

TWO CHAIN RULES FOR DIVIDED DIFFERENCES AND FAÀ DI BRUNO'S FORMULA

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ABSTRACT. In this paper we derive two formulas for divided differences of a function of a function. Both formulas lead to other divided difference formulas, such as reciprocal and quotient rules. The two formulas can also be used to derive Faà di Bruno's formula and other formulas for higher derivatives of composite functions. We also derive a divided difference version of Faà di Bruno's determinant formula.

1. INTRODUCTION

Faà di Bruno's formula [3] is the higher chain rule for differentiation: it expresses an arbitrary derivative of a composite function $g = f \circ \phi$ in terms of derivatives of f and ϕ . Though not as well known as the Leibniz formula, it has appeared in various branches of mathematics, notably in mathematical statistics; see the survey paper of Johnson [8].

The formula has also played a useful role in geometric modelling. A parametric curve $\mathbf{f} : [a, b] \rightarrow \mathbb{R}^d$, with $d \geq 2$, can be parameterized in many different ways. If $\phi : [\alpha, \beta] \rightarrow \mathbb{R}$ is an increasing function such that $\phi(\alpha) = a$ and $\phi(\beta) = b$, then the curve represented by \mathbf{f} can be equally well represented by $\mathbf{g} : [\alpha, \beta] \rightarrow \mathbb{R}^d$ where $\mathbf{g} = \mathbf{f} \circ \phi$. Since it is frequently necessary to express the derivatives of the new representation, \mathbf{g} , in terms of the old, \mathbf{f} , it is hardly surprising that Faà di Bruno's formula will sooner or later play a role in any consideration of derivatives of \mathbf{g} of arbitrarily high order. For example, the formula was used by Goodman [6], Gregory [5] and Dyn and Micchelli [2] in dealing with the continuity of spline curves.

More recently, the formula has turned out to be an essential tool in the error analysis of various curve interpolation methods [11, 4]. In this application, the formula has been used to bound the size (the Euclidean norm) of a derivative $\mathbf{g}^{(k)}(t)$ in terms of the sizes of $\mathbf{f}'(\phi(t))$, $\mathbf{f}''(\phi(t))$, \dots , $\mathbf{f}^{(k)}(\phi(t))$ and the sizes (absolute values) of $\phi'(t)$, $\phi''(t)$, \dots , $\phi^{(k)}(t)$.

In fact, what was required in [11, 4] was a bound on certain *divided differences* of \mathbf{g} , and even though this task could be reduced there to bounding the size of a derivative of \mathbf{g} , there might be situations in future work of this kind where switching from divided differences to derivatives might not be valid (for example if \mathbf{g} is not smooth enough). Even if the switch is valid, more precise results might nevertheless

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follow from a more direct approach: bounding divided differences of \mathbf{g} in terms of divided differences of \mathbf{f} and ϕ .

It was this that motivated this paper: to derive an explicit formula that expresses an arbitrary divided difference of a composite function $g = f \circ \phi$ in terms of divided differences of f and ϕ . No such formula seems to exist in the literature (see [13], [18], [7, Chap 6], and [1]) and we derive *two* natural formulas of this kind. In one the divided differences of f are at consecutive points while in the other the divided differences of ϕ are at consecutive points. Both of these divided difference chain rules lead to other divided difference formulas, such as reciprocal and quotient rules. The two chain rules also have the attractive feature that they both provide a simple proof of Faà di Bruno's formula. We also derive a divided difference version of Faà di Bruno's determinant formula.

2. THE FIRST CHAIN RULE

As with derivatives there are several notations currently in use for divided differences. In this paper we will denote the divided difference of a real-valued function ϕ at the real values t_0, t_1, \dots, t_n by $[t_0, t_1, \dots, t_n]\phi$; see de Boor [1] for a discussion of divided differences and alternative notations. We have $[t_i]\phi = \phi(t_i)$, and when t_0 and t_n are distinct we have $[t_0, \dots, t_n]\phi = ([t_1, \dots, t_n]\phi - [t_0, \dots, t_{n-1}]\phi)/(t_n - t_0)$. We can allow any of the t_i to be equal if ϕ has sufficiently many derivatives to allow it. In particular, if all the t_i are equal to t say, then $[t_0, t_1, \dots, t_n]\phi = \phi^{(n)}(t)/n!$. We will make use of the product rule

$$(1) \quad [t_0, \dots, t_n](\phi\psi) = \sum_{i=0}^n [t_0, \dots, t_i]\phi [t_i, \dots, t_n]\psi$$

due to Popoviciu [12, 13] and Steffensen [18]. This formula is often called the Leibniz rule [1] since it generalizes the Leibniz formula for differentiation. Now define the composition $g = f \circ \phi$ given by $g(t) = f(\phi(t))$ and let $\phi_i = \phi(t_i)$. We will prove

Theorem 1. *For $n \geq 1$ and for ϕ and f smooth enough,*

$$(2) \quad [t_0, \dots, t_n]g = \sum_{k=1}^n [\phi_0, \dots, \phi_k]f A_{k,n}\phi,$$

where

$$(3) \quad A_{k,n}\phi = [t_k, \dots, t_n]([t_0, \cdot]\phi \cdots [t_{k-1}, \cdot]\phi).$$

In order to get a more explicit expression for $A_{k,n}\phi$, we can use the product rule (1) extended to the product of r functions, namely,

$$(4) \quad [t_0, \dots, t_n](\psi_1\psi_2 \cdots \psi_r) = \sum_{0=\alpha_0 \leq \alpha_1 \leq \cdots \leq \alpha_r=n} \prod_{\beta=0}^{r-1} [t_{\alpha_\beta}, \dots, t_{\alpha_{\beta+1}}]\psi_{\beta+1},$$

the sum being over integers $\alpha_1, \dots, \alpha_{r-1}$ such that $0 \leq \alpha_1 \leq \cdots \leq \alpha_{r-1} \leq n$. Since $A_{k,n}\phi$ is a divided difference of the product of the k functions $[t_0, \cdot]\phi, \dots, [t_{k-1}, \cdot]\phi$, the extended product rule (4) yields

$$(5) \quad A_{k,n}\phi = \sum_{k=\alpha_0 \leq \alpha_1 \leq \cdots \leq \alpha_k=n} \prod_{\beta=0}^{k-1} [t_\beta, t_{\alpha_\beta}, \dots, t_{\alpha_{\beta+1}}]\phi.$$

Using (5) the first three cases of the formula are

$$\begin{aligned}
 (6) \quad & [t_0, t_1]g = [\phi_0, \phi_1]f [t_0, t_1]\phi, \\
 (7) \quad & [t_0, t_1, t_2]g = [\phi_0, \phi_1, \phi_2]f [t_0, t_2]\phi [t_1, t_2]\phi + [\phi_0, \phi_1]f [t_0, t_1, t_2]\phi, \\
 & [t_0, t_1, t_2, t_3]g = [\phi_0, \phi_1, \phi_2, \phi_3]f [t_0, t_3]\phi [t_1, t_3]\phi [t_2, t_3]\phi \\
 & \quad + [\phi_0, \phi_1, \phi_2]f \left([t_0, t_2]\phi [t_1, t_2, t_3]\phi + [t_0, t_2, t_3]\phi [t_1, t_3]\phi \right) \\
 (8) \quad & \quad + [\phi_0, \phi_1]f [t_0, t_1, t_2, t_3]\phi.
 \end{aligned}$$

Proof. Assume initially that the t_i are distinct and consider the polynomial that interpolates f at ϕ_0, \dots, ϕ_n in Newton form,

$$(9) \quad p(x) = \sum_{k=0}^n (x - \phi_0) \cdots (x - \phi_{k-1}) [\phi_0, \dots, \phi_k] f,$$

valid whether or not the ϕ_i are distinct as long as f is smooth enough. Then we find that $g(t_i) = f(\phi_i) = p(\phi_i)$ for $0 \leq i \leq n$, and therefore

$$[t_0, \dots, t_n]g = [t_0, \dots, t_n](p \circ \phi).$$

Thus replacing x in (9) by $\phi(t)$ and applying $[t_0, \dots, t_n]$ gives (2) where

$$(10) \quad A_{k,n}\phi = [t_0, \dots, t_n]((\phi - \phi_0) \cdots (\phi - \phi_{k-1})).$$

But

$$(\phi(t) - \phi_0) \cdots (\phi(t) - \phi_{k-1}) = \omega_{k-1}(t) [t_0, t] \phi \cdots [t_{k-1}, t] \phi,$$

where $\omega_{k-1}(t) = (t - t_0) \cdots (t - t_{k-1})$, and so the product rule (1) gives

$$A_{k,n}\phi = \sum_{i=0}^n [t_0, \dots, t_i] \omega_{k-1} [t_i, \dots, t_n] ([t_0, \cdot] \phi \cdots [t_{k-1}, \cdot] \phi).$$

Since moreover ω_{k-1} is a polynomial of degree k which is zero at t_0, \dots, t_{k-1} , and whose leading coefficient is 1, we have $[t_0, \dots, t_i] \omega_{k-1} = \delta_{ik}$, and this gives equation (3). Finally, we can let the t_i coalesce in the formula provided ϕ (and therefore also g) is smooth enough. \square

We note that Popoviciu already made some progress in [13] towards finding the expression (5). He found $A_{2,n}\phi$ using equation (10), but for general k he only deduced the number of terms in $A_{k,n}\phi$. Due to equation (3), $A_{k,n}$ is invariant to permutations of the values t_0, \dots, t_{k-1} and to permutations of t_k, \dots, t_n . For $n \geq 3$ this leads to alternatives to equation (5). For example, by permuting t_0 and t_1 in (3) before applying the product rule gives the expression

$$A_{2,3}\phi = [t_1, t_2]\phi [t_0, t_2, t_3]\phi + [t_1, t_2, t_3]\phi [t_0, t_3]\phi,$$

as an alternative to the coefficient of $[\phi_0, \phi_1, \phi_2]f$ in (8).

3. THE SECOND CHAIN RULE

While the divided differences of f in (2) are over consecutive points ϕ_i , the divided differences of ϕ in (5) are not at consecutive points t_i . We now give an alternative formula in which the opposite is true.

Theorem 2. For $n \geq 1$ and for ϕ and f smooth enough,

$$(11) \quad [t_0, \dots, t_n]g = \sum_{k=1}^n \sum_{0=i_0 < \dots < i_k=n} [\phi_{i_0}, \dots, \phi_{i_k}] f \prod_{j=0}^{k-1} [t_{i_j}, \dots, t_{i_{j+1}}] \phi.$$

This formula is fairly easy to remember. We sum over the $\binom{n-1}{k-1}$ choices of $k-1$ strictly increasing integers $\{i_1, \dots, i_{k-1}\}$ from the set $\{1, 2, \dots, n-1\}$. Summing over k we see that the divided difference of g contains 2^{n-1} terms, the same number as in the first chain rule (2) using (5). The f differences are of order k and the first and last point ϕ_0 and ϕ_n are always included. For the product terms making up the ϕ differences we simply fill the gaps between each t_{i_j} and $t_{i_{j+1}}$. The first three cases are

$$(12) \quad [t_0, t_1]g = [\phi_0, \phi_1]f[t_0, t_1]\phi,$$

$$[t_0, t_1, t_2]g = [\phi_0, \phi_2]f[t_0, t_1, t_2]\phi$$

$$(13) \quad + [\phi_0, \phi_1, \phi_2]f[t_0, t_1]\phi[t_1, t_2]\phi,$$

$$[t_0, t_1, t_2, t_3]g = [\phi_0, \phi_3]f[t_0, t_1, t_2, t_3]\phi$$

$$+ [\phi_0, \phi_1, \phi_3]f[t_0, t_1]\phi[t_1, t_2, t_3]\phi$$

$$+ [\phi_0, \phi_2, \phi_3]f[t_0, t_1, t_2]\phi[t_2, t_3]\phi$$

$$(14) \quad + [\phi_0, \phi_1, \phi_2, \phi_3]f[t_0, t_1]\phi[t_1, t_2]\phi[t_2, t_3]\phi.$$

Proof. It is enough to prove (11) for distinct t_0, \dots, t_n and ϕ_0, \dots, ϕ_n since a divided difference is a continuous function of its arguments and also of the function we apply it to. We use induction on n . Using (12) it is easily seen that (11) holds for $n = 1$. Suppose that (11) holds for divided differences of order n and consider $[t_0, \dots, t_{n+1}]g$. Using the last two points to reduce the order of the divided difference we have

$$(15) \quad [t_0, \dots, t_{n+1}]g = \frac{[t_0, \dots, t_{n-1}, t_{n+1}]g - [t_0, \dots, t_n]g}{t_{n+1} - t_n}.$$

By the induction hypothesis

$$(16) \quad [t_0, \dots, t_{n-1}, t_{n+1}]g = \sum_{k=1}^n \sum_{0=i_0 < \dots < i_{k-1} < n} [\phi_{i_0}, \dots, \phi_{i_{k-1}}, \phi_{n+1}]f \\ \times [t_{i_{k-1}}, \dots, t_{n-1}, t_{n+1}]\phi \prod_{j=0}^{k-2} [t_{i_j}, \dots, t_{i_{j+1}}]\phi,$$

$$[t_0, \dots, t_{n-1}, t_n]g = \sum_{k=1}^n \sum_{0=i_0 < \dots < i_{k-1} < n} [\phi_{i_0}, \dots, \phi_{i_{k-1}}, \phi_n]f \\ \times [t_{i_{k-1}}, \dots, t_{n-1}, t_n]\phi \prod_{j=0}^{k-2} [t_{i_j}, \dots, t_{i_{j+1}}]\phi.$$

Consider the difference between the two sums in (16). For each choice of (i_0, \dots, i_{k-1}) we have a common product term multiplying a difference of the form $A_1 B_1 - A_0 B_0$ where

$$A_j := [\phi_{i_0}, \dots, \phi_{i_{k-1}}, \phi_{n+j}]f, \quad B_j = [t_{i_{k-1}}, \dots, t_{n-1}, t_{n+j}]\phi, \quad j = 0, 1.$$

Now

$$\begin{aligned} \frac{A_1 B_1 - A_0 B_0}{t_{n+1} - t_n} &= \frac{A_1(B_1 - B_0) + (A_1 - A_0)B_0}{t_{n+1} - t_n} \\ &= [\phi_{i_0}, \dots, \phi_{i_{k-1}}, \phi_{n+1}]f [t_{i_{k-1}}, \dots, t_{n+1}]\phi \\ &\quad + [\phi_{i_0}, \dots, \phi_{i_{k-1}}, \phi_n, \phi_{n+1}]f [t_{i_{k-1}}, \dots, t_n]\phi [t_n, t_{n+1}]\phi. \end{aligned}$$

We insert these expressions in (15) and (16) and obtain, with $i_k = n + 1$,

$$\begin{aligned} &[t_0, \dots, t_{n+1}]g \\ &= \sum_{k=1}^n \sum_{0=i_0 < \dots < i_{k-1} < n} [\phi_{i_0}, \dots, \phi_{i_{k-1}}, \phi_{n+1}]f \prod_{j=0}^{k-1} [t_{i_j}, \dots, t_{i_{j+1}}]\phi \\ &\quad + \sum_{k=2}^{n+1} \sum_{0=i_0 < \dots < i_{k-1} = n} [\phi_{i_0}, \dots, \phi_{i_{k-1}}, \phi_{n+1}]f \prod_{j=0}^{k-1} [t_{i_j}, \dots, t_{i_{j+1}}]\phi \\ &= \sum_{k=1}^{n+1} \sum_{0=i_0 < \dots < i_k = n+1} [\phi_{i_0}, \dots, \phi_{i_k}]f \prod_{j=0}^{k-1} [t_{i_j}, \dots, t_{i_{j+1}}]\phi \end{aligned}$$

which is (11) with n replaced by $n + 1$. □

4. RECIPROCAL AND QUOTIENT RULES

We can use the two chain rules to obtain further formulas that might be of interest. It is easily shown by induction that the divided difference of the function $f(x) = 1/x$ is $[t_0, \dots, t_n]f = (-1)^n / (t_0 \cdots t_n)$; see [17, p. 20] and [1]. Thus, applying the first chain rule (2) with this f gives a reciprocal rule for divided differences of order $n \geq 1$,

$$[t_0, \dots, t_n] \frac{1}{\phi} = \sum_{k=1}^n \frac{(-1)^k A_{k,n} \phi}{\phi_0 \cdots \phi_k}.$$

Combining this with the product rule (1) gives a quotient rule for divided differences. For smooth enough functions ϕ and ψ we get

$$[t_0, \dots, t_n] \frac{\psi}{\phi} = \frac{1}{\phi_0} [t_0, \dots, t_n] \psi + \sum_{r=1}^n \sum_{k=1}^r \frac{(-1)^k A_{k,r} \phi}{\phi_0 \cdots \phi_k} [t_r, \dots, t_n] \psi.$$

Alternatively we could apply the second chain rule (11) giving, for $n \geq 1$, the reciprocal rule

$$[t_0, \dots, t_n] \frac{1}{\phi} = \sum_{k=1}^n (-1)^k \sum_{0=i_0 < \dots < i_k = n} \frac{\prod_{j=0}^{k-1} [t_{i_j}, \dots, t_{i_{j+1}}]\phi}{\phi_{i_0} \phi_{i_1} \cdots \phi_{i_k}},$$

and the quotient rule

$$\begin{aligned} [t_0, \dots, t_n] \frac{\psi}{\phi} &= \frac{1}{\phi_0} [t_0, \dots, t_n] \psi \\ &\quad + \sum_{r=1}^n \sum_{k=1}^r (-1)^k \sum_{0=i_0 < \dots < i_k = r} \frac{\prod_{j=0}^{k-1} [t_{i_j}, \dots, t_{i_{j+1}}]\phi [t_r, \dots, t_n] \psi}{\phi_{i_0} \phi_{i_1} \cdots \phi_{i_k}}. \end{aligned}$$

5. FAÀ DI BRUNO'S FORMULA

Equation (6) is familiar because for $t_0 \neq t_1$ and $\phi_0 \neq \phi_1$ it is simply

$$(17) \quad \frac{g(t_1) - g(t_0)}{t_1 - t_0} = \frac{f(\phi_1) - f(\phi_0)}{\phi_1 - \phi_0} \frac{\phi_1 - \phi_0}{t_1 - t_0},$$

from which the chain rule

$$(18) \quad g'(t) = f'(\phi(t))\phi'(t)$$

follows as the limiting case $t_0 = t_1 = t$. The limiting cases $t_i = t$ of equations (7) and (8) (or (13) and (14)) are, after cancellation of factorials,

$$\begin{aligned} g''(t) &= f'(\phi(t))\phi''(t) + f''(\phi(t))(\phi'(t))^2. \\ g'''(t) &= f'(\phi(t))\phi'''(t) + 3f''(\phi(t))\phi'(t)\phi''(t) + f'''(\phi(t))(\phi'(t))^3. \end{aligned}$$

These would normally be found by differentiating (18). It was Faà di Bruno who first found the general formula (without proof) in 1857 in [3]:

$$(19) \quad g^{(n)}(t) = \sum \frac{n!}{b_1! \cdots b_n!} f^{(k)}(\phi(t)) \left(\frac{\phi^{(1)}(t)}{1!} \right)^{b_1} \cdots \left(\frac{\phi^{(n)}(t)}{n!} \right)^{b_n},$$

where the sum is over all $k = 1, \dots, n$ and solutions $b_1, \dots, b_n \geq 0$ to

$$(20) \quad b_1 + 2b_2 + \cdots + nb_n = n, \quad b_1 + \cdots + b_n = k.$$

Various approaches to proving this formula have been proposed by Riordan in [14] and [15, pp. 34–36], Jordan [9, Sec. 12], Knuth [10, p. 481], Roman [16], and Johnson [8]. A nice survey of these and earlier approaches can be found in [8]. In addition to these, the formula was also rediscovered, and a rigorous proof given, by Goodman [6]. The “modern” proof which has emerged through the work of Riordan, Goodman, and Johnson is to use set partitions. A *partition* π of a set S is a collection of disjoint subsets of S whose union is S . The subsets are known as the *blocks* of the partition. Let P_n be the collection of all partitions of the set $\{1, 2, \dots, n\}$. For example, $P_2 = \{\pi_1, \pi_2\}$, where

$$\pi_1 = \{\{1\}, \{2\}\}, \quad \pi_2 = \{\{1, 2\}\},$$

and $P_3 = \{\pi_1, \dots, \pi_5\}$, where

$$\begin{aligned} \pi_1 &= \{\{1\}, \{2\}, \{3\}\}, & \pi_2 &= \{\{1, 2\}, \{3\}\}, & \pi_3 &= \{\{1, 3\}, \{2\}\}, \\ \pi_4 &= \{\{2, 3\}, \{1\}\}, & \pi_5 &= \{\{1, 2, 3\}\}. \end{aligned}$$

One can then show that

$$(21) \quad g^{(n)}(t) = \sum_{\pi \in P_n} f^{(\#\pi)}(\phi(t)) \prod_{B \in \pi} \phi^{(\#B)}(t),$$

where π is a partition of the set $\{1, 2, \dots, n\}$, B is a block of π , and $\#$ denotes set cardinality. Unlike (19), this “set partition” formula can be proved relatively easily by induction on n . By differentiating (21), and using the fact that every partition in P_{n+1} can be constructed from a partition in P_n by adding the element $n+1$ either to one of its blocks or as a new singleton block, one establishes the formula with n replaced by $n+1$. Once the set partition formula has been established, a combinatorial argument can be used to collect together repeated terms to arrive at (19).

We can now instead deduce Faà di Bruno’s formula (19) from either of the two chain rules for $[t_0, \dots, t_n]g$. The special case where all the t_i are equal to t in the first chain rule (2), (5) gives

$$(22) \quad \frac{g^{(n)}(t)}{n!} = \sum_{k=1}^n \frac{f^{(k)}(\phi(t))}{k!} c_{k,n}(t),$$

where

$$(23) \quad c_{k,n}(t) = \sum_{k=\alpha_0 \leq \dots \leq \alpha_k=n} \prod_{\beta=0}^{k-1} \frac{\phi^{(\alpha_{\beta+1}-\alpha_\beta+1)}(t)}{(\alpha_{\beta+1} - \alpha_\beta + 1)!}.$$

Alternatively, letting all the t_i equal t in the second chain rule (11) also gives equation (22), but now with

$$(24) \quad c_{k,n}(t) = \sum_{0=i_0 < \dots < i_k=n} \prod_{j=0}^{k-1} \frac{\phi^{(i_{j+1}-i_j)}(t)}{(i_{j+1} - i_j)!}.$$

Clearly both formulas (23) and (24) can be rewritten as

$$(25) \quad c_{k,n}(t) = \sum_{\substack{j_1+\dots+j_k=n \\ j_1, \dots, j_k \geq 1}} \left(\frac{\phi^{(j_1)}(t)}{j_1!} \right) \dots \left(\frac{\phi^{(j_k)}(t)}{j_k!} \right).$$

Now two terms in the sum in (25) are the same whenever their corresponding sequences (j_1, \dots, j_k) contain the same number of ones, the same number of twos, and so on up to the n ’s. Thus, since the number of positive integer solutions to the equation $j_1 + \dots + j_k = n$ containing b_1 ones, b_2 twos, and so on up to b_n n ’s is the multinomial coefficient $k!/(b_1! \dots b_n!)$, it follows that

$$(26) \quad c_{k,n}(t) = \sum \frac{k!}{b_1! \dots b_n!} \left(\frac{\phi^{(1)}(t)}{1!} \right)^{b_1} \dots \left(\frac{\phi^{(n)}(t)}{n!} \right)^{b_n},$$

where the sum is over all solutions $b_1, \dots, b_n \geq 0$ to (20). Substituting this into (22) gives Faà di Bruno’s formula (19).

6. A DETERMINANT FORMULA

The second chain rule (11) can also be expressed in the form of a determinant, analogous to Faà di Bruno’s determinant formula [3].

Theorem 3. *If f and ϕ are sufficiently smooth functions, $g = f \circ \phi$, and $n \geq 1$ then*

$$(27) \quad [t_0, \dots, t_n]g = \begin{vmatrix} (0, 1) & (0, 2) & (0, 3) & \dots & (0, n-1) & (0, n) \\ -1 & (1, 2) & (1, 3) & \dots & (1, n-1) & (1, n) \\ 0 & -1 & (2, 3) & \dots & (2, n-1) & (2, n) \\ \vdots & \vdots & \vdots & & \vdots & \vdots \\ 0 & 0 & 0 & \dots & (n-2, n-1) & (n-2, n) \\ 0 & 0 & 0 & \dots & -1 & (n-1, n) \end{vmatrix},$$

where a product $(i, \dots, j)(j, \dots, k)$ is to be interpreted as (i, \dots, j, \dots, k) and for $0 \leq i_0 < i_1 < \dots < i_k \leq n$ we define

$$(i_0, \dots, i_k) := [\phi_{i_0}, \dots, \phi_{i_k}]f \prod_{j=0}^{k-1} [t_{i_j}, \dots, t_{i_{j+1}}]\phi.$$

We illustrate with the first few cases of n . For $n = 2$ we have

$$\begin{aligned} \begin{vmatrix} (0, 1) & (0, 2) \\ -1 & (1, 2) \end{vmatrix} &= (0, 1)(1, 2) + (0, 2) = (0, 1, 2) + (0, 2) \\ &= [\phi_0, \phi_1, \phi_2]f [t_0, t_1]\phi [t_1, t_2]\phi + [\phi_0, \phi_2]f [t_0, t_1, t_2]\phi, \end{aligned}$$

while for $n = 3$ we expand the determinant with respect to the first row and obtain

$$\begin{aligned} \begin{vmatrix} (0, 1) & (0, 2) & (0, 3) \\ -1 & (1, 2) & (1, 3) \\ 0 & -1 & (2, 3) \end{vmatrix} &= (0, 1)(1, 2)(2, 3) + (0, 1)(1, 3) + (0, 2)(2, 3) + (0, 3) \\ &= (0, 1, 2, 3) + (0, 1, 3) + (0, 2, 3) + (0, 3), \end{aligned}$$

which gives (14).

Proof. We define $D_{0,n} = 1$ and for $k = 0, 1, \dots, n - 1$

$$D_{n-k,k} := \begin{vmatrix} (k, k + 1) & (k, k + 2) & \dots & (k, n) \\ -1 & (k + 1, k + 2) & \dots & (k + 1, n) \\ 0 & -1 & \dots & (k + 2, n) \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \dots & (n - 1, n) \end{vmatrix}.$$

Then $D_{n,0}$ is the determinant in (27) and by expanding this determinant with respect to the first row it is easy to see that $D_{n,0} = \sum_{k=1}^n (0, k)D_{n-k,k}$. The proof follows by induction on the size of the determinants. Using the current notation equation (11) implies that

$$(28) \quad [t_r, \dots, t_n]g = \sum_{k=0}^{n-1-r} \sum_{r < i_1 < \dots < i_k < n} (r, i_1, \dots, i_k, n), \quad r = 0, \dots, n - 1.$$

Suppose that $D_{n-r,r} = [t_r, \dots, t_n]g$ for $r = 1, \dots, n - 1$. Note that the orders of these determinants are $< n$. Thus using (28) with a slight change of notation we assume that

$$D_{n-i_1,i_1} = \sum_{k=0}^{n-i_1} \sum_{i_1 < i_2 < \dots < i_k < n} (i_1, i_2, \dots, i_k, n), \quad i_1 = 1, \dots, n - 1.$$

Then

$$\begin{aligned} D_{n,0} &= \sum_{i_1=1}^n (0, i_1)D(n - i_1, i_1) = \sum_{i_1=1}^n (0, i_1) \sum_{k=0}^{n-i_1} \sum_{i_1 < i_2 < \dots < i_k < n} (i_1, i_2, \dots, i_k, n) \\ &= \sum_{k=0}^{n-1} \sum_{i_1=1}^{n-k} (0, i_1) \sum_{i_1 < i_2 < \dots < i_k < n} (i_1, i_2, \dots, i_k, n) \\ &= \sum_{k=0}^{n-1} \sum_{1 \leq i_1 < i_2 < \dots < i_k < n} (0, i_1, i_2, \dots, i_k, n) = [t_0, \dots, t_n]g. \end{aligned}$$

The last equality follows from (28) with $r = 0$. □

7. OTHER FORMULAS

Johnson, in [8, Sec. 3], lists four other formulas for arbitrary derivatives of composite functions from the literature, namely those of T.A. (believed to be an artillery captain named J. F. C. Tiburce Abadie), Scott, Meyer, and Hoppe. The first two formulas follow easily from our two divided difference formulas.

The special case where all the t_i are equal to t in $A_{k,n}\phi$ in (3) gives

$$c_{k,n}(t) = A_{k,n}\phi = \underbrace{[t, \dots, t]}_{n-k+1}([t, \cdot]\phi)^k = \frac{1}{(n-k)!} \frac{d^{n-k}}{dx^{n-k}} \left(\frac{\phi(x) - \phi(t)}{x-t} \right)^k \Big|_{x=t},$$

which, when substituted into (22), and after writing $x = t+h$, gives T.A.'s formula:

$$g^{(n)}(t) = \sum_{k=1}^n \binom{n}{k} f^{(k)}(\phi(t)) \frac{d^{n-k}}{dh^{n-k}} \left(\frac{\phi(t+h) - \phi(t)}{h} \right)^k \Big|_{h=0}.$$

On the other hand, recall equation (25). Since the Leibniz rule applied to ϕ^k gives

$$\frac{d^n}{dt^n} (\phi(t)^k) = n! \sum_{\substack{j_1 + \dots + j_k = n \\ j_1, \dots, j_k \geq 0}} \left(\frac{\phi^{(j_1)}(t)}{j_1!} \right) \dots \left(\frac{\phi^{(j_k)}(t)}{j_k!} \right),$$

it follows that

$$c_{k,n}(t) = \frac{1}{n!} \frac{d^n}{dt^n} (\phi(t)^k) \Big|_{\phi(t)=0},$$

which gives Scott's formula

$$(29) \quad g^{(n)}(t) = \sum_{k=1}^n \frac{f^{(k)}(\phi(t))}{k!} \left\{ \frac{d^n}{dt^n} (\phi(t)^k) \Big|_{\phi(t)=0} \right\}.$$

From (29) one can easily derive Meyer's formula

$$g^{(n)}(t) = \sum_{k=1}^n \frac{f^{(k)}(\phi(t))}{k!} \left\{ \frac{d^n}{dh^n} (\phi(t+h) - \phi(t))^k \right\} \Big|_{h=0}$$

and subsequently Hoppe's formula

$$g^{(n)}(t) = \sum_{k=1}^n \frac{f^{(k)}(\phi(t))}{k!} \sum_{j=0}^k \binom{k}{j} (-\phi(t))^{k-j} \frac{d^n}{dt^n} (\phi(t))^j.$$

8. FINAL REMARKS

We found two chain rules for divided differences; (2), (5), and (11). The formulas are the same for $n = 1$ and the same for $n = 2$ after permuting t_1 and t_2 . For $n \geq 3$ they are distinct. After we derived the two formulas, we found alternative proofs. The first formula (2) can be proved quite easily by induction on n using the same recursion (15) used in the proof of the second formula (11). On the other hand, the second chain rule (11) can be derived using polynomials in the spirit of the proof of the first rule (2). Since this latter observation could be useful for deriving multivariate versions of (11), we will now give the derivation.

Observe that it is enough to prove (11) when f is a polynomial of degree at most n , for if not we interpolate f with a polynomial p at ϕ_0, \dots, ϕ_n and prove the formula for p . Further, due to the linearity of divided differences, it is sufficient to

prove the formula for the monomial $f(x) = x^r$ for all r , $1 \leq r \leq n$. In this case, we can use the extended product rule (4) to obtain

$$(30) \quad [t_0, \dots, t_n]g = [t_0, \dots, t_n](\phi^r) = \sum_{0=\alpha_0 \leq \alpha_1 \leq \dots \leq \alpha_r = n} \prod_{\beta=0}^{r-1} [t_{\alpha_\beta}, \dots, t_{\alpha_{\beta+1}}] \phi.$$

Now by counting repeated terms, each sequence $(\alpha_0, \alpha_1, \dots, \alpha_r)$ can be written as

$$(\alpha_0, \alpha_1, \dots, \alpha_r) = (\underbrace{i_0, \dots, i_0}_{1+\mu_0}, \underbrace{i_1, \dots, i_1}_{1+\mu_1}, \dots, \underbrace{i_k, \dots, i_k}_{1+\mu_k})$$

for some k with $1 \leq k \leq r$, and where $0 = i_0 < i_1 < \dots < i_k = n$ and $\mu_0 + \dots + \mu_k = r - k$. The corresponding product in (30) then becomes

$$\prod_{\beta=0}^{r-1} [t_{\alpha_\beta}, \dots, t_{\alpha_{\beta+1}}] \phi = \phi_{i_0}^{\mu_0} \phi_{i_1}^{\mu_1} \dots \phi_{i_k}^{\mu_k} \prod_{j=0}^{k-1} [t_{i_j}, \dots, t_{i_{j+1}}] \phi.$$

It follows that

$$\begin{aligned} [t_0, \dots, t_n]g &= \sum_{k=1}^r \sum_{0=i_0 < \dots < i_k = n} \sum_{\mu_0 + \dots + \mu_k = r-k} \phi_{i_0}^{\mu_0} \dots \phi_{i_k}^{\mu_k} \prod_{j=0}^{k-1} [t_{i_j}, \dots, t_{i_{j+1}}] \phi \\ &= \sum_{k=1}^n \sum_{0=i_0 < \dots < i_k = n} [\phi_{i_0}, \dots, \phi_{i_k}] f \prod_{j=0}^{k-1} [t_{i_j}, \dots, t_{i_{j+1}}] \phi \end{aligned}$$

for $f(x) = x^r$, which proves equation (11) for $f(x) = x^r$ and therefore for arbitrary f .

We are planning a second paper dealing with multivariate generalizations of the two divided difference chain rules.

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