Combinatorics of Partial Derivatives

Michael Hardy

School of Mathematics
University of Minnesota, Minneapolis, MN 55455, USA
hardy@math.umn.edu

Submitted: Oct 1, 2005; Accepted: Dec 24, 2005; Published: Jan 7, 2006
Mathematics Subject Classifications: 05A15, 05A18, 11B73, 05-02

Abstract

The natural forms of the Leibniz rule for the kth derivative of a product and of Faà di Bruno's formula for the kth derivative of a composition involve the differential operator $\partial^k/\partial x_1 \cdots \partial x_k$ rather than d^k/dx^k, with no assumptions about whether the variables $x_1, \ldots, x_k$ are all distinct, or all identical, or partitioned into several distinguishable classes of indistinguishable variables. Coefficients appearing in forms of these identities in which some variables are indistinguishable are just multiplicities of indistinguishable terms (in particular, if all variables are distinct then all coefficients are 1). The computation of the multiplicities in this generalization of Faà di Bruno's formula is a combinatorial enumeration problem that, although completely elementary, seems to have been neglected. We apply the results to cumulants of probability distributions.

1 Introduction

Both the well-known Leibniz rule

$$\frac{d^k}{dx^k}(uv) = \sum_{\ell=0}^{k} \binom{k}{\ell} \frac{d^\ell u}{dx^\ell} \cdot \frac{d^{k-\ell} v}{dx^{k-\ell}} \tag{1}$$

and the celebrated formula of Francesco Faà di Bruno

$$\frac{d^k}{dx^k} f(y) = \sum \frac{k!}{1!^{m_1} \cdots k!^{m_k} m_1! \cdots m_k!} f^{(m_1+\cdots+m_k)}(y) \prod_{j\,:\,m_j \neq 0} \frac{d^{m_j} y}{dx^{m_j}} \tag{2}$$

(where the sum is over all k-tuples $(m_1, \ldots, m_k)$ of non-negative integers satisfying the constraint $m_1 + 2m_2 + 3m_3 + \cdots + km_k = k$) are formulas for kth derivatives of functions of functions of x. That is what the left sides of these identities share in common. The right sides of both identities are sums whose terms have products of higher derivatives with respect to x as factors.

All mathematicians know the combinatorial interpretation of the coefficients in the Leibniz rule (the number of size-ℓ subsets of a size-k set), and all combinatorialists know the combinatorial interpretation of the coefficients in Faà di Bruno's formula (the number of partitions of a size-k set into m_j parts of size j, for $j = 1, \ldots, k$). However, the following two points appear not to be widely known:

1. The natural form of these identities involves the differential operator

$$\frac{\partial^k}{\partial x_1 \cdots \partial x_k}$$

instead of d^k/dx^k. In that form, all coefficients on the right sides are 1.

2. There should be no assumptions about whether the variables $x_1, \ldots, x_k$ are all distinct, or all identical, or partitioned into several distinguishable classes of indistinguishable variables. When some variables become indistinguishable, so do some of the terms on the right sides of the identities. Indistinguishable terms then get collected, so that each constant coefficient of a term on the right side is that term's multiplicity. When *all* of the variables are indistinguishable, then the multiplicities are the coefficients in (1) and (2) above.

We will call the above Point 1 and Point 2.

Finding the multiplicities in Point 2 applied to (2) is a combinatorial problem that may have escaped explicit treatment until the present paper, in which the solution is Proposition 4. The problem is that of enumeration of what we will call "collapsing partitions".

As an example of Point 2, if x_2 and x_3 collapse into two indistinguishable variables called x_2, so that $\partial^3/(\partial x_1\,\partial x_2\,\partial x_3)$ becomes $\partial^3/(\partial x_1\,\partial x_2^2)$, then the two-term sum

$$\frac{\partial y}{\partial x_2} \cdot \frac{\partial^2 y}{\partial x_1\,\partial x_3} + \frac{\partial y}{\partial x_3} \cdot \frac{\partial^2 y}{\partial x_1\,\partial x_2}$$

collapses to the term

$$2 \cdot \frac{\partial y}{\partial x_2} \cdot \frac{\partial^2 y}{\partial x_1\,\partial x_2}$$

with multiplicity 2.

The chain rule and the product rule are enough to entail that the coefficients must be positive integers. But without Point 1 and Point 2, it is not obvious what, if anything, they enumerate.

Two papers, Constantine and Savits [5] and Leipnik and Reid [9], give an identity expressing $(\partial^{k_1+\cdots+k_n}/\partial x_1^{k_1} \cdots \partial x_n^{k_n}) f(y)$ as a linear combination of products of derivatives of $f(y)$ with respect to y and of y with respect to the independent variables. But neither of those sources mentions that as more and more variables become indistinguishable the identity does not change except in the collection of newly indistinguishable terms. Without that observation, the combinatorial content of the problem is invisible. Leipnik and Reid in [9], p. 1, wrote, “Obviously, ‘pure’ derivatives, such as $\frac{\partial^4 G(z_1,z_2)}{\partial z_1^4}$ are easier to deal with than mixed derivatives like $\frac{\partial^4 G}{\partial z_1^2\,\partial z_2^2}$.” But from our point of view, it will be *maximally* “mixed” derivatives like $\partial^4 G/(\partial z_1\,\partial z_2\,\partial z_3\,\partial z_4)$ that are the easiest and most basic.

Proposition 2 of this paper is partially anticipated by Terry Speed in [14], page 382. That paper gives only the special case in which f is the exponential function, in which the derivatives appear as coefficients of power series, and is stated in an inconspicuous and somewhat tangential way that mixes it so thoroughly with the theory of cumulants in probability theory that it can be understood only by understanding what the paper is saying about cumulants. Speed wrote: “...the general results are most transparent when all ... variables under discussion are taken to be distinct.” That remark played a role in inspiring this paper. Its influence will be seen not only in our Proposition 1, but also in our treatment of product rules–a topic not directly relevant to that of Speed’s paper and not mentioned there. Speed went on: “The identification of some or all [variables] at a later stage merely introduces extra factors, and at times these multiplicities are not particularly easy to calculate.” The multiplicities are given by our Proposition 4.

Unlike [5] and [9], Warren Johnson [8] states a version of Faà di Bruno’s formula that is explicit about the combinatorial meaning of the coefficients. But Johnson treats only functions of one variable and gives nothing like Proposition 2 of the present paper. The same is true of the “compositional formula” on page 3 of Richard P. Stanley’s treatise [15]. Like Speed, Stanley gives a power-series version of the formula. He mentions the name of Faà di Bruno only in endnotes. One also finds a very combinatorics-flavored views of Faà di Bruno’s formula in [19]. Other variations on the theme are in [10], [11], and [18].

We conclude this paper with the application of the results to cumulants.

2 Partial derivatives and partitions of sets

In the identity

$$\begin{aligned}\frac{\partial^3}{\partial x_1\,\partial x_2\,\partial x_3}e^y \;=\; e^y\Bigg(&\frac{\partial^3 y}{\partial x_1\,\partial x_2\,\partial x_3} + \frac{\partial y}{\partial x_1}\cdot\frac{\partial^2 y}{\partial x_2\,\partial x_3} + \frac{\partial y}{\partial x_2}\cdot\frac{\partial^2 y}{\partial x_1\,\partial x_3}\\ &+ \frac{\partial y}{\partial x_3}\cdot\frac{\partial^2 y}{\partial x_1\,\partial x_2} + \frac{\partial y}{\partial x_1}\cdot\frac{\partial y}{\partial x_2}\cdot\frac{\partial y}{\partial x_3}\Bigg),\end{aligned}\tag{3}$$

where y is a function of x_1, x_2, x_3, the terms correspond in an obvious way to the five partitions of the set $\{1,2,3\}$. We will see that this holds generally: the partial derivative $(\partial^n/\partial x_1\cdots\partial x_n)e^y$ is e^y times the sum whose terms correspond in just this way to the partitions of the set $\{1,\ldots,n\}$. Using the notation (for example) $\partial^3 y \Big/ \prod_{j\in\{2,4,9\}}\partial x_j$ to mean $\partial^3 y/\,\partial x_2\,\partial x_4\,\partial x_9$, we can say

$$\frac{\partial^n}{\partial x_1\cdots\partial x_n}e^y = e^y\sum_\pi\prod_{B\in\pi}\frac{\partial^{|B|}y}{\prod_{j\in B}\partial x_j}\tag{4}$$

where the sum is over all partitions π of the set $\{1, \ldots, n\}$ and the product is over all of the parts B, or "blocks" as we will call them, of the partition π, and we denote the number of members of any set S by $|S|$.

If we have $f(y)$ instead of e^y, then the orders of the derivatives of f must be mentioned. The order of each derivative of f is just the number of blocks in the partition. This is the first result that we will prove (in Section 3):

Proposition 1.

$$\frac{\partial^n}{\partial x_1 \cdots \partial x_n} f(y) = \sum_{\pi} f^{(|\pi|)}(y) \prod_{B \in \pi} \frac{\partial^{|B|} y}{\prod_{j \in B} \partial x_j}. \tag{5}$$

Example 1.

$$\begin{aligned} \frac{\partial^3}{\partial x_1\, \partial x_2\, \partial x_3} f(y) = \;& \underbrace{f'(y) \frac{\partial^3 y}{\partial x_1\, \partial x_2\, \partial x_3}}_{\text{1 block; 1st derivative of } f.} \\ + \;& \underbrace{f''(y) \left(\frac{\partial y}{\partial x_1} \cdot \frac{\partial^2 y}{\partial x_2\, \partial x_3} + \frac{\partial y}{\partial x_2} \cdot \frac{\partial^2 y}{\partial x_1\, \partial x_3} + \frac{\partial y}{\partial x_3} \cdot \frac{\partial^2 y}{\partial x_1\, \partial x_2} \right)}_{\text{2 blocks in each partition; 2nd derivative of } f.} \\ + \;& \underbrace{f'''(y) \frac{\partial y}{\partial x_1} \cdot \frac{\partial y}{\partial x_2} \cdot \frac{\partial y}{\partial x_3}}_{\text{3 blocks; 3rd derivative of } f.}. \end{aligned}$$

Proposition 2. If some of the x_is become indistinguishable, then so do the corresponding terms in the sum; nothing else changes.

This will also be proved in Section 3.

Example 2. Suppose that in Example 1, the two variables x_2 and x_3 become indistinguishable from each other. Call them both x_2. Then we have

$$\begin{aligned} \frac{\partial^3}{\partial x_1\, \partial x_2^2} f(y) \;=\;& \overbrace{f'(y) \frac{\partial^3 y}{\partial x_1\, \partial x_2^2}}^{\text{1 block; 1st derivative of } f.} \\ &+ \overbrace{f''(y) \left(\frac{\partial y}{\partial x_1} \cdot \frac{\partial^2 y}{\partial x_2^2} + 2 \cdot \underbrace{\frac{\partial y}{\partial x_2} \cdot \frac{\partial^2 y}{\partial x_1\, \partial x_2}}_{\uparrow\ \text{The multiplicity of this term is 2.}} \right)}^{\text{2 blocks in each partition; 2nd derivative of } f.} \\ &+ \overbrace{f'''(y) \frac{\partial y}{\partial x_1} \cdot \left(\frac{\partial y}{\partial x_2} \right)^2}^{\text{3 blocks; 3rd derivative of } f.}. \end{aligned}$$

The multiplicity mentioned above is how many formerly distinguishable terms get collected to form that term. The problem of finding such multiplicities is treated in Section 4. Applying the language of that section to Example 2, we would ask: how many partitions of the set $\{1,2,3\}$ collapse to the partition $\{2\}+\{1,2\}$ of the multiset $\{1,2,2\}$ when the set $\{1,2,3\}$ collapses to the multiset $\{1,2,2\}$, i.e., when the members 2 and 3 become indistinguishable? The answer in this case is 2.

3 Proofs of the first two Propositions

Proof of Proposition 1. This proof relies on this simple standard algorithm for converting a list of all partitions of $\{1,\ldots,n\}$ into a list of all partitions of $\{1,\ldots,n+1\}$:

1. To each partition of $\{1,\ldots,n\}$, add the 1-member-set $\{n+1\}$ as a new block. This gives a list of some of the partitions of $\{1,\ldots,n+1\}$.
2. To each block of each partition of $\{1,\ldots,n\}$, add $n+1$ as a new member of the block. This gives a list of $\sum_\pi |\pi|$ additional partitions of $\{1,\ldots,n+1\}$.

The union of these two lists clearly contains all partitions of $\{1,\ldots,n+1\}$.

In particular, it works when $n=0$, since the empty set has exactly one partition[1]. That establishes the basis for a proof by mathematical induction on n.

Next we use the Proposition in case n to prove the Proposition in case $n+1$.

$$\begin{aligned}
&\frac{\partial^{n+1}}{\partial x_1\cdots\partial x_{n+1}}f(y)\\
=&\sum_\pi \frac{\partial}{\partial x_{n+1}}\left[f^{(|\pi|)}(y)\prod_{B\in\pi}\frac{\partial^{|B|}y}{\prod_{j\in B}\partial x_j}\right]\\
=&\sum_\pi\left[f^{(|\pi|+1)}(y)\frac{\partial y}{\partial x_{n+1}}\prod_{B\in\pi}\frac{\partial^{|B|}y}{\prod_{j\in B}\partial x_j}+f^{(|\pi|)}(y)\frac{\partial}{\partial x_{n+1}}\prod_{B\in\pi}\frac{\partial^{|B|}y}{\prod_{j\in B}\partial x_j}\right]\\
=&\sum_\pi\Bigg[f^{(|\pi|+1)}(y)\frac{\partial y}{\partial x_{n+1}}\prod_{B\in\pi}\frac{\partial^{|B|}y}{\prod_{j\in B}\partial x_j}\\
&\qquad+f^{(|\pi|)}(y)\sum_{B\in\pi}\left(\frac{\partial^{|B|+1}y}{\partial x_{n+1}\prod_{j\in B}\partial x_j}\cdot\prod_{C\in\pi\,:\,C\neq B}\frac{\partial^{|C|}y}{\prod_{j\in C}\partial x_j}\right)\Bigg].
\end{aligned}$$

[1]Perhaps as a result of studying set theory, I was surprised when I learned that some respectable combinatorialists consider such things as this to be mere convention. One of them even said a case could be made for setting the number of partitions to 0 when $n=0$. By stark contrast, Gian-Carlo Rota wrote in [13], p. 15, that "the kind of mathematical reasoning that physicists find unbearably pedantic" leads not only to the conclusion that the elementary symmetric function in no variables is 1, but straight from there to the theory of the Euler characteristic, so that "such reasoning does pay off." The only other really sexy example I know is from applied statistics: the non-central chi-square distribution with zero degrees of freedom, unlike its "central" counterpart, is non-trivial.

Inside the last square brackets is a sum of two terms. The first term corresponds to step 1 in our algorithm: we have added $\{\, n+1 \,\}$ as a new block to our partition π of $\{\, 1, \ldots, n \,\}$, getting a partition with $|\pi| + 1$ blocks, of the set $\{\, 1, \ldots, n+1 \,\}$. The second corresponds to step 2 in our algorithm: we have added $n+1$ to each block of our partition π of $\{\, 1, \ldots, n \,\}$, getting a partition with $|\pi|$ blocks, of the set $\{\, 1, \ldots, n+1 \,\}$. We now have a sum over all partitions of $\{\, 1, \ldots, n+1 \,\}$, each partition being represented as a product of partial derivatives, each partial derivative representing a block. And for each partition there is a factor $f^{(\bullet)}(y)$, the order of the derivative being the number of blocks of the partition. This proves case $n+1$, and the proof by induction on n is complete. ■

Proof of Proposition 2. Observe that if, in the argument above, we had differentiated at the $(n+1)$th step with respect to x_k for some $k \in \{\, 1, \ldots, n \,\}$, rather than with respect to x_{n+1}, then nothing would change except that some formerly distinguishable terms would become indistinguishable. ■

4 Multisets and collapsing partitions

4.1 Definitions and conventions

The first two bullet points and the fifth in the definition below are standard but make clear which notational conventions we will follow. The third and fourth may be less standard.

- A **multiset** is a "set with multiplicities", i.e., positive integers, assigned to each member x, thought of as the number of times x occurs as a member. We will write $\{\, \underbrace{x_1, \ldots, x_1}_{m_1}, \ldots, \underbrace{x_n, \ldots, x_n}_{m_n} \,\}$, indicating multiplicities with underbraces, or, in simple cases, for example $\{\, a, a, a, b, b, c, c, c, c, c \,\}$, the multiplicity being the number of times the member is named. In particular, we identify every set with a multiset in which every multiplicity is 1.

  Perhaps the most widely known example is the multiset of prime factors of a natural number: each prime factor has a multiplicity.

- The **size** $|S|$ of a multiset S is the sum of the multiplicities.

- The **sum** of multisets is given by term-by-term addition of multiplicities:

$$\begin{aligned} &\{\, \underbrace{x_1, \ldots, x_1}_{\ell_1}, \ldots, \underbrace{x_n, \ldots, x_n}_{\ell_n} \,\} + \{\, \underbrace{x_1, \ldots, x_1}_{m_1}, \ldots, \underbrace{x_n, \ldots, x_n}_{m_n} \,\} \\ = \; &\{\, \underbrace{x_1, \ldots, x_1}_{\ell_1+m_1}, \ldots, \underbrace{x_n, \ldots, x_n}_{\ell_n+m_n} \,\}. \end{aligned}$$

  Only when sets are disjoint is their sum the same as their union.

- A **partition** of a multiset expresses that multiset as a sum of multisets.

- A **partition** of a positive integer expresses that integer as a sum of positive integers.

The next proposition is trivial but crucial.

Proposition 3.

- The concept of *partition of a set* is a special case of that of *partition of a multiset.*
- If we identify any multiset in which "all members are equal" (i.e., there is just one member, whose multiplicity may be any positive integer) with the multiplicity of that one member (for example, the multiset $\{ a, a, a \}$ is identified with the number 3), then the concept of *partition of an integer* becomes a special case of that of *partition of a multiset.*

4.2 Collapsing partitions

If the members 1, 2, 3, 4 of the set $\{ 1, 2, 3, 4, 5, 6, 7, 8 \}$ are made indistinguishable from each other and are called "1", and 5 and 6 are made indistinguishable from each other and are called "5", then we say that the set $\{ 1, 2, 3, 4, 5, 6, 7, 8 \}$ has "collapsed" to the multiset $\{ 1, 1, 1, 1, 5, 5, 7, 8 \}$. Then we can ask: how many set-partitions collapse to the multiset-partition

$$\{ 1, 1, 5 \} + \{ 1, 1, 5 \} + \{ 7, 8 \} ?$$

It is a simple exercise to find that the answer is 6. Consequently, via the correspondence

$$\tau = \{ \underbrace{1, \ldots, 1}_{k_1}, \ldots, \underbrace{n, \ldots, n}_{k_n} \} \longleftrightarrow \frac{\partial^{k_1+\cdots+k_n}}{\partial x_1^{k_1} \cdots \partial x_n^{k_n}} = \partial_\tau \tag{6}$$

between multisets and partial differential operators, Proposition 2 entails that the expansion of the partial derivative

$$\partial_{\{ 1,1,1,1,5,5,7,8 \}} f(y) = \frac{\partial^8}{\partial x_1^4 \, \partial x_5^2 \, \partial x_7 \, \partial x_8} f(y) \tag{7}$$

contains (among many others) this term:

$$6 f'''(y) \left(\partial_{\{ 1,1,5 \}} y \right)^2 \, \partial_{\{ 7,8 \}} y = 6 f'''(y) \left(\frac{\partial^3 y}{\partial x_1^2 \, \partial x_5} \right)^2 \cdot \frac{\partial^2 y}{\partial x_7 \, \partial x_8} \tag{8}$$

(the order of the derivative of f is 3 because that is how many blocks are in this partition).

An extreme case of "collapsing" is exemplified by the question: How many partitions of the set $\{ 1, 2, 3, 4, 5, 6, 7, 8 \}$ collapse to the partition $3 + 3 + 2$ of the number 8 when all 8 members of the set $\{ 1, 2, 3, 4, 5, 6, 7, 8 \}$ collapse into indistinguishability? Again, a simple exercise shows that the answer is 280. In this extreme case where all members of the set become indistinguishable and partitions of the multiset become partitions of an integer, the answer to the problem of enumeration of collapsing partitions is well known to be given by the coefficients in Faà di Bruno's formula – in this case by the coefficient of

$$f'''(y) \left(\frac{d^3 y}{dx^3} \right)^2 \frac{d^2 y}{dx^2}$$

in the expansion of $(d^8/dx^8)f(y)$.

In general, we have this result:

Corollary to Propositions 1 and 2. Let $\tau = \{\, \underbrace{1,\ldots,1}_{k_1},\ldots,\underbrace{n,\ldots,n}_{k_n} \,\}$. Use the notation introduced in (6) above. Then

$$\partial_\tau f(y) = \frac{\partial^{k_1+\cdots+k_n}}{\partial x_1^{k_1}\cdots\partial x_n^{k_n}} f(y) = \sum_{\tau_1+\tau_2+\cdots} M f^{(\bullet)}(y)\cdot(\partial_{\tau_1}y\cdot\partial_{\tau_2}y\cdot\cdots),$$

where the sum is over all partitions $\tau_1+\tau_2+\cdots$ of the multiset τ, the order of the derivative $f^{(\bullet)}(y)$ is the number of terms in the partition $\tau_1+\tau_2+\cdots$, and the multiplicity M is the number of partitions of the set $\{\,1,2,3,\ldots,k_1+\cdots+k_n\,\}$ that collapse to the partition $\tau_1+\tau_2+\cdots$ of the multiset τ when the set $\{\,1,2,3,\ldots,k_1+\cdots+k_n\,\}$ collapses to the multiset τ.

In order to use it in the next result, we introduce a convention:

Notational convention. For any multiset σ let $\sigma!!$ denote the product of the factorials of the multiplicities of the members of σ. For example, $\{\,1,1,1,1,2,2,2\,\}!! = 4!3! = 144$.

The next result will be proved in Section 5:

Proposition 4.

Let $\tau = \{\, \underbrace{1,\ldots,1}_{k_1},\ldots,\underbrace{n,\ldots,n}_{k_n} \,\}$. Consider a partition

$$\tau = \underbrace{\tau_1+\cdots+\tau_1}_{m_1}+\underbrace{\tau_2+\cdots+\tau_2}_{m_2}+\cdots$$

in which τ_1, τ_2, ... are *all distinct* (so that $m_1, m_2, m_3, \ldots$ are multiplicities of yet another sort). Denote this by

$$\tau = m_1\tau_1 + m_2\tau_2 + \cdots.$$

Then the number of partitions of the set $\{\,1,2,3,\ldots,k_1+\cdots+k_n\,\}$ that collapse to the partition $m_1\tau_1+m_2\tau_2+m_3\tau_3+\cdots$ of the multiset τ when the set $\{\,1,2,3,\ldots,k_1+\cdots+k_n\,\}$ collapses to the multiset τ is

$$\frac{k_1!\cdots k_n!}{\tau_1!!^{m_1}\tau_2!!^{m_2}\tau_3!!^{m_3}\cdots m_1!m_2!m_3!\cdots}. \tag{9}$$

4.3 The most extreme case

In the most extreme case of indistinguishability of independent variables, the operator $\partial^k/\partial x_1\cdots\partial x_k$ collapses to d^k/dx^k:

$$\frac{d^k}{dx^k}f(y) = \sum_\pi f^{(|\pi|)}(y)\prod_{B\in\pi}\left(\frac{d}{dx}\right)^{|B|} y, \tag{10}$$

where, again, the sum is over all partitions π of $\{1, \ldots, k\}$. In this sum, two terms are indistinguishable whenever two partitions of the set $\{1, \ldots, k\}$ both collapse to the same partition of the integer k when *all* of the members of $\{1, \ldots, k\}$ become indistinguishable.

In this extreme case, the multiplicities are given by the classic formula of Francesco Faà di Bruno (2). Francesco Faà di Bruno (1825 – 1888) was (in chronological order) a military officer, a mathematician, and a priest. He published this formula in [2] and [3] and was posthumously beatified by the Pope[2].

Alex Craik's *Prehistory of Faa di Bruno's Formula* [6] points out that Faà di Bruno was anticipated in 1800 by L.F.A. Arbogast; see [1].

Although (2) is the well-known form of this identity, Warren P. Johnson has written in [8] (bottom of page 231), that (10) "is really the fundamental form" of Faà di Bruno's formula. We propose that the conjunction of our first two Propositions is more fundamental.

4.4 Conservation of Bell numbers

By now it should be clear that, when the derivative

$$\frac{\partial^n}{\cdots\cdots} f(y)$$

is expanded as a sum in terms of derivatives of $f(y)$ with respect to y and derivatives of y with respect to whichever independent variables appear, then the sum of the coefficients is always the number B_n of partitions of a set of n members. This is called the nth Bell number, in honor of Eric Temple Bell. The first several of these are $B_0 = 1, B_1 = 1, B_2 = 2, B_3 = 5, B_4 = 15, B_5 = 52, B_6 = 203, B_7 = 877, B_8 = 4140, \ldots$. For an account of these numbers, see [12]. As more and more of the n independent variables get identified with each other, the sum of the multiplicities never changes.

5 Proof of Proposition 4

Imagine $k_1 + \cdots + k_n$ Scrabble tiles. On the first k_1 of these, the number "1" is written; on the next k_2 of them, "2" appears; and so on. These are partitioned into m_1 copies of the multiset τ_1, m_2 copies of τ_2, and so on.

Permuting the k_1 "1"s or the k_2 "2"s, etc., does not alter the set of $m_1 + \cdots + m_n$ "words". Thus there are $k_1! \cdots k_n!$ permutations of the $k_1 + \cdots + k_n$ tiles representing the partition

$$\tau = m_1\tau_1 + m_2\tau_2 + \cdots .$$

Permuting the identical elements within any block of this partition does not alter which partition of τ we have, and therefore the product $k_1! \cdots k_n!$ gets divided by $\tau_1!!^{m_1}\tau_2!!^{m_2}\cdots$. Neither does permuting the m_i blocks identical to τ_i, and therefore it also gets divided by $m_1! \cdots m_n!$. ■

[2] An anonymous referee suggests that that pontiff may have been influenced more by Faà di Bruno's charitable than mathematical work.

6 Product rules

In the identity

$$\begin{aligned}
&\frac{\partial^3}{\partial x_1\,\partial x_2\,\partial x_3}(uv)\\
=\;& u\cdot\frac{\partial^3 v}{\partial x_1\,\partial x_2\,\partial x_3}+\frac{\partial u}{\partial x_1}\cdot\frac{\partial^2 v}{\partial x_2\,\partial x_3}+\frac{\partial u}{\partial x_2}\cdot\frac{\partial^2 v}{\partial x_1\,\partial x_3}+\frac{\partial u}{\partial x_3}\cdot\frac{\partial^2 v}{\partial x_1\,\partial x_2}\\
&+\frac{\partial^2 u}{\partial x_1\,\partial x_2}\cdot\frac{\partial v}{\partial x_3}+\frac{\partial^2 u}{\partial x_1\,\partial x_3}\cdot\frac{\partial v}{\partial x_2}+\frac{\partial^2 u}{\partial x_2\,\partial x_3}\cdot\frac{\partial v}{\partial x_1}+\frac{\partial^3 u}{\partial x_1\,\partial x_2\,\partial x_3}\cdot v,
\end{aligned}$$

the terms correspond in an obvious way to the eight subsets of the set $\{1,2,3\}$. This exemplifies the first part of our next result.

Proposition 5.

- $$\frac{\partial^n}{\partial x_1\cdots\partial x_n}(uv)=\sum_S\frac{\partial^{(|S|)}u}{\prod_{j\in S}\partial x_j}\cdot\frac{\partial^{(n-|S|)}v}{\prod_{j\notin S}\partial x_j},$$

  where the index S runs through the set of all subsets of $\{1,\ldots,n\}$.

- If some of the variables become indistinguishable, then so do some of the terms in the sum; nothing else changes.

Example 4.

$$\begin{aligned}
\frac{\partial^3}{\partial x_1\,\partial x_2^2}(uv) \;=\;& u\cdot\frac{\partial^3 v}{\partial x_1\,\partial x_2^2}+\frac{\partial u}{\partial x_1}\cdot\frac{\partial^2 v}{\partial x_2^2}+2\cdot\frac{\partial u}{\partial x_2}\cdot\frac{\partial^2 v}{\partial x_1\,\partial x_2}\\
&+2\cdot\frac{\partial^2 u}{\partial x_1\,\partial x_2}\cdot\frac{\partial v}{\partial x_2}+\frac{\partial^2 u}{\partial x_2^2}\cdot\frac{\partial v}{\partial x_1}+\frac{\partial^3 u}{\partial x_1\,\partial x_2^2}\cdot v.
\end{aligned}$$

In this case the solution of the combinatorial problem is simpler:

Proposition 6.

$$\frac{\partial^{k_1+\cdots+k_n}}{\partial x_1^{k_1}\,\cdots\,\partial x_n^{k_n}}(uv)=\sum_{\ell_1=0}^{k_1}\cdots\sum_{\ell_n=0}^{k_n}\binom{k_1}{\ell_1}\cdots\binom{k_n}{\ell_n}\frac{\partial^{\ell_1+\cdots+\ell_n}u}{\partial x_1^{\ell_1}\,\cdots\,\partial x_n^{\ell_n}}\cdot\frac{\partial^{k_1-\ell_1+\cdots+k_n-\ell_n}v}{\partial x_1^{k_1-\ell_1}\,\cdots\,\partial x_n^{k_n-\ell_n}}.$$

In the most extreme case, all of the independent variables become indistinguishable, and we have the familiar Leibniz rule (1). The proofs of Propositions 5 and 6 are left as exercises.

As far as the present writer knows, the second part of Proposition 5 is new. It identifies the easy combinatorial problem that Proposition 6 solves. Proposition 6 can be found in both [5] and [4], p. 131, but without the combinatorial interpretation of the coefficients. The first part of Proposition 5 is an important special case of Proposition 6, and we do not know of any earlier explicit statement of it than that in the present paper (a referee says "it could be just about anywhere" and I have not succeeded in proving otherwise).

7 Cumulants

The omitted fragment represented by the second ellipsis "..." in the first quote from Terry Speed in Section 1 is the word *random*. That is because Speed's topic is that of cumulants of random variables.

For positive integers n, the nth cumulant functional κ_n assigns a real number $\kappa_n(X)$ to real-valued random variables X. Let $\mu = \mathrm{E}(X)$ be the expected value of X. Then the nth central moment of X is $\mathrm{E}((X-\mu)^n)$. For $n \geq 2$, the nth cumulant shares with the nth central moment the properties of nth-degree homogeneity and translation-invariance:

$$\begin{aligned} \kappa_n(cX) &= c^n \kappa_n(X), \\ \kappa_n(X+c) &= \kappa_n(X). \end{aligned}$$

Moreover, if the random variables $X_1, \ldots, X_m$ are independent, then

$$\kappa_n(X_1 + \cdots + X_m) = \kappa_n(X_1) + \cdots + \kappa_n(X_m).$$

The nth central moment has this additivity property *only* when $n \leq 3$. In fact, when $n =$ either 2 or 3, the cumulant is just the central moment. When $n = 1$, then the cumulant is the expected value. For all n, the nth cumulant is an nth-degree polynomial in the first n moments.

Cumulants were introduced in the 19th century in [16] by the Danish actuary Thorvald Thiele, who called them half-invariants; an English translation was published in 1931; see [17]. They were first publicly given the name *cumulants* in 1931 by the statisticians Ronald Fisher and John Wishart in [7], the name having been suggested to Fisher in private correspondence from the statistician Harold Hotelling. There are also *joint cumulants*

$$\kappa(X_1, \ldots, X_n).$$

When $n = 2$, this is just the covariance. All probabilists and statisticians know that the covariance between a random variable and itself is its variance. A similar thing happens with joint cumulants: When the n random variables collapse into indistinguishability, then the joint cumulant coincides with the nth cumulant of one random variable:

$$\kappa(\underbrace{X, \ldots, X}_{n}) = \kappa_n(X).$$

Beyond this talk of "collapsing into indistinguishability", a parallel between cumulants and the partial derivatives treated in the foregoing sections is seen in the identity that expresses the nth raw moment $\mathrm{E}(X^n)$ (not the nth *central* moment) in terms of the first n cumulants:

$$\mathrm{E}(X^n) = \sum_{\pi} \prod_{B \in \pi} \kappa_{|B|}(X). \tag{11}$$

For random variables $X_1, \ldots, X_n$, a similar identity holds:

$$\mathrm{E}(X_1 \cdots X_n) = \sum_{\pi} \prod_{B \in \pi} \kappa(X_i : i \in B). \tag{12}$$

The identities (11) and (12) completely characterize all of the cumulant functionals.

That is how Terry Speed came to consider the question of these multiplicities, of which all he wrote was that they are not always easy to calculate. Workers with cumulants know what to do in the two opposite extreme cases: when *none* of the random variables are identified then all coefficients are equal to 1, and when *all* are identified then the classic Faà di Bruno formula (2) gives the coefficients. But if one were to judge by Speed's comments, they might seem at something of a loss in cases intermediate between "all" and "none". That case is handled by our Proposition 4.

Speed's topic and that of partial derivatives are not two disparate applications of our Proposition 4. The joint cumulant may be characterized as the coefficient of $t_1 \cdots t_n$ in the power-series expansion of

$$\log \mathrm{E}\left(\exp(t_1 X_1 + \cdots + t_n X_n)\right)$$

(at least in the case in which all moments exist). More tersely stated, the joint cumulant-generating function is the logarithm of the joint moment-generating function. Since the coefficients of a power series of the form $\sum_{i_1,\ldots,i_n} c_{i_1,\ldots,i_n} t_1^{i_1} \cdots t_n^{i_n} / (i_1! \cdots i_n!)$ are its partial derivatives at $t_1 = \cdots = t_n = 0$, Speed's topic is a special case of ours.

8 Acknowledgments

Ezra Miller and Jay Goldman offered helpful suggestions. Unlike some copyeditors, Ellen Stuttle found the actual content interesting. Alex Craik pointed out some relevant references and reminded me of Arbogast's anticipation of Faà di Bruno's formula. In addition to some encouraging words, Doron Zeilberger pointed out his paper [19]; which is even more "discretely" oriented than the present paper (which, the reader will have noticed, disdains even to mention such "analytical" things as differentiability).

References

[1] L.F.A. Arbogast, *Du Calcul des Dérivations*, Levrault, Strasbourg, 1800.

[2] F. Faà di Bruno, Sullo Sviluppo delle Funzioni, *Annali di Scienze Matematiche e Fisiche* **6**, 1855 pp. 479-480.

[3] F. Faà di Bruno, Note sur un nouvelle formule de calcul différentiel, *Quarterly Journal of Pure and Applied Mathematics*, **1**, 1857, pp. 359-360.

[4] L. Comtet, *Advanced Combinatorics: The Art of Finite and Infinite Expansions*, Reidel, Dordrecht-Holland/Boston, 1974.

[5] G.M. Constantine and T.H. Savits, A Multivariate Faa di Bruno Formula with Applications, *Transactions of the American Mathematical Society*, **348**, 1996 pp. 503-520.

[6] A. Craik, Prehistory of Faa di Bruno's Formula, *American Mathematical Monthly*, **112 (2)**, February 2005, pp. 119–130.

[7] R.A. Fisher and J. Wishart, The derivation of the pattern formulae of two-way partitions from those of simpler patterns, *Proceedings of the London Mathematical Society, Series 2*, **33**, 1931, pp. 195-208.

[8] W.P. Johnson, The Curious History of Faà di Bruno's Formula, *Am. Math. Monthly* **109**, 2002, pp. 217-227.

[9] R. Leipnik and T. Reid, Multivariable Faa di Bruno Formulas, *Electronic Proceedings of the Ninth Annual International Conference on Technology in Collegiate Mathematics*, http://archives.math.utk.edu/ICTCM/EP-9.html#C23 .

[10] R. Mishkov, Generalization of the Formula of Faa di Bruno for a Composite Function with a Vector Argument, *International Journal of Mathematical Sciences*, **24**, 2000, pp. 481-491.

[11] S. Noschese and P.E. Ricci, Differentiation of Multivariable Composite Functions and Bell Polynomials, *Journal of Computational Analysis and Applications*, **5**, 2003, pp. 333-340.

[12] G-C. Rota, The Number of Partitions of a Set, *Am. Math. Monthly* **71**, 1964, pp. 498-504.

[13] C-C. Rota, Geometric Probability, *Mathematical Intelligencer*, **20 (4)**, 1998, pp. 11-16.

[14] T.P. Speed, Cumulants and Partition Lattices, *Australian Journal of Statistics*, **25 (2)**, 1983, pp. 378-388.

[15] R.P. Stanley, *Enumerative Combinatorics, Volume 2*, Cambridge University Press, Cambridge, 1999.

[16] T.N. Thiele, *Forlæsinger over Almindelig Iagttagelselære*, Reitzel, Copenhagen, 1889.

[17] T.N. Thiele, *Theory of Observations*, Layton, London, 1903. Reprinted in *Annals of Mathematical Statistics*, **2**, 1931, pp. 165-308.

[18] W.C. Yang, Derivatives are Essentially Integer Partitions, *Discrete Mathematics*, **222**, 2000, pp. 235-245.

[19] D. Zeilberger, "Toward a Combinatorial Proof of the Jacobian Conjecture", in *Lecture Notes in Mathematics v. 1234, Combinatoire Énumérative*, Springer-Verlag, Berlin, 1986.