

# 计数组组合学 (卷1)

(英文版)

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## Enumerative Combinatorics Volume I

**RICHARD P. STANLEY**

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机械工业出版社  
China Machine Press

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# Foreword

It is regrettable that a book, once published and on the way to starting a life of its own, can no longer bear witness to the painful choices that the author had to face in the course of his writing. There are choices that confront the writer of every book: who is the intended audience? who is to be proved wrong? who will be the most likely critic? Most of us have indulged in the idle practice of drafting tables of contents of books we know will never see the light of day. In some countries, some such particularly imaginative drafts have actually been sent to press (though they may not be included among the author's list of publications).

In mathematics, however, the burden of choice faced by the writer is so heavy as to turn off all but the most courageous. And of all mathematics, combinatorics is nowadays perhaps the hardest to write on, despite an eager audience that cuts across the party lines. Shall an isolated special result be granted a section of its own? Shall a fledgling new theory with as yet sparse applications be gingerly thrust in the middle of a chapter? Shall the author yield to one of the contrary temptations of recreational math at one end, and categorical rigor at the other? or to the highly rewarding lure of the algorithm?

Richard Stanley has come through these hurdles with flying colors. It has been said that combinatorics has too many theorems, matched with very few theories; Stanley's book belies this assertion. Together with a sage choice of the most attractive theories on today's stage, he blends a variety of examples democratically chosen from topology to computer science, from algebra to complex variables. The reader will never be at a loss for an illustrative example, or for a proof that fails to meet G. H. Hardy's criterion of pleasant surprise.

His choice of exercises will at last enable us to give a satisfying reference to the colleague who knocks at our door with his combinatorial problem. But best of all, Stanley has succeeded in dramatizing the subject, in a book that will engage from start to finish the attention of any mathematician who will open it at page one.

*Gian-Carlo Rota*



# Preface

Enumerative combinatorics is concerned with counting the number of elements of a finite set  $S$ . This definition, as it stands, tells us little about the subject since virtually any mathematical problem can be cast in these terms. In a genuine enumerative problem, the elements of  $S$  will usually have a rather simple combinatorial definition and very little additional structure. It will be clear that  $S$  has many elements, and the main issue will be to count (or estimate) them all and not, for example, to find a particular element. Of course there are many variants of this basic problem that also belong to enumerative combinatorics and that will appear throughout this book.

There has been an explosive growth in combinatorics in recent years, including enumerative combinatorics. One important reason for this growth has been the fundamental role that combinatorics plays as a tool in computer science and related areas. A further reason has been the prodigious effort, inaugurated by G.-C. Rota around 1964, to bring coherence and unity to the discipline of combinatorics, particularly enumeration, and to incorporate it into the mainstream of contemporary mathematics. Enumerative combinatorics has been greatly elucidated by this effort, as has its role in such areas of mathematics as finite group theory, representation theory, commutative algebra, algebraic geometry, and algebraic topology.

This book has three intended audiences and serves three different purposes. First, it may be used as a graduate-level introduction to a fascinating area of mathematics. Basic knowledge of linear algebra and perhaps a semester of abstract algebra is a necessary prerequisite for most of the book. Chapter 1 may serve as an introduction to enumeration at a somewhat less advanced level. The second intended audience consists of professional combinatorialists, for whom this book could serve as a general reference. While it is impossible to be completely comprehensive, we have tried to include at least the major topics within enumerative combinatorics. Finally, this book may be used by mathematicians outside combinatorics whose work requires them to solve a combinatorial problem. Judging from countless discussions I've had with mathematicians in diverse

areas, this situation arises quite frequently. As a result, I have made a special effort in this book to include coverage of topics from enumerative combinatorics that arise in other branches of mathematics.

The exercises found at the end of each chapter play a vital role in achieving the three purposes of this book. The easier exercises (say, with difficulty ratings of 1 – to 3 –) may be attempted by students using this book as a text; the more difficult exercises are not really meant to be solved (though some readers will undoubtedly be unable to resist a real challenge), but rather serve as an entry into areas that are not directly covered by the text. I hope that these more difficult exercises will convince the reader of the depth and the wide applicability of enumerative combinatorics, especially in Chapter 3, where it is by no means *a priori* evident that partially ordered sets are more than a convenient bookkeeping device. Solutions or references to solutions are provided for almost all of the exercises.

The method of citation and referencing is, I hope, largely self-explanatory. All citations to references in another chapter are preceded by the relevant chapter number. For instance, [3.16] refers to reference 16 in Chapter 3. I have included no references to outside literature within the text itself; all such references appear in the *Notes* at the end of each chapter. Each chapter has its own list of references, while the references relevant to an exercise are given separately in the solution to that exercise.

Many people have contributed in many ways to the writing of this book. Special mention must go to G.-C. Rota for introducing me to the pleasures of enumerative combinatorics and for his constant encouragement and stimulation. I must also mention Donald Knuth, whose superb texts on computer science inspired me to include a wide range of solved exercises with a difficulty level prescribed in advance. The following people have contributed valuable suggestions and encouragement, and I thank them: Ed Bender, Lou Billera, Anders Björner, Thomas Brylawski, Persi Diaconis, Dominique Foata, Adriano Garsia, Ira Gessel, Jay Goldman, Curtis Greene, Victor Klee, Pierre Leroux, and Ronald C. Mullin. In addition, the names of many whose ideas I have borrowed are mentioned in the *Notes* and *Exercises*. I am grateful to a number of typists for their fine preparation of the manuscript, including Ruby Aguirre, Louise Balzarini, Margaret Beucler, Benito Rakower, and Phyllis Ruby. Finally, thanks to John Kimmel of Wadsworth & Brooks/Cole Advanced Books & Software for his support and encouragement throughout the preparation of this book, and to Phyllis Larimore for her careful editing.

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*Richard Stanley*

## Notation

$\mathbb{C}$	complex numbers
$\mathbb{N}$	nonnegative integers
$\mathbb{P}$	positive integers
$\mathbb{Q}$	rational numbers
$\mathbb{R}$	real numbers
$\mathbb{Z}$	integers
$[n]$	the set $\{1, 2, \dots, n\}$ , for $n \in \mathbb{N}$ (so $[0] = \emptyset$ )
$[i, j]$	for integers $i \leq j$ , the set $\{i, i + 1, \dots, j\}$
$\lfloor x \rfloor$	greatest integer $\leq x$
$\lceil x \rceil$	least integer $\geq x$
$\text{card } X, \# X,  X $	all used for the number of elements of the finite set $X$
$\{a_1, \dots, a_k\}_<$	the set $\{a_1, \dots, a_k\} \subseteq \mathbb{R}$ , where $a_1 < \dots < a_k$
$\delta_{ij}$	the Kronecker delta, equal to 1 if $i = j$ and 0 otherwise
$:=$	equals by definition
$\text{im } A$	image of the function $A$
$\ker A$	kernel of the homomorphism or linear transformation $A$
$\text{tr } A$	trace of the linear transformation $A$
$GF(q), \mathbb{F}_q$	the finite field (unique up to isomorphism) with $q$ elements
$\coprod_i V_i$	direct sum of the vector spaces (or modules, rings, etc.) $V_i$
$R[x]$	ring of polynomials in the indeterminate $x$ with coefficients in the integral domain $R$
$R(x)$	ring of rational functions in $x$ with coefficients in $R$ ( $R(x)$ is the quotient field of $R[x]$ when $R$ is a field)
$R[[x]]$	ring of formal power series $\sum_{n \geq 0} a_n x^n$ in $x$ with coefficients $a_n$ in $R$
$R((x))$	ring of formal Laurent series $\sum_{n \geq n_0} a_n x^n$ , for some $n_0 \in \mathbb{Z}$ , in $x$ with coefficients $a_n$ in $R$ ( $R((x))$ is the quotient field of $R[[x]]$ when $R$ is a field)

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# What Is Enumerative Combinatorics?

## 1.1 How to Count

The basic problem of enumerative combinatorics is that of counting the number of elements of a finite set. Usually we are given an infinite class of finite sets  $S_i$  where  $i$  ranges over some index set  $I$  (such as the nonnegative integers  $\mathbb{N}$ ), and we wish to count the number  $f(i)$  of elements of each  $S_i$  “simultaneously.” Immediate philosophical difficulties arise. What does it mean to “count” the number of elements of  $S_i$ ? There is no definitive answer to this question. Only through experience does one develop an idea of what is meant by a “determination” of a counting function  $f(i)$ . The counting function  $f(i)$  can be given in several standard ways:

1. The most satisfactory form of  $f(i)$  is a completely explicit closed formula involving only well-known functions, and free from summation symbols. Only in rare cases will such a formula exist. As formulas for  $f(i)$  become more complicated, our willingness to accept them as “determinations” of  $f(i)$  decreases. Consider the following examples.

**1.1.1 Example.** For each  $n \in \mathbb{N}$ , let  $f(n)$  be the number of subsets of the set  $[n] = \{1, 2, \dots, n\}$ . Then  $f(n) = 2^n$ , and no one will quarrel about this being a satisfactory formula for  $f(n)$ .

**1.1.2 Example.** Suppose  $n$  men give their  $n$  hats to a hat-check person. Let  $f(n)$  be the number of ways that the hats can be given back to the men, each man receiving one hat, so that no man receives his own hat. For instance,  $f(1) = 0$ ,  $f(2) = 1$ ,  $f(3) = 2$ . We will see in Chapter 2 that

$$f(n) = n! \sum_{i=0}^n (-1)^i / i!. \quad (1)$$

This formula for  $f(n)$  is not as elegant as the formula in Example 1.1.1, but for lack of a simpler answer we are willing to accept (1) as a satisfactory formula. In

fact, once the derivation of (1) is understood (using the Principle of Inclusion-Exclusion), every term of (1) has an easily understood combinatorial meaning. This enables us to “understand” (1) intuitively, so our willingness to accept it is enhanced. We also remark that it follows easily from (1) that  $f(n)$  is the nearest integer to  $n!/e$ . This is certainly a simple explicit formula, but it has the disadvantage of being “non-combinatorial”; that is, dividing by  $e$  and rounding off to the nearest integer has no direct combinatorial significance.

**1.1.3 Example.** Let  $f(n)$  be the number of  $n \times n$  matrices  $\mathbf{M}$  of zeros and ones such that every row and column of  $\mathbf{M}$  has three ones. For example,  $f(0) = f(1) = f(2) = 0$ ,  $f(3) = 1$ . The most explicit formula known at present for  $f(n)$  is

$$f(n) = 6^{-n} \sum \frac{(-1)^{\beta} n!^2 (\beta + 3\gamma)! 2^{\alpha} 3^{\beta}}{\alpha! \beta! \gamma! 2^{\gamma}} \quad (2)$$

where the sum is over all  $(n+2)(n+1)/2$  solutions to  $\alpha + \beta + \gamma = n$  in non-negative integers. This formula gives very little insight into the behavior of  $f(n)$ , but it does allow one to compute  $f(n)$  much faster than if only the combinatorial definition of  $f(n)$  were used. Hence with some reluctance we accept (2) as a “determination” of  $f(n)$ . Of course if someone were later to prove  $f(n) = (n-1)(n-2)/2$  (rather unlikely), then our enthusiasm for (2) would be considerably diminished.

**1.1.4 Example.** There are actually formulas in the literature (“nameless here for evermore”) for certain counting functions  $f(n)$  whose evaluation requires listing all (or almost all) of the  $f(n)$  objects being counted! Such a “formula” is completely worthless.

2. A recurrence for  $f(i)$  may be given in terms of previously calculated  $f(j)$ ’s, thereby giving a simple procedure for calculating  $f(i)$  for any desired  $i \in I$ . For instance, let  $f(n)$  be the number of subsets of  $[n]$  that do not contain two consecutive integers. For example, for  $n = 4$  we have the subsets  $\emptyset, \{1\}, \{2\}, \{3\}, \{4\}, \{1, 3\}, \{1, 4\}, \{2, 4\}$ , so  $f(4) = 8$ . It is easily seen that  $f(n) = f(n-1) + f(n-2)$  for  $n \geq 2$ . This makes it trivial, for example, to compute  $f(20)$ . On the other hand, it can be shown that

$$f(n) = \frac{1}{\sqrt{5}} (\tau^{n+2} - \bar{\tau}^{n+2}),$$

where  $\tau = \frac{1}{2}(1 + \sqrt{5})$ ,  $\bar{\tau} = \frac{1}{2}(1 - \sqrt{5})$ . This is an explicit answer, but because it involves irrational numbers it is a matter of opinion whether it is a better answer than the recurrence  $f(n) = f(n-1) + f(n-2)$ .

3. An estimate may be given for  $f(i)$ . If  $I = \mathbb{N}$ , this estimate frequently takes the form of an asymptotic formula  $f(n) \sim g(n)$ , where  $g(n)$  is a “familiar function.” The notation  $f(n) \sim g(n)$  means that  $\lim_{n \rightarrow \infty} f(n)/g(n) = 1$ . For instance, let  $f(n)$  be the function of Example 1.1.3. It can be shown that

$$f(n) \sim e^{-2} 36^{-n} (3n)!.$$

For many purposes this estimate is superior to the “explicit” formula (2).

4. The most useful but most difficult to understand method for evaluating  $f(i)$  is to give its *generating function*. We will not develop in this chapter a rigorous abstract theory of generating functions, but will instead content ourselves with an informal discussion and some examples. Informally, a generating function is an “object” that represents a counting function  $f(i)$ . Usually this object is a *formal power series*. The two most common types of generating functions are *ordinary generating functions* and *exponential generating functions*. If  $I = \mathbb{N}$ , then the ordinary generating function of  $f(n)$  is the formal power series

$$\sum_{n \geq 0} f(n)x^n,$$

while the exponential generating function of  $f(n)$  is the formal power series

$$\sum_{n \geq 0} f(n)x^n/n!.$$

(If  $I = \mathbb{P}$ , the positive integers, then these sums begin at  $n = 1$ .) These power series are called “formal” because we are not concerned with letting  $x$  take on particular values, and we ignore questions of convergence and divergence. The term  $x^n$  or  $x^n/n!$  merely marks the place where  $f(n)$  is written. If  $F(x) = \sum_{n \geq 0} a_n x^n$ , we call  $a_n$  the *coefficient* of  $x^n$  in  $F(x)$  and write

$$a_n = [F(x)]_n \quad \text{or} \quad a_n = F(x)|_n.$$

Similarly we can deal with generating functions of several variables, such as

$$\sum_{l \geq 0} \sum_{m \geq 0} \sum_{n \geq 0} f(l, m, n) x^l y^m z^n / n!$$

(which may be considered as “ordinary” in the indices  $l, m$  and “exponential” in  $n$ ), or even of infinitely many variables. In this latter case every term should involve only finitely many of the variables.

Why bother with generating functions if they are merely another way of writing a counting function? The answer is that we can perform various natural operations on generating functions that have a combinatorial significance. For instance, we can add two generating functions (in one variable) by the rule

$$\left( \sum_{n \geq 0} a_n x^n \right) + \left( \sum_{n \geq 0} b_n x^n \right) = \sum_{n \geq 0} (a_n + b_n) x^n$$

or

$$\left( \sum_{n \geq 0} \frac{a_n x^n}{n!} \right) + \left( \sum_{n \geq 0} \frac{b_n x^n}{n!} \right) = \sum_{n \geq 0} \frac{(a_n + b_n) x^n}{n!}.$$

Similarly, we can multiply generating functions according to the rule

$$\left( \sum_{n \geq 0} a_n x^n \right) \left( \sum_{n \geq 0} b_n x^n \right) = \sum_{n \geq 0} c_n x^n,$$

where  $c_n = \sum_{i=0}^n a_i b_{n-i}$ , or

$$\left( \sum_{n \geq 0} \frac{a_n x^n}{n!} \right) \left( \sum_{n \geq 0} \frac{b_n x^n}{n!} \right) = \sum_{n \geq 0} \frac{d_n x^n}{n!},$$

where  $d_n = \sum_{i=0}^n \binom{n}{i} a_i b_{n-i}$ , with  $\binom{n}{i} = n!/i!(n-i)!$ . Note that these operations are just what we would obtain by treating generating functions as if they obeyed the ordinary laws of algebra, such as  $x^i x^j = x^{i+j}$ . These operations coincide with the addition and multiplication of functions when the power series converge for appropriate values of  $x$ , and they obey such familiar laws of algebra as associativity and commutativity of addition and multiplication, distributivity of multiplication over addition, and cancellation of multiplication (i.e., if  $F(x)G(x) = F(x)H(x)$  and  $F(x) \neq 0$ , then  $G(x) = H(x)$ ). In fact, the set of all formal power series  $\sum_{n \geq 0} a_n x^n$  with complex coefficients  $a_n$  forms a (commutative) integral domain under the operations just defined. This integral domain is denoted by  $\mathbb{C}[[x]]$ . (Actually,  $\mathbb{C}[[x]]$  is a very special type of integral domain. For readers with some familiarity with algebra, we remark that  $\mathbb{C}[[x]]$  is a principal ideal domain and therefore a unique factorization domain. In fact, every ideal of  $\mathbb{C}[[x]]$  has the form  $(x^n)$  for some  $n \geq 0$ . From the viewpoint of commutative algebra,  $\mathbb{C}[[x]]$  is a one-dimensional complete regular local ring. These general algebraic considerations will not concern us here; rather we will discuss from an elementary viewpoint the properties of  $\mathbb{C}[[x]]$  that will be useful to us.) Similarly, the set of formal power series in the  $m$  variables  $x_1, \dots, x_m$  (where  $m$  may be infinite) is denoted  $\mathbb{C}[[x_1, \dots, x_m]]$  and forms a unique factorization domain (though not a principal ideal domain for  $m \geq 2$ ).

It is primarily through experience that the combinatorial significance of the algebraic operations of  $\mathbb{C}[[x]]$  or  $\mathbb{C}[[x_1, \dots, x_m]]$  is understood, as well as the problem of whether to use ordinary or exponential generating functions (or various other kinds discussed in later chapters). In Section 3.15, we will explain to some extent the combinatorial significance of these operations, but even then experience is indispensable.

If  $F(x)$  and  $G(x)$  are elements of  $\mathbb{C}[[x]]$  satisfying  $F(x)G(x) = 1$ , then we (naturally) write  $G(x) = F(x)^{-1}$ . (Here 1 is short for  $1 + 0x + 0x^2 + \dots$ .) It is easy to see that  $F(x)^{-1}$  exists (in which case it is unique) if and only if  $a_0 \neq 0$ , where  $F(x) = \sum_{n \geq 0} a_n x^n$ . One commonly writes "symbolically"  $a_0 = F(0)$ , even though  $F(x)$  is not considered to be a function of  $x$ . If  $F(0) \neq 0$  and  $F(x)G(x) = H(x)$ , then  $G(x) = F(x)^{-1}H(x)$ . More generally, the operation  $^{-1}$  satisfies all the familiar laws of algebra, provided it is only applied to power series  $F(x)$  satisfying  $F(0) \neq 0$ . For instance,  $(F(x)G(x))^{-1} = F(x)^{-1}G(x)^{-1}$ ,  $(F(x)^{-1})^{-1} = F(x)$ , and so on. Similar results hold for  $\mathbb{C}[[x_1, \dots, x_n]]$ .

**1.1.5 Example.** Let  $(\sum_{n \geq 0} \alpha^n x^n)(1 - \alpha x) = \sum_{n \geq 0} c_n x^n$ , where  $\alpha$  is a non-zero complex number. Then by the definition of power series multiplication,

$$c_n = \begin{cases} 1, & n = 0 \\ \alpha^n - \alpha(\alpha^{n-1}) = 0, & n \geq 1. \end{cases}$$

Hence  $\sum_{n \geq 0} \alpha^n x^n = (1 - \alpha x)^{-1}$ , which can also be written

$$\sum_{n \geq 0} \alpha^n x^n = \frac{1}{1 - \alpha x}.$$

This formula comes as no surprise; it is simply the formula (in a formal setting) for summing a geometric series.

Example 1.1.5 provides a simple illustration of a general principle that, informally speaking, states that if we have an identity involving power series that is valid when the power series are regarded as functions (so that the variables are sufficiently small complex numbers), then this identity continues to remain valid when regarded as an identity among formal power series, *provided* the operations involved in the formulas are well-defined for formal power series. It would be unnecessarily pedantic for us to state a precise form of this principle here, since the reader should have little trouble justifying in any particular case the formal validity of our manipulations with power series. We will give several examples throughout this section to illustrate this contention.

**1.1.6 Example.** The identity

$$\left( \sum_{n \geq 0} x^n/n! \right) \left( \sum_{n \geq 0} (-1)^n x^n/n! \right) = 1 \quad (3)$$

is valid at the function-theoretic level (it states that  $e^x e^{-x} = 1$ ) and is well-defined as a statement involving formal power series. Hence (3) is a valid formal power series identity. In other words (equating coefficients of  $x^n/n!$  on both sides of (3)), we have

$$\sum_{k=0}^n (-1)^k \binom{n}{k} = \delta_{0n}. \quad (4)$$

To justify this identity directly from (3), we may reason as follows. Both sides of (3) converge for all  $x \in \mathbb{C}$ , so we have

$$\sum_{n \geq 0} \left( \sum_{k=0}^n (-1)^k \binom{n}{k} \right) \frac{x^n}{n!} = 1, \quad \text{for all } x \in \mathbb{C}.$$

But if two power series in  $x$  represent the same function  $f(x)$  in a neighborhood of 0, then these two power series must agree term-by-term, by a standard elementary result concerning power series. Hence (4) follows.

**1.1.7 Example.** The identity

$$\sum_{n \geq 0} (x+1)^n/n! = e \sum_{n \geq 0} x^n/n!$$

is valid at the function-theoretic level (it states that  $e^{x+1} = e \cdot e^x$ ), but does not make sense as a statement involving formal power series. There is no *formal* procedure for writing  $\sum_{n \geq 0} (x+1)^n/n!$  as a member of  $\mathbb{C}[[x]]$ .

Although the expression  $\sum_{n \geq 0} (x+1)^n/n!$  does not make sense *formally*, there are nevertheless certain infinite processes that can be carried out formally in  $\mathbb{C}[[x]]$ . (These concepts extend straightforwardly to  $\mathbb{C}[[x_1, \dots, x_m]]$ , but for simplicity we consider only  $\mathbb{C}[[x]]$ .) To define these processes, we need to put some additional structure on  $\mathbb{C}[[x]]$ —namely, the notion of *convergence*.



From an algebraic standpoint, the definition of convergence is inherent in the statement that  $\mathbb{C}[[x]]$  is *complete* in a certain standard topology that can be put on  $\mathbb{C}[[x]]$ . However, we will assume no knowledge of topology on the part of the reader and will instead give a self-contained, elementary treatment of convergence.

If  $F_1(x), F_2(x), \dots$  is a sequence of formal power series, and if  $F(x) = \sum_{n \geq 0} a_n x^n$  is another formal power series, we say by definition that  $F_i(x)$  *converges* to  $F(x)$  as  $i \rightarrow \infty$ , written  $F_i(x) \rightarrow F(x)$ , provided that for all  $n \geq 0$  there is a number  $\delta(n)$  such that the coefficient of  $x^n$  in  $F_i(x)$  is  $a_n$  whenever  $i \geq \delta(n)$ . In other words, for every  $n$  the sequence

$$\left\{ \begin{matrix} F_1(x) \\ F_2(x) \\ \vdots \end{matrix} \right\}_n$$

of complex numbers eventually becomes constant with value  $a_n$ . An equivalent definition of convergence is the following. Define the *degree* of a non-zero formal power series  $F(x) = \sum_{n \geq 0} a_n x^n$ , denoted  $\deg F(x)$ , to be the least integer  $n$  such that  $a_n \neq 0$ . Note that  $\deg F(x)G(x) = \deg F(x) + \deg G(x)$ . Then  $F_i(x)$  converges if and only if  $\lim_{i \rightarrow \infty} \deg(F_{i+1}(x) - F_i(x)) = \infty$ .

We now say that an infinite sum  $\sum_{j \geq 0} F_j(x)$  has the value  $F(x)$  provided that  $\sum_{j=0}^i F_j(x) \rightarrow F(x)$ . A similar definition is made for the infinite product  $\prod_{j \geq 1} F_j(x)$ . To avoid unimportant technicalities we assume that in any infinite product  $\prod_{j \geq 1} F_j(x)$ , each factor  $F_j(x)$  satisfies  $F_j(0) = 1$ . For instance, let  $F_j(x) = a_j x^j$ . Then for  $i \geq n$ , the coefficient of  $x^n$  in  $\sum_{j=0}^i F_j(x)$  is  $a_n$ . Hence  $\sum_{j \geq 0} F_j(x)$  is just the power series  $\sum_{n \geq 0} a_n x^n$ . Thus we can think of the formal power series  $\sum_{n \geq 0} a_n x^n$  as actually being the "sum" of its individual terms. The proofs of the following two elementary results are left to the reader.

**1.1.8 Proposition.** The infinite series  $\sum_{j \geq 0} F_j(x)$  converges if and only if  $\lim_{j \rightarrow \infty} \deg F_j(x) = \infty$ .  $\square$

**1.1.9 Proposition.** The infinite product  $\prod_{j \geq 1} (1 + F_j(x))$ , where  $F_j(0) = 0$ , converges if and only if  $\lim_{j \rightarrow \infty} \deg F_j(x) = \infty$ .  $\square$

It is essential to realize that in evaluating a convergent series  $\sum_{j \geq 0} F_j(x)$  (or similarly a product  $\prod_{j \geq 1} F_j(x)$ ), the coefficient of  $x^n$  for any given  $n$  can be computed using only *finite* processes. For if  $j$  is sufficiently large, say  $j > \delta(n)$ , then  $\deg F_j(x) > n$ , so that

$$\left\{ \sum_{j \geq 0} F_j(x) \right\}_n = \left\{ \sum_{j=0}^{\delta(n)} F_j(x) \right\}_n$$

The latter expression involves only a *finite* sum.

The most important combinatorial application of the notion of convergence is to the idea of power series composition. If  $F(x) = \sum_{n \geq 0} a_n x^n$  and  $G(x)$  are formal power series with  $G(0) = 0$ , define the *composition*  $F(G(x))$  to be the infinite sum  $\sum_{n \geq 0} a_n G(x)^n$ . Since  $\deg G(x)^n = n \cdot \deg G(x) \geq n$ , we see by Proposition 1.1.8 that  $F(G(x))$  is well-defined as a *formal* power series. We also see why an expression such as  $e^{1+x}$  does not make sense formally; namely, the infinite series

$\sum_{n \geq 0} (1+x)^n/n!$  does not converge in accordance with the above definition. On the other hand, an expression like  $e^{e^x-1}$  makes good sense formally, since it has the form  $F(G(x))$  where  $F(x) = \sum_{n \geq 0} x^n/n!$  and  $G(x) = \sum_{n \geq 1} x^n/n!$ .

**1.1.10 Example.** If  $F(x) \in \mathbb{C}[[x]]$  satisfies  $F(0) = 0$ , then we can *define* for any  $\lambda \in \mathbb{C}$  the formal power series

$$(1 + F(x))^\lambda = \sum_{n \geq 0} \binom{\lambda}{n} F(x)^n, \quad (5)$$

where  $\binom{\lambda}{n} = \lambda(\lambda-1)\cdots(\lambda-n+1)/n!$ . In fact, we may regard  $\lambda$  as an indeterminate and take (5) as the definition of  $(1 + F(x))^\lambda$  as an element of  $\mathbb{C}[[x, \lambda]]$  (or of  $\mathbb{C}[\lambda][[x]]$ ; that is, the coefficient of  $x^n$  in  $(1 + F(x))^\lambda$  is a *polynomial* in  $\lambda$ ). All the expected properties of exponentiation are indeed valid, such as  $(1 + F(x))^{\lambda+\mu} = (1 + F(x))^\lambda (1 + F(x))^\mu$  (regarded as an identity in the ring  $\mathbb{C}[[x, \lambda, \mu]]$ , or in the ring  $\mathbb{C}[[x]]$  where one takes  $\lambda, \mu \in \mathbb{C}$ ).

If  $F(x) = \sum_{n \geq 0} a_n x^n$ , define the *formal derivative*  $F'(x)$  (also denoted  $\frac{dF}{dx}$  or  $DF(x)$ ) to be the formal power series  $\sum_{n \geq 0} n a_n x^{n-1} = \sum_{n \geq 0} (n+1) a_{n+1} x^n$ . It is easy to check that all the familiar laws of differentiation that are well-defined formally continue to be valid for formal power series. In particular

$$(F + G)' = F' + G'$$

$$(FG)' = F'G + FG'$$

$$F(G(x))' = G'(x)F'(G(x)).$$

We thus have a theory of *formal calculus* for formal power series. The usefulness of this theory will become apparent in subsequent examples. We first give an example of the use of the formal calculus that should shed some additional light on the validity of manipulating formal power series as if they were actual functions of  $x$ .

**1.1.11 Example.** Suppose  $F(0) = 1$ , and let  $G(x)$  be the unique power series satisfying

$$G'(x) = F'(x)/F(x), \quad G(0) = 0. \quad (6)$$

From the function-theoretic viewpoint we can “solve” (6) to obtain  $F(x) = \exp G(x)$ , where by definition  $\exp G(x) = \sum_{n \geq 0} G(x)^n/n!$ . Since  $G(0) = 0$  everything is well-defined formally, so (6) should remain equivalent to  $F(x) = \exp G(x)$  even if the power series for  $F(x)$  converges only at  $x = 0$ . How can this assertion be justified without actually proving a combinatorial identity? Let  $F(x) = 1 + \sum_{n \geq 1} a_n x^n$ . From (6) we can compute explicitly  $G(x) = \sum_{n \geq 1} b_n x^n$ , and it is quickly seen that each  $b_n$  is a *polynomial* in finitely many of the  $a_i$ ’s. It then follows that if  $\exp G(x) = 1 + \sum_{n \geq 1} c_n x^n$ , then each  $c_n$  will also be a polynomial in finitely many of the  $a_i$ ’s, say  $c_n = p_n(a_1, a_2, \dots, a_m)$ , where  $m$  depends on  $n$ . Now we know that  $F(x) = \exp G(x)$  provided  $1 + \sum_{n \geq 1} a_n x^n$  converges. If two Taylor series convergent in some neighborhood of the origin represent the same function, then their coefficients coincide. Hence  $a_n = p_n(a_1, a_2, \dots, a_m)$  provided  $1 + \sum_{n \geq 1} a_n x^n$

converges. Thus the two polynomials  $a_n$  and  $p_n(a_1, a_2, \dots, a_m)$  agree in some neighborhood of the origin of  $\mathbb{C}^m$ , so they must be equal. (It is well-known that if two complex polynomials in  $m$  variables agree in some open set of  $\mathbb{C}^m$ , then they are identical.) Since  $a_n = p_n(a_1, a_2, \dots, a_m)$  as polynomials, the identity  $F(x) = \exp G(x)$  continues to remain valid for formal power series.

There is an alternative method for justifying the formal solution  $F(x) = \exp G(x)$  to (6), which may appeal to topologically inclined readers. Given  $G(x)$  with  $G(0) = 0$ , define  $F(x) = \exp G(x)$  and consider a map  $\phi: \mathbb{C}[[x]] \rightarrow \mathbb{C}[[x]]$  defined by  $\phi(G(x)) = G'(x) - \frac{F'(x)}{F(x)}$ . One easily verifies the following: (a) if  $G$  converges in some neighborhood of 0 then  $\phi(G(x)) = 0$ ; (b) the set  $\mathcal{G}$  of all power series  $G(x) \in \mathbb{C}[[x]]$  that converge in some neighborhood of 0 is dense in  $\mathbb{C}[[x]]$ , in the topology defined above (in fact, the set  $\mathbb{C}[x]$  of polynomials is dense); and (c) the function  $\phi$  is continuous in the topology defined above. From this it follows that  $\phi(G(x)) = 0$  for all  $G(x) \in \mathbb{C}[[x]]$  with  $G(0) = 0$ .

We now present various illustrations in the manipulation of generating functions. Throughout we will be making heavy use of the principle that formal power series can be treated as if they were functions.

**1.1.12 Example.** Find a simple expression for the generating function  $F(x) = \sum_{n \geq 0} a_n x^n$ , where  $a_0 = a_1 = 1$ ,  $a_n = a_{n-1} + a_{n-2}$  if  $n \geq 2$ . We have

$$\begin{aligned} F(x) &= \sum_{n \geq 0} a_n x^n = 1 + x + \sum_{n \geq 2} a_n x^n \\ &= 1 + x + \sum_{n \geq 2} (a_{n-1} + a_{n-2}) x^n \\ &= 1 + x + x \sum_{n \geq 2} a_{n-1} x^{n-1} + x^2 \sum_{n \geq 2} a_{n-2} x^{n-2} \\ &= 1 + x + x(F(x) - 1) + x^2 F(x). \end{aligned}$$

Solving for  $F(x)$  yields  $F(x) = 1/(1 - x - x^2)$ .

**1.1.13 Example.** Find a simple expression for the generating function  $F(x) = \sum_{n \geq 0} a_n x^n/n!$ , where  $a_0 = a_1 = 1$ ,  $a_n = a_{n-1} + (n-1)a_{n-2}$  if  $n \geq 2$ . We have

$$\begin{aligned} F(x) &= \sum_{n \geq 0} a_n x^n/n! \\ &= 1 + x + \sum_{n \geq 2} a_n x^n/n! \\ &= 1 + x + \sum_{n \geq 2} (a_{n-1} + (n-1)a_{n-2}) x^n/n!. \end{aligned} \tag{7}$$

Let  $G(x) = \sum_{n \geq 2} a_{n-1} x^n/n!$  and  $H(x) = \sum_{n \geq 2} (n-1)a_{n-2} x^n/n!$ . Then  $G'(x) = \sum_{n \geq 2} a_{n-1} x^{n-1}/(n-1)! = F(x) - 1$ , and  $H'(x) = \sum_{n \geq 2} a_{n-2} x^{n-1}/(n-2)! = xF(x)$ . Hence if we differentiate (7) we obtain

$$F'(x) = 1 + (F(x) - 1) + xF(x) = (1 + x)F(x).$$

The unique solution to this differential equation satisfying  $F(0) = 1$  is  $F(x) = \exp(x + \frac{1}{2}x^2)$ . (As shown in Example 1.1.11, solving this differential equation is a purely formal procedure.)