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ON THE SAUER-XU FORMULA FOR THE ERROR IN MULTIVARIATE POLYNOMIAL INTERPOLATION

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ABSTRACT. Use of a new notion of multivariate divided difference leads to a short proof of a formula by Sauer and Xu for the error in interpolation, by polynomials of total degree $\le n$ in d variables, at a 'correct' point set.

It is the purpose of this note to give a short proof of a remarkable formula for the error in polynomial interpolation given in [3].

In [3], Sauer and Xu consider interpolation from the space $\Pi_n(\mathbf{R}^d)$ of d-variate polynomials of degree $\le n$ at a point set $\mathcal{X}$ which is **correct** for it in the sense that, for an arbitrary g, there is exactly one $p \in \Pi_n(\mathbf{R}^d)$, denoted here by

$$P_n g,$$

which agrees with g on $\mathcal{X}$. Such a correct point set can, as Sauer and Xu point out, be partitioned into subsets

$$x^{(i)} := \{x_r^{(i)} : r = 1, \ldots, r_i^d := \dim \Pi_i - \dim \Pi_{i-1} = \binom{i-1+d}{i}\}, \quad i = 0, 1, \ldots, n,$$

in such a way that, for each $j \le n$, polynomial interpolation from Π_j at the points in

$$x^{(\le j)} := x^{(0)} \cup \cdots \cup x^{(j)}$$

is uniquely possible. They denote the corresponding Lagrange polynomial in Π_j associated with the point $x_r^{(j)}$ by

$$p_r^{[j]};$$

i.e., $p_r^{[j]}$ is the unique element of Π_j which satisfies

$$p_r^{[j]}(x_s^{(i)}) \ = \ \delta_{ji}\delta_{rs}, \quad s = 1, \ldots, r_i^d; \ i = 0, \ldots, j,$$

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but is called a Newton polynomial in [3], probably because any $p \in \Pi_j$ which vanishes on $x^{(<j)}$ can be written in the form

$$p = \sum_{r=1}^{r_j^d} p_r^{[j]}\ p(x_r^{(j)}). \tag{1}$$

Let $E_j g$ denote the error in the polynomial interpolant from Π_j to g, i.e.,

$$g = P_j g + E_j g.$$

Sauer and Xu prove that (in roughly the same notation, except for a slight reordering and the use of a divided difference here)

$$(E_j g)(x) = \sum_{r=1}^{r_j^d} p_r^{[j]}(x) \sum_{\mu\in\Lambda_r^{(j)}} c_\mu [x_\mu, x; \Delta x_\mu, x - x_r^{(j)}]g, \tag{2}$$

with the following definition of the various quantities appearing here:

$$\Lambda_r^{(j)} \ := \ \{\mu \in \times_{i=0}^{j}\{1,\ldots,r_i^d\} : \mu_j = r\};$$

$$c_\mu := \prod_{i=0}^{j-1} p_{\mu_i}^{[i]}(x_{\mu_{i+1}}^{(i+1)});$$

$$x_\mu := (x_{\mu_i}^{(i)} : i = 0,\ldots,j), \qquad \Delta x_\mu := (x_{\mu_{i+1}}^{(i+1)} - x_{\mu_i}^{(i)} : i = 0,\ldots,j-1);$$

and, finally, $[t_0,\ldots,t_j;\xi_1,\ldots,\xi_j]$ is the j**th divided difference** introduced in [1], i.e.,

$$[t_0,\ldots,t_j;\xi_1,\ldots,\xi_j]g := \int_{[t_0,\ldots,t_j]} D_{\xi_1}\cdots D_{\xi_j} g, \tag{3}$$

with

$$f \ \mapsto \ \int_{[t_0,\ldots,t_j]} f \ := \ \int_0^1 \int_0^{s_1} \cdots \int_0^{s_{j-1}} f(t_0 + s_1\nabla t_1 + \cdots + s_j \nabla t_j)\ \mathrm{d}s_j \cdots \mathrm{d}s_1$$

the linear functional which was used to such advantage by Micchelli in his analysis of Kergin interpolation and the simplex spline, and which has been dubbed by him in [2] the **divided difference functional for $\mathbf{R}^d$**. The only facts about the jth divided difference (3) needed here are that it is symmetric in the *points* $t_0,\ldots,t_j$, and is symmetric and *linear* in the *directions* $\xi_1,\ldots,\xi_j$ (which is obvious), and that, for an arbitrary point sequence T, points a, b, and arbitrary direction sequence Ξ (with $\#T = \#\Xi$),

$$[T,a,b;\Xi,a-b] \ = \ [T,a;\Xi] - [T,b;\Xi], \tag{4}$$

which can be verified directly (see [1]).

The short proof of (2) about to be given here is by induction (as is the proof in [3]). For $j = 0$, (2) is the special case $T = () = \Xi$, $a = x$, $b = x_1^{(0)}$ of (4). Assuming (2) to hold for $j = n$, we observe that

$$(E_n g)(x) = G_n(x, x),$$

with

$$G_n(x, y) := \sum_{r=1}^{r_n^d} p_r^{[n]}(x) \sum_{\mu \in \Lambda_r^{(n)}} c_\mu \, [x_\mu, y; \Delta x_\mu, x - x_r^{(n)}]g.$$

Now note that, for arbitrary y, $G_n(\,\cdot\,, y)$ is a polynomial of degree $\le n+1$ (since the $p_r^{[n]}$ are in Π_n while $x \mapsto [T; \Xi, x]g$ is a linear (scalar-valued) function), and $G_n(\,\cdot\,, y)$ vanishes at every $x_r^{(n)}$, hence, as in (1), $G_n(\,\cdot\,, y)$ is writeable as

$$G_n(\,\cdot\,, y) = \sum_{s=1}^{r_{n+1}^d} p_s^{[n+1]} \, G_n(x_s^{(n+1)}, y).$$

On the other hand, since $g = P_n g + E_n g$, the function

$$P_n g + \sum_{s=1}^{r_{n+1}^d} p_s^{[n+1]} \, (E_n g)(x_s^{(n+1)})$$

agrees with g at $x^{(\le n+1)}$ and is in Π_{n+1}, hence must equal $P_{n+1} g$. Therefore,

$$\begin{aligned} E_{n+1} g &= E_n g - \sum_s p_s^{[n+1]} \, (E_n g)(x_s^{(n+1)}) \\ &= \sum_s p_s^{[n+1]} \, \big(G_n(x_s^{(n+1)}, \,\cdot\,) \;-\; G_n(x_s^{(n+1)}, x_s^{(n+1)})\big), \end{aligned}$$

and this implies (2) for $j = n+1$ since

$$G_n(x_s^{(n+1)}, \,\cdot\,) \;-\; G_n(x_s^{(n+1)}, x_s^{(n+1)}) \;=\; \sum_{r=1}^{r_n^d} p_r^{[n]}(x_s^{(n+1)}) \sum_{\mu \in \Lambda_r^{(n)}} c_\mu \, d_{\mu,r} g$$

with

$$\begin{aligned} d_{\mu,r} \;:=\; [x_\mu, \,\cdot\,; \Delta x_\mu, x_s^{(n+1)} - x_r^{(n)}] \;-\; [x_\mu, x_s^{(n+1)}; \Delta x_\mu, x_s^{(n+1)} - x_r^{(n)}] = \\ [x_\mu, x_s^{(n+1)}, \,\cdot\,; \Delta x_\mu, x_s^{(n+1)} - x_r^{(n)}, \,\cdot\, - x_s^{(n+1)}], \end{aligned}$$

by (4). □

It follows that

$$P_n g = \sum_{j=0}^{n} \sum_{r=1}^{r_j^d} p_r^{[j]} \, (E_{j-1} g)(x_r^{(j)}),$$

with

$$E_{-1}g := g.$$

Since $(p_r^{[j]} : r = 1, \ldots, r_j^d; j = 0, 1, \ldots)$ is linearly independent, it follows that, for any j, $[x;]E_j$ is a linear combination of the linear functionals $[x;]$ and $[x_r^{(i)};]$, $r = 1, \ldots, r_i^d; i = 0, \ldots, j$. However, its constituents, i.e., the jth divided differences

$$[x_\mu, x; \Delta x_\mu, x - x_{\mu_j}^{(j)}]$$

by themselves, are not necessarily such linear combinations, as the simple example

$$[0, \mathbf{i}_1, \mathbf{i}_1 + \mathbf{i}_2; \mathbf{i}_1, \mathbf{i}_2],$$

with $\mathbf{i}_j$ the jth unit vector, readily shows.

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