other on a circle with an even number $2n$ of points.	215
11.2. Murasaki diagrams and partitions	216
11.3. Path couples with the same ends in a square grid.	218
11.4. Path couples with same starting point and length.	220
11.5. Decomposition of words based on two letters as a product of words linked to mountain ranges	222
Chapter 12. Burnside's Formula	227
12.1. Example 1: context in which we obtain the formula	227
12.2. Burnside's formula.	231
12.2.1. Complementary exercise: rotation-type colorings of the vertices of a square	232
12.2.2. Example 2: pawns on a chessboard	232
12.2.3. Example 3: pearl necklaces	237
12.2.4. Example 4: coloring of a stick	239
12.3. Exercises.	239
12.3.1. Coloring the vertices of a square	239
12.3.2. Necklaces with stones in several colors	241
12.3.3. Identical balls in identical boxes	244
12.3.4. Tiling an Aztec diamond using l -squares	244
12.3.5. The 4×4 Sudoku: search for fundamentally different symmetry-type girls	246
Chapter 13. Matrices and Circulation on a Graph	253
13.1. Number of paths of a given length on a complete or a regular graph .	254
13.2. Number of paths and matrix powers	255

13.2.1. Example 1: n -length words in an alphabet of three letters 1, 2, 3, with prohibition of blocks 11 and 23	257
13.2.2. Simplification of the calculation	259
13.2.3. Example 2: n -length words based on three letters 1, 2, 3 with blocks 11, 22 and 33 prohibited	261
13.3. Link between cyclic words and closed paths in an oriented graph	262
13.4. Examples	263
13.4.1. Dominos on a chessboard	263
13.4.2. Words with a dependency link between two successive letters of words	265
13.4.3. Routes on a graded segment	266
13.4.4. Molecular chain	270
Chapter 14. Parts and Partitions of a Set	275
14.1. Parts of a set	275
14.1.1. Program getting all parts of a set	275
14.1.2. Exercises	277
14.2. Partitions of a n -object set	281
14.2.1. Definition	281
14.2.2. A second kind of Stirling numbers, and partitions of a n -element set in k parts	281
14.2.3. Number of partitions of a set and Bell numbers	283
14.2.4. Enumeration algorithm for all partitions of a set	285
14.2.5. Exercise: Sterling numbers modulo 2	286
Chapter 15. Partitions of a Number	289
15.1. Enumeration algorithm	289
15.2. Euler formula	290
15.3. Exercises	292
15.3.1. Exercise 1: partitions of a number n in k distinct elements	292
15.3.2. Exercise 2: ordered partitions	296
15.3.3. Exercise 3: sum of the products of all the ordered partitions of a number	297
15.3.4. Exercise 4: partitions of a number in completely distinct parts	298
15.3.5. Exercise 5: partitions and routes in a square grid	299
15.3.6. Exercise 6: Ferrers graphs	302
Chapter 16. Flags	305
16.1. Checkered flags	305
16.2. Flags with vertical stripes	306

Chapter 17. Walls and Stacks	315
17.1. Brick walls	315
17.2. Walls of bricks made from continuous horizontal rows	316
17.2.1. Algorithm for classifying various types of walls.	317
17.2.2. Possible positions of one row above another	317
17.2.3. Coordinates of bricks	318
17.3. Heaps.	319
17.4. Stacks of disks	322
17.5. Stacks of disks with continuous rows.	324
17.6. Horizontally connected polyominoes	326
Chapter 18. Tiling of Rectangular Surfaces using Simple Shapes	331
18.1. Tiling of a $2 \times n$ chessboard using dominos.	331
18.1.1. First algorithm for constructing tilings	332
18.1.2. Second construction algorithm	333
18.2. Other tilings of a chessboard $2 \times n$ squares long	334
18.2.1. With squares and horizontal dominos	334
18.2.2. With squares and horizontal or vertical dominos	335
18.2.3. With dominos and l -squares we can turn and reflect	335
18.2.4. With squares, l -squares and dominos	336
18.3. Tilings of a $3 \times n$ chessboard using dominos	337
18.4. Tilings of a $4 \times n$ chessboard with dominos	339
18.5. Domino tilings of a rectangle	340
Chapter 19. Permutations	345
19.1. Definition and properties	345
19.2. Decomposition of a permutation as a product of disjoint cycles	347
19.2.1. Particular cases of permutations defined by their decomposition in cycles	349
19.2.2. Number of permutations of n elements with k cycles: Stirling numbers of the first kind	352
19.2.3. Type of permutation	353
19.3. Inversions in a permutation.	354
19.3.1. Generating function of the number of inversions	356
19.3.2. Signature of a permutation: odd and even permutations	357
19.4. Conjugated permutations	359
19.5. Generation of permutations.	360
19.5.1. The symmetrical group S_n is generated by the transpositions $(i\ j)$	361
19.5.2. S_n is generated by transpositions of adjacent elements of the form $(i\ i+1)$	362
19.5.3. S_n is generated by transpositions $(0\ 1)(0\ 2)\dots(0\ n-1)$	362

19.5.4. S_n is generated by cycles $(0\ 1)$ and $(0\ 1\ 2\ 3\ \dots\ n-1)$	363
19.6. Properties of the alternating group A_n	363
19.6.1. A_n is generated by cycles three units long: $(i\ j\ k)$	363
19.6.2. A_n is generated by $n-2$ cycles $(0\ 1\ k)$	363
19.6.3. For $n > 3$, A_n is generated by the cycle chain three units long, of the form $(0\ 1\ 2)(2\ 3\ 4)(4\ 5\ 6)\ \dots\ (n-3\ n-2\ n-1)$	364
19.7. Applications of these properties	365
19.7.1. Card shuffling	365
19.7.2. Taquin game in a n by p (n and $p > 1$) rectangle	368
19.7.3. Cyclic shifts in a rectangle	371
19.7.4. Exchanges of lines and columns in a square	375
19.8. Exercises on permutations	376
19.8.1. Creating a permutation at random	376
19.8.2. Number of permutations $\begin{pmatrix} 0 & 1 & 2 & \dots & n-1 \\ a(0) & a(1) & a(2) & \dots & a(n-1) \end{pmatrix}$ with n elements $0, 1, 2, \dots, n-1$, such that $ a(i)-i =0$ or 1	377
19.8.3. Permutations with $a(i)-i=\pm 1$ or ± 2	379
19.8.4. Permutations with n elements $0, 1, 2, \dots, n-1$ without two consecutive elements	379
19.8.5. Permutations with n elements $0, 1, 2, \dots, n-1$, made up of a single cycle in which no two consecutive elements modulo n are found .	381
19.8.6. Involutive permutations	383
19.8.7. Increasing subsequences in a permutation	384
19.8.8. Riffle shuffling of type O and I for N cards when N is a power of 2	386
PART 2. PROBABILITY	387
Part 2. Introduction	389
Chapter 20. Reminders about Discrete Probabilities	395
20.1. And/or in probability theory	396
20.2. Examples	398
20.2.1. The Chevalier de Mere problem	398
20.2.2. From combinatorics to probabilities	399
20.2.3. From combinatorics of weighted words to probabilities	400
20.2.4. Drawing a parcel of objects from a box	401
20.2.5. Hypergeometric law	401
20.2.6. Draws with replacement in a box	402
20.2.7. Numbered balls in a box and the smallest number obtained during draws	403

20.2.8. Wait for the first double heads in a repeated game of heads or tails	404
20.2.9. Succession of random cuts made in a game of cards	405
20.2.10. Waiting time for initial success	407
20.2.11. Smallest number obtained during successive draws	409
20.2.12. The pool problem	411
20.3. Total probability formula	412
20.3.1. Classic example	412
20.3.2. The formula	413
20.3.3. Examples	413
20.4. Random variable X , law of X , expectation and variance	418
20.4.1. Average value of X	418
20.4.2. Variance and standard deviation	418
20.4.3. Example	419
20.5. Some classic laws	420
20.5.1. Bernoulli's law	420
20.5.2. Geometric law	420
20.5.3. Binomial law	421
20.6. Exercises	422
20.6.1. Exercise 1: throwing balls in boxes	422
20.6.2. Exercise 2: series of repetitive tries	423
20.6.3. Exercise 3: filling two boxes	425
Chapter 21. Chance and the Computer	427
21.1. Random number generators	428
21.2. Dice throwing and the law of large numbers	429
21.3. Monte Carlo methods for getting the approximate value of the number π	430
21.4. Average value of a random variable X , variance and standard deviation	432
21.5. Computer calculation of probabilities, as well as expectation and variance, in the binomial law example	433
21.6. Limits of the computer	437
21.7. Exercises	439
21.7.1. Exercise 1: throwing balls in boxes	439
21.7.2. Exercise 2: boys and girls	439
21.7.3. Exercise 3: conditional probability	441
21.8. Appendix: chi-squared law	443
21.8.1. Examples of the test for uniform distribution	443
21.8.2. Chi-squared law and its link with Poisson distribution	445

Chapter 22. Discrete and Continuous	447
22.1. Uniform law	448
22.1.1. Programming	448
22.1.2. Example 1	449
22.1.3. Example 2: two people meeting	450
22.2. Density function for a continuous random variable and distribution function	451
22.3. Normal law	452
22.4. Exponential law and its link with uniform law	454
22.4.1. An application: geometric law using exponential law	456
22.4.2. Program for getting the geometric law with parameter p	457
22.5. Normal law as an approximation of binomial law	458
22.6. Central limit theorem: from uniform law to normal law	460
22.7. Appendix: the distribution function and its inversion – application to binomial law $B(n, p)$	465
22.7.1. Program	465
22.7.2. The inverse function	467
22.7.3. Program causing us to move from distribution function to probability law	468
Chapter 23. Generating Function Associated with a Discrete Random Variable in a Game	469
23.1. Generating function: definition and properties	469
23.2. Generating functions of some classic laws	470
23.2.1. Bernoulli's law	470
23.2.2. Geometric law	470
23.2.3. Binomial law	473
23.2.4. Poisson distribution	475
23.3. Exercises	476
23.3.1. Exercise 1: waiting time for double heads in a game of heads or tails	476
23.3.2. Exercise 2: in a repeated game of heads or tails, what is the parity of the number of heads?	481
23.3.3. Exercise 3: draws until a certain threshold is exceeded	482
23.3.4. Exercise 4: Pascal's law	487
23.3.5. Exercise 5: balls of two colors in a box	488
23.3.6. Exercise 6: throws of N dice until each gives the number 1	492
Chapter 24. Graphs and Matrices for Dealing with Probability Problems.	497
24.1. First example: counting of words based on three letters	497
24.2. Generating functions and determinants	499

24.3. Examples	500
24.3.1. Exercise 1: waiting time for double heads in a game of heads or tails	500
24.3.2. Draws from three boxes	503
24.3.3. Alternate draws from two boxes	505
24.3.4. Successive draws from one box to the next	506
Chapter 25. Repeated Games of Heads or Tails	509
25.1. Paths on a square grid	509
25.2. Probability of getting a certain number of wins after n equiprobable tosses	511
25.2.1. Probability $p(n, x)$ of getting winnings of x at the end of n moves	512
25.2.2. Standard deviation in relation to a starting point	512
25.2.3. Probability $\rho(2n')$ of a return to the origin at stage $n = 2n'$	513
25.3. Probabilities of certain routes over n moves	514
25.4. Complementary exercises	516
25.4.1. Last visit to the origin	516
25.4.2. Number of winnings sign changes throughout the game	517
25.4.3. Probability of staying on the positive winnings side for a certain amount of time during the $N = 2n$ equiprobable tosses	519
25.4.4. Longest range of winnings with constant sign	520
25.5. The gambler's ruin problem	521
25.5.1. Probability of ruin	522
25.5.2. Average duration of the game	524
25.5.3. Results and program	525
25.5.4. Exercises	526
25.5.5. Temperature equilibrium and random walk	530
Chapter 26. Random Routes on a Graph	535
26.1. Movement of a particle on a polygon or graduated segment	535
26.1.1. Average duration of routes between two points	535
26.1.2. Paths of a given length on a polygon	542
26.1.3. Particle circulating on a pentagon: time required using one side or the other to get to the end	546
26.2. Movement on a polyhedron	547
26.2.1. Case of the regular polyhedron	547
26.2.2. Circulation on a cube with any dimensions	550
26.3. The robot and the human being	555
26.4. Exercises	559
26.4.1. Movement of a particle on a square-based pyramid	559
26.4.2. Movement of two particles on a square-based pyramid	561
26.4.3. Movement of two particles on a graph with five vertices	563

Chapter 27. Repetitive Draws until the Outcome of a Certain Pattern	565
27.1. Patterns are arrangements of K out of N letters	566
27.1.1. Wait for a given arrangement of the K letters in the form of a block	566
27.1.2. Wait for a given cyclic arrangement of K letters in the form of a block	568
27.1.3. The pattern is a given arrangement of K out of N letters in scattered form	570
27.2. Patterns are combinations of K letters drawn from N letters	571
27.2.1. Wait for the outcome of a part made of K numbers in the form of a block	571
27.2.2. Wait for the outcome of any part of K numbers in the form of a block, out of N	574
27.2.3. Wait for the outcome of a part with K given numbers out of N in scattered form	577
27.2.4. Wait for the outcome of any part of K numbers out of N , in scattered form	577
27.2.5. Some examples of comparative results for waiting times	579
27.3. Wait for patterns with eventual repetitions of identical letters	580
27.3.1. For an alphabet of N letters, we wait for a given pattern in the form of a n -length block	580
27.3.2. Wait for one of two patterns of the same length L	581
27.4. Programming exercises	586
27.4.1. Wait for completely different letters	586
27.4.2. Waiting time for a certain pattern.	588
27.4.3. Number of words without two-sided factors	589
Chapter 28. Probability Exercises	597
28.1. The elevator	597
28.1.1. Deal with the case where $P = 2$ floors and the number of people N is at least equal to 2	597
28.1.2. Determine the law of X , i.e. the probability associated with each value of X	598
28.1.3. Average value $E(X)$	599
28.1.4. Direct calculation of $S(K+1, K)$	600
28.1.5. Another way of dealing with the previous question	601
28.2. Matches	601
28.3. The tunnel	602
28.3.1. Dealing with the specific case where $N = 3$	606
28.3.2. Variation with an absorbing boundary and another method	608
28.3.3. Complementary exercise: drunken man's walk on a straight line, with resting time	610

28.4. Repetitive draws from a box	613
28.4.1. Probability law for the number of draws	615
28.4.2. Extra questions	616
28.4.3. Probability of getting ball number k during the game	617
28.4.4. Probability law associated with the number of balls drawn	617
28.4.5. Complementary exercise: variation of the previous problem	618
28.5. The sect	620
28.5.1. Can the group last forever?	620
28.5.2. Probability law of the size of the tree	621
28.5.3. Average tree size	622
28.5.4. Variance of the variable size	624
28.5.5. Algorithm giving the probability law of the organization's lifespan	625
28.6. Surfing the web (or how Google works)	627
PART 3. GRAPHS	637
Part 3. Introduction	639
Chapter 29. Graphs and Routes	643
29.1. First notions on graphs	643
29.1.1. A few properties of graphs.	645
29.1.2. Constructing graphs from points	646
29.2. Representing a graph in a program	647
29.2.1. From vertices to edges	649
29.2.2. From edges to vertices	649
29.3. The tree as a specific graph.	649
29.3.1. Definitions and properties	649
29.3.2. Programming exercise: network converging on a point.	652
29.4. Paths from one point to another in a graph.	654
29.4.1. Dealing with an example.	654
29.4.2. Exercise: paths on a complete graph, from one vertex to another .	656
Chapter 30. Explorations in Graphs.	661
30.1. The two ways of visiting all the vertices of a connected graph.	661
30.2. Visit to all graph nodes from one node, following depth-first traversal	662
30.3. The pedestrian's route	665
30.4. Depth-first exploration to determine connected components of the graph	669
30.5. Breadth-first traversal	671
30.5.1. Program	671

30.5.2. Example: traversal in a square grid	673
30.6. Exercises	676
30.6.1. Searching in a maze	676
30.6.2. Routes in a square grid, with rising shapes without entangling	680
30.6.3. Route of a fluid in a graph	683
30.6.4. Connected graphs with n vertices	683
30.6.5. Bipartite graphs	685
30.7. Returning to a depth-first exploration tree	686
30.7.1. Returning edges in an undirected graph	687
30.7.2. Isthmuses in an undirected graph	688
30.8. Case of directed graphs	690
30.8.1. Strongly connected components in a directed graph	690
30.8.2. Transitive closure of a directed graph	693
30.8.3. Orientation of a connected undirected graph to become strongly connected	696
30.8.4. The best orientations on a graph	696
30.9. Appendix: constructing the maze (simplified version)	700
Chapter 31. Trees with Numbered Nodes, Cayley's Theorem and Prüfer Code	705
31.1. Cayley's theorem	705
31.2. Prüfer code	706
31.2.1. Passage from a tree to its Prüfer code	707
31.2.2. Reverse process	707
31.2.3. Program	709
31.3. Randomly constructed spanning tree	715
31.3.1. Wilson's algorithm	715
31.3.2. Maze and domino tiling	718
Chapter 32. Binary Trees	723
32.1. Number of binary trees with n nodes	725
32.2. The language of binary trees	725
32.3. Algorithm for creation of words from the binary tree language	728
32.4. Triangulation of polygons with numbered vertices and binary trees	729
32.5. Binary tree sort or quicksort	733
Chapter 33. Weighted Graphs: Shortest Paths and Minimum Spanning Tree	737
33.1. Shortest paths in a graph	737
33.1.1. Dijkstra's algorithm	738
33.1.2. Floyd's algorithm	741
33.2. Minimum spanning tree	746

33.2.1. Prim's algorithm	747
33.2.2. Kruskal's algorithm	749
33.2.3. Comparison of the two algorithms	754
33.2.4. Exercises	754
Chapter 34. Eulerian Paths and Cycles, Spanning Trees of a Graph	759
34.1. Definition of Eulerian cycles and paths	759
34.2. Euler and Königsberg bridges	761
34.2.1. Returning to Königsberg bridges	763
34.2.2. Examples	764
34.2.3. Constructing Eulerian cycles by fusing cycles	767
34.3. Number of Eulerian cycles in a directed graph, link with directed spanning trees	768
34.3.1. Number of directed spanning trees	771
34.3.2. Examples	774
34.4. Spanning trees of an undirected graph	776
34.4.1. Example 1: complete graph with p vertices	777
34.4.2. Example 2: tetrahedron	778
Chapter 35. Enumeration of Spanning Trees of an Undirected Graph	779
35.1. Spanning trees of the fan graph	779
35.2. The ladder graph and its spanning trees	782
35.3. Spanning trees in a square network in the form of a grid	784
35.3.1. Experimental enumeration of spanning trees of the square network	785
35.3.2. Spanning trees program in the case of the square network	786
35.3.3. Passage to the undirected graph, its dual and formula giving the number of spanning trees	788
35.4. The two essential types of (undirected) graphs based on squares	789
35.5. The cyclic square graph	791
35.6. Examples of regular graphs.	792
35.6.1. Example 1	792
35.6.2. Example 2: hypercube with n dimensions.	793
35.6.3. Example 3: the ladder graph and its variations	793
Chapter 36. Enumeration of Eulerian Paths in Undirected Graphs	799
36.1. Polygon graph with n vertices with double edges.	799
36.2. Eulerian paths in graph made up of a frieze of triangles	801
36.3. Algorithm for Eulerian paths and cycles on an undirected graph	804
36.3.1. The arborescence for the paths	804
36.3.2. Program for enumerating Eulerian cycles	805

36.3.3. Enumeration in the case of multiple edges between vertices	807
36.3.4. Another example: square with double diagonals	810
36.4. The game of dominos	813
36.4.1. Number of domino chains	813
36.4.2. Algorithms	816
36.5. Congo graphs	820
36.5.1. A simple case: graphs $P(2n, 5)$	822
36.5.2. The first type of Congolese drawings, on $P(n+1, n)$ graphs, with their Eulerian paths	826
36.5.3. The second type of Congolese drawings, on $P(2N, N)$ graphs . .	826
36.5.4. Case of Eulerian cycles on $P(2N+1, 2N-1)$ graphs	830
36.5.5. Case of $I(2N+1, 2N+1)$ graphs with their Eulerian cycles . .	832
Chapter 37. Hamiltonian Paths and Circuits	835
37.1. Presence or absence of Hamiltonian circuits.	836
37.1.1. First examples	836
37.1.2. Hamiltonian circuits on a cube	837
37.1.3. Complete graph and Hamiltonian circuits.	839
37.2. Hamiltonian circuits covering a complete graph	840
37.2.1. Case where the number of vertices is a prime number other than two	840
37.2.2. General case	841
37.3. Complete and antisymmetric directed graph.	843
37.3.1. A few theoretical considerations	843
37.3.2. Experimental verification and algorithms	848
37.3.3. Complete treatment of case $N=4$	851
37.4. Bipartite graph and Hamiltonian paths	854
37.5. Knights tour graph on the $N \times N$ chessboard	855
37.5.1. Case where N is odd	855
37.5.2. Coordinates of the neighbors of a vertex	855
37.5.3. Hamiltonian cycles program.	856
37.5.4. Another algorithm.	857
37.6. de Bruijn sequences	859
37.6.1. Preparatory example	859
37.6.2. Definition.	860
37.6.3. de Bruijn graph	862
37.6.4. Number of Eulerian and Hamiltonian cycles of G_n	865
APPENDICES	867
Appendix 1. Matrices	869
A1.1. Notion of linear application	869

A1.2. Bijective linear application	872
A1.3. Base change	873
A1.4. Product of two matrices	874
A1.5. Inverse matrix	875
A1.6. Eigenvalues and eigenvectors	877
A1.7. Similar matrices	879
A1.8. Exercise	881
A1.9. Eigenvalues of circulant matrices and circular graphs.	882
Appendix 2. Determinants and Route Combinatorics	885
A2.1. Recalling determinants	885
A2.2. Determinants and tilings	887
A2.3. Path sets and determinant	892
A2.3.1. First example: paths without intersection in a square network . .	892
A2.3.2. Second example: mountain ranges without intersection, based on two diagonal lines.	895
A2.3.3. Third example: mountain ranges without intersection based on diagonal lines and plateaus. Link with Aztec diamond tilings	896
A2.3.4. Diamond tilings	899
A2.4. The hamburger graph: disjoint cycles	901
A2.4.1. First example: domino tiling of a rectangular checkerboard N long, 2 wide.	902
A2.4.2. Second example: domino tilings of the Aztec diamond	904
Bibliography	907
Index	911