

Interpolation and Polynomial Approximation
Divided Differences, and Hermite Interpolatory Polynomials
Lecture Notes #5

Joe Mahaffy

Department of Mathematics

San Diego State University

San Diego, CA 92182-7720

mahaffy@math.sdsu.edu

http://www-rohan.sdsu.edu/~jmahaffy

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Previously:

Neville's Method to successively generate higher degree polynomial approximations *at a specific point*. — If we need to compute the polynomial at many points, we have to re-run Neville's method for each point. $\mathcal{O}(n^2)$ operations/point.

Next:

Use divided differences to *generate the polynomials* themselves*.

* The coefficients of the polynomials. Once we have those, we can quickly (remember Horner's method?) compute the polynomial in any desired points. $\mathcal{O}(n)$ operations/point.

Representing Polynomials

If $P_n(x)$ is the n^{th} degree polynomial that agrees with $f(x)$ at the points $\{x_0, x_1, \dots, x_n\}$, then we can (for the appropriate constants $\{a_0, a_1, \dots, a_n\}$) write:

$$P_n(x) = a_0 + a_1(x - x_0) + a_2(x - x_0)(x - x_1) + \dots \\ \dots + a_n(x - x_0)(x - x_1) \dots (x - x_{n-1})$$

Note that we can evaluate this "Horner-style," by writing

$$P_n(x) = a_0 + (x - x_0)(a_1 + (x - x_1)(a_2 + \dots \\ \dots + (x - x_{n-2})(a_{n-1} + a_n(x - x_{n-1}))))),$$

so that each step in the Horner-evaluation consists of a subtraction, a multiplication, and an addition.

Finding the Constants $\{a_0, a_1, \dots, a_n\}$

"Just Algebra"

Given the relation

$$P_n(x) = a_0 + a_1(x - x_0) + a_2(x - x_0)(x - x_1) + \dots \\ \dots + a_n(x - x_0)(x - x_1) \dots (x - x_{n-1})$$

at \mathbf{x}_0 : $a_0 = P_n(x_0) = f(x_0)$.

at \mathbf{x}_1 : $f(x_0) + a_1(x_1 - x_0) = P_n(x_1) = f(x_1)$

$$\Rightarrow a_1 = \frac{f(x_1) - f(x_0)}{x_1 - x_0}$$

at \mathbf{x}_2 : $a_2 = \frac{f(x_2) - f(x_0)}{(x_2 - x_0)(x_2 - x_1)} - \frac{f(x_1) - f(x_0)}{(x_2 - x_0)(x_1 - x_0)}$.

Clearly, this gets massively ugly fast!

We need some nice clean notation!

Sir Isaac Newton to the Rescue: Divided Differences

Zeroth Divided Difference:

$$f[x_i] = f(x_i).$$

First Divided Difference:

$$f[x_i, x_{i+1}] = \frac{f[x_{i+1}] - f[x_i]}{x_{i+1} - x_i}.$$

Second Divided Difference:

$$f[x_i, x_{i+1}, x_{i+2}] = \frac{f[x_{i+1}, x_{i+2}] - f[x_i, x_{i+1}]}{x_{i+2} - x_i}.$$

kth Divided Difference:

$$f[x_i, x_{i+1}, \dots, x_{i+k}] = \frac{f[x_{i+1}, x_{i+2}, \dots, x_{i+k}] - f[x_i, x_{i+1}, \dots, x_{i+k-1}]}{x_{i+k} - x_i}.$$

The Constants $\{a_0, a_1, \dots, a_n\}$ — Revisited

We had

$$\text{at } \mathbf{x}_0: a_0 = P_n(x_0) = f(x_0).$$

$$\text{at } \mathbf{x}_1: f(x_0) + a_1(x_1 - x_0) = P_n(x_1) = f(x_1)$$

$$\Rightarrow a_1 = \frac{f(x_1) - f(x_0)}{x_1 - x_0}.$$

$$\text{at } \mathbf{x}_2: a_2 = \frac{f(x_2) - f(x_0)}{(x_2 - x_0)(x_2 - x_1)} - \frac{f(x_1) - f(x_0)}{(x_2 - x_0)(x_1 - x_0)}.$$

Clearly:

$$a_0 = f[x_0], \quad a_1 = f[x_0, x_1].$$

We may suspect that $a_2 = f[x_0, x_1, x_2]$, that is indeed so (a little bit of careful algebra will show it), and in general

$$\mathbf{a}_k = \mathbf{f}[\mathbf{x}_0, \mathbf{x}_1, \dots, \mathbf{x}_k].$$

Algebra: Chasing down $a_2 = f[x_0, x_1, x_2]$

$$\begin{aligned} a_2 &= \frac{f(x_2) - f(x_0)}{(x_2 - x_0)(x_2 - x_1)} - \frac{f(x_1) - f(x_0)}{(x_2 - x_1)(x_1 - x_0)} \\ &= \frac{(f(x_2) - f(x_0))(x_1 - x_0) - (f(x_1) - f(x_0))(x_2 - x_0)}{(x_2 - x_0)(x_2 - x_1)(x_1 - x_0)} \\ &= \frac{(x_1 - x_0)f(x_2) - (x_2 - x_0)f(x_1) + (x_2 - x_0 - x_1 + x_0)f(x_0)}{(x_2 - x_0)(x_2 - x_1)(x_1 - x_0)} \\ &= \frac{(x_1 - x_0)f(x_2) - (\mathbf{x}_1 - x_0 + x_2 - \mathbf{x}_1)f(x_1) + (x_2 - x_1)f(x_0)}{(x_2 - x_0)(x_2 - x_1)(x_1 - x_0)} \\ &= \frac{(x_1 - x_0)(f(x_2) - f(x_1)) - (x_2 - x_1)(f(x_1) - f(x_0))}{(x_2 - x_0)(x_2 - x_1)(x_1 - x_0)} \\ &= \frac{(f(x_2) - f(x_1))}{(x_2 - x_0)(x_2 - x_1)} - \frac{(f(x_1) - f(x_0))}{(x_2 - x_0)(x_1 - x_0)} \\ &= \frac{f[x_1, x_2]}{x_2 - x_0} - \frac{f[x_0, x_1]}{x_2 - x_0} = \mathbf{f}[\mathbf{x}_0, \mathbf{x}_1, \mathbf{x}_2] \quad (!!!) \end{aligned}$$

Newton's Interpolatory Divided Difference Formula

Hence, we can write

$$P_n(x) = f[x_0] + \sum_{k=1}^n \left[f[x_0, \dots, x_k] \prod_{m=0}^{k-1} (x - x_m) \right].$$

$$\begin{aligned} P_n(x) &= f[x_0] + \\ &f[x_0, x_1](x - x_0) + \\ &f[x_0, x_1, x_2](x - x_0)(x - x_1) + \\ &f[x_0, x_1, x_2, x_3](x - x_0)(x - x_1)(x - x_2) + \dots \end{aligned}$$

This expression is known as **Newton's Interpolatory Divided Difference Formula**.

Computing the Divided Differences (by table)

x	f(x)	1st Div. Diff.	2nd Div. Diff.
x_0	$f[x_0]$		
x_1	$f[x_1]$	$f[x_0, x_1] = \frac{f[x_1] - f[x_0]}{x_1 - x_0}$	
x_2	$f[x_2]$	$f[x_1, x_2] = \frac{f[x_2] - f[x_1]}{x_2 - x_1}$	$f[x_0, x_1, x_2] = \frac{f[x_1, x_2] - f[x_0, x_1]}{x_2 - x_0}$
x_3	$f[x_3]$	$f[x_2, x_3] = \frac{f[x_3] - f[x_2]}{x_3 - x_2}$	$f[x_1, x_2, x_3] = \frac{f[x_2, x_3] - f[x_1, x_2]}{x_3 - x_1}$
x_4	$f[x_4]$	$f[x_3, x_4] = \frac{f[x_4] - f[x_3]}{x_4 - x_3}$	$f[x_2, x_3, x_4] = \frac{f[x_3, x_4] - f[x_2, x_3]}{x_4 - x_2}$
x_5	$f[x_5]$	$f[x_4, x_5] = \frac{f[x_5] - f[x_4]}{x_5 - x_4}$	$f[x_3, x_4, x_5] = \frac{f[x_4, x_5] - f[x_3, x_4]}{x_5 - x_3}$

Note: The table can be extended with three 3rd divided differences, two 4th divided differences, and one 5th divided difference.

Algorithm: Computing the Divided Differences

Algorithm: Newton's Divided Difference —

Given the points $(x_i, f(x_i))$, $i = 0, \dots, n$.

Step 1: Initialize $F_{i,0} = f(x_i)$, $i = 0, \dots, n$

Step 2:

```

FOR i = 1 : n
  FOR j = 1 : i
     $F_{i,j} = \frac{F_{i,j-1} - F_{i-1,j-1}}{x_i - x_{i-j}}$ 
  END
END
    
```

Result: The diagonal, $F_{i,i}$ now contains $f[x_0, \dots, x_i]$.

A Theoretical Result: Generalization of the Mean Value Theorem

Theorem: — Suppose that $f \in C^n[a, b]$ and $\{x_0, \dots, x_n\}$ are distinct number is $[a, b]$. Then $\exists \xi \in (a, b)$:

$$f[x_0, \dots, x_n] = \frac{f^{(n)}(\xi)}{n!}.$$

For $n = 1$ this is exactly the *Mean Value Theorem*...

So we have extended to MVT to higher order derivatives!

What is the theorem telling us?

— *Newton's n^{th} divided difference is in some sense an approximation to the n^{th} derivative of f*

Newton vs. Taylor...

Using Newton's Divided Differences...

$$\begin{aligned}
 P_n^N(x) = & f[x_0] + f[x_0, x_1](x - x_0) + \\
 & f[x_0, x_1, x_2](x - x_0)(x - x_1) + \\
 & f[x_0, x_1, x_2, x_3](x - x_0)(x - x_1)(x - x_2) + \dots
 \end{aligned}$$

Using Taylor expansion

$$\begin{aligned}
 P_n^T(x) = & f(x_0) + f'(x_0)(x - x_0) + \\
 & \frac{1}{2!} f''(x_0)(x - x_0)^2 + \\
 & \frac{1}{3!} f'''(x_0)(x - x_0)^3 + \dots
 \end{aligned}$$

It makes sense that the divided differences are approximating the derivatives in some sense!

Simplification: Equally Spaced Points

When the points $\{x_0, \dots, x_n\}$ are equally spaced, *i.e.*

$$h = x_{i+1} - x_i, \quad i = 0, \dots, n-1.$$

We can write $x = x_0 + sh$, $x - x_k = (s - k)h$ so that

$$P_n(x) = P_n(x_0 + sh) = \sum_{k=0}^n s(s-1) \cdots (s-k+1) h^k f[x_0, \dots, x_k].$$

Using the binomial coefficients $\binom{s}{k} = \frac{s(s-1) \cdots (s-k+1)}{k!}$ we can write

$$P_n(\mathbf{x}_0 + s\mathbf{h}) = f[\mathbf{x}_0] + \sum_{k=1}^n \binom{s}{k} k! h^k f[\mathbf{x}_0, \dots, \mathbf{x}_k].$$

This is *Newton's Forward Divided Difference Formula*.

Notation, Notation, Notation...

Another form, **Newton's Forward Difference Formula** is constructed by using the forward difference operator Δ :

$$\Delta f(x_n) = f(x_{n+1}) - f(x_n)$$

using this notation:

$$f[x_0, x_1] = \frac{f(x_1) - f(x_0)}{x_1 - x_0} = \frac{1}{h} \Delta f(x_0).$$

$$f[x_0, x_1, x_2] = \frac{1}{2h} \left[\frac{\Delta f(x_1) - \Delta f(x_0)}{h} \right] = \frac{1}{2h^2} \Delta^2 f(x_0).$$

$$f[x_0, \dots, x_k] = \frac{1}{k! h^k} \Delta^k f(x_0).$$

Thus we can write **Newton's Forward Difference Formula**

$$P_n(\mathbf{x}_0 + s\mathbf{h}) = f[\mathbf{x}_0] + \sum_{k=1}^n \binom{s}{k} \Delta^k f(\mathbf{x}_0).$$

Notation, Notation, Notation... Backward Formulas

If we reorder $\{x_0, x_1, \dots, x_n\} \rightarrow \{x_n, \dots, x_1, x_0\}$, and define the backward difference operator ∇ :

$$\nabla f(x_n) = f(x_n) - f(x_{n-1}),$$

we can define the backward divided differences:

$$f[x_n, \dots, x_{n-k}] = \frac{1}{k! h^k} \nabla^k f(x_n).$$

We write down **Newton's Backward Difference Formula**

$$P_n(\mathbf{x}) = f[\mathbf{x}_n] + \sum_{k=1}^n (-1)^k \binom{-s}{k} \nabla^k f(\mathbf{x}_n),$$

where

$$\binom{-s}{k} = (-1)^k \frac{s(s+1) \cdots (s+k-1)}{k!}.$$

Forward? Backward? I'm Confused!!!

x	$f(x)$	1st Div. Diff.	2nd Div. Diff.
x_0	$f[x_0]$		
x_1	$f[x_1]$	$f[x_0, x_1] = \frac{f[x_1] - f[x_0]}{x_1 - x_0}$	
x_2	$f[x_2]$	$f[x_1, x_2] = \frac{f[x_2] - f[x_1]}{x_2 - x_1}$	$f[x_0, x_1, x_2] = \frac{f[x_1, x_2] - f[x_0, x_1]}{x_2 - x_0}$
x_3	$f[x_3]$	$f[x_2, x_3] = \frac{f[x_3] - f[x_2]}{x_3 - x_2}$	$f[x_1, x_2, x_3] = \frac{f[x_2, x_3] - f[x_1, x_2]}{x_3 - x_1}$
x_4	$f[x_4]$	$f[x_3, x_4] = \frac{f[x_4] - f[x_3]}{x_4 - x_3}$	$f[x_2, x_3, x_4] = \frac{f[x_3, x_4] - f[x_2, x_3]}{x_4 - x_2}$
x_5	$f[x_5]$	$f[x_4, x_5] = \frac{f[x_5] - f[x_4]}{x_5 - x_4}$	$f[x_3, x_4, x_5] = \frac{f[x_4, x_5] - f[x_3, x_4]}{x_5 - x_3}$

Forward: The fwd div. diff. are the top entries in the table.

Backward: The bwd div. diff. are the bottom entries in the table.

Forward? Backward? — Straight Down the Center!

The Newton formulas works best for points close to the edge of the table; if we want to approximate $f(x)$ close to the center, we have to work some more...

x	$f(x)$	1st Div. Diff.	2nd Div. Diff.	3rd Div. Diff.	4th Div. Diff.
x_{-2}	$f[x_{-2}]$	$f[x_{-2}, x_{-1}]$			
x_{-1}	$f[x_{-1}]$	$f[x_{-1}, x_0]$	$f[x_{-2}, x_{-1}, x_0]$		
x_0	$f[x_0]$	$f[x_0, x_1]$	$f[x_{-1}, x_0, x_1]$	$f[x_{-2}, x_{-1}, x_0, x_1]$	$f[x_{-2}, x_{-1}, x_0, x_1, x_2]$
x_1	$f[x_1]$	$f[x_1, x_2]$	$f[x_0, x_1, x_2]$	$f[x_{-1}, x_0, x_1, x_2]$	$f[x_{-1}, x_0, x_1, x_2, x_3]$
x_2	$f[x_2]$	$f[x_2, x_3]$	$f[x_1, x_2, x_3]$		
x_3	$f[x_3]$				

We are going to construct **Stirling's Formula** — a scheme using *centered differences*. In particular we are going to use the **blue** (centered at x_0) entries, and averages of the **red** (straddling the x_0 point) entries.

Stirling's Formula — Approximating at Interior Points

Assume we are trying to approximate $f(x)$ close to the interior point x_0 :

$$\begin{aligned}
 P_n(x) = P_{2m+1}(x) &= f[x_0] + sh \frac{f[x_{-1}, x_0] + f[x_0, x_1]}{2} \\
 &+ s^2 h^2 f[x_{-1}, x_0, x_1] \\
 &+ s(s^2 - 1)h^3 \frac{f[x_{-2}, x_{-1}, x_0, x_1] + f[x_{-1}, x_0, x_1, x_2]}{2} \\
 &+ s^2(s^2 - 1)h^4 f[x_{-2}, x_{-1}, x_0, x_1, x_2] \\
 &+ \dots \\
 &+ s^2(s^2 - 1) \dots (s^2 - (m - 1)^2)h^{2m} f[x_{-m}, \dots, x_m] \\
 &+ s(s^2 - 1) \dots (s^2 - m^2)h^{2m+1} \\
 &\cdot \frac{f[x_{-m-1}, \dots, x_m] + f[x_{-m}, \dots, x_{m+1}]}{2}
 \end{aligned}$$

If $n = 2m + 1$ is odd, otherwise delete the last two lines.

Combining Taylor and Lagrange Polynomials

A **Taylor polynomial of degree n** matches the function and its first n derivatives at one point.

A **Lagrange polynomial of degree n** matches the function values at $n + 1$ points.

Question: Can we combine the ideas of Taylor and Lagrange to get an interpolating polynomial that matches both the function values and some number of derivatives at multiple points?

Answer: To our euphoric joy, such polynomials exist! They are called **Osculating Polynomials**.

The Concise Oxford Dictionary:

Osculate 1. (arch. or joc.) kiss. **2.** (Biol., of species, etc.) be related through intermediate species etc., have common characteristics *with* another or with each other. **3.** (Math., of curve or surface) have contact of higher than first order with, meet at three or more coincident points.

Osculating Polynomials

In Painful Generality

Given $(n + 1)$ distinct points $\{x_0, x_1, \dots, x_n\} \in [a, b]$, and non-negative integers $\{m_0, m_1, \dots, m_n\}$.

Notation: Let $m = \max\{m_0, m_1, \dots, m_n\}$.

The **osculating polynomial approximation** of a function $f \in C^m[a, b]$ at $x_i, i = 0, 1, \dots, n$ is the polynomial (of lowest possible order) that agrees with

$$\{f(x_i), f'(x_i), \dots, f^{(m_i)}(x_i)\} \text{ at } x_i \in [a, b], \forall i.$$

The degree of the osculating polynomial is **at most**

$$M = n + \sum_{i=0}^n m_i.$$

In the case where $m_i = 1, \forall i$ the polynomial is called a **Hermite Interpolatory Polynomial**.

Hermite Interpolatory Polynomials The Existence Statement

If $f \in C^1[a, b]$ and $\{x_0, x_1, \dots, x_n\} \in [a, b]$ are distinct, the unique polynomial of least degree ($\leq 2n + 1$) agreeing with $f(x)$ and $f'(x)$ at $\{x_0, x_1, \dots, x_n\}$ is

$$\mathbf{H}_{2n+1}(\mathbf{x}) = \sum_{j=0}^n \mathbf{f}(x_j) \mathbf{H}_{n,j}(\mathbf{x}) + \sum_{j=0}^n \mathbf{f}'(x_j) \widehat{\mathbf{H}}_{n,j}(\mathbf{x}),$$

where

$$H_{n,j}(x) = [1 - 2(x - x_j)L'_{n,j}(x_j)] L_{n,j}^2(x)$$

$$\widehat{H}_{n,j}(x) = (x - x_j)L_{n,j}^2(x),$$

and $L_{n,j}(x)$ are our old friends, the **Lagrange coefficients**:

$$L_{n,j}(x) = \prod_{i=0, i \neq j}^n \frac{x - x_i}{x_j - x_i}.$$

Further, if $f \in C^{2n+2}[a, b]$, then for some $\xi(x) \in [a, b]$

$$f(x) = H_{2n+1}(x) + \frac{\prod_{i=0}^n (x - x_i)^2}{(2n + 2)!} f^{(2n+2)}(\xi(x)).$$

That's Hardly Obvious — Proof Needed!

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Recall: $L_{n,j}(x_i) = \delta_{i,j} = \begin{cases} 0, & \text{if } i \neq j \\ 1 & \text{if } i = j \end{cases}$ ($\delta_{i,j}$ is Kronecker's delta).

It follows that when $i \neq j$: $H_{n,j}(x_i) = \widehat{H}_{n,j}(x_i) = 0$.

When $i = j$: $\begin{cases} H_{n,j}(x_j) = [1 - 2(x_j - x_j)L'_{n,j}(x_j)] \cdot 1 = 1 \\ \widehat{H}_{n,j}(x_j) = (x_j - x_j)L_{n,j}^2(x_j) = 0. \end{cases}$

Thus $\mathbf{H}_{2n+1}(\mathbf{x}_j) = \mathbf{f}(\mathbf{x}_j)$.

$$\begin{aligned} H'_{n,j}(x) &= [-2L'_{n,j}(x_j)]L_{n,j}^2(x) + [1 - 2(x - x_j)L'_{n,j}(x_j)] \cdot 2L_{n,j}(x)L'_{n,j}(x) \\ &= L_{n,j}(x) [-2L'_{n,j}(x_j)L_{n,j}(x) + [1 - 2(x - x_j)L'_{n,j}(x_j)] \cdot 2(x)L'_{n,j}(x)] \end{aligned}$$

Since $L_{n,j}(x)$ is a factor in $H'_{n,j}(x)$: $H'_{n,j}(x_i) = 0$ when $i \neq j$.

Proof, continued...

$$\begin{aligned} H'_{n,j}(x_j) &= [-2L'_{n,j}(x_j)] \underbrace{L_{n,j}^2(x_j)}_1 \\ &+ [1 - \underbrace{2(x_j - x_j)L'_{n,j}(x_j)}_0] \cdot \underbrace{2L_{n,j}(x_j)L'_{n,j}(x_j)}_1 \\ &= -2L'_{n,j}(x_j) + 1 \cdot 2 \cdot L'_{n,j}(x_j) = 0 \end{aligned}$$

i.e. $\mathbf{H}'_{n,j}(\mathbf{x}_i) = \mathbf{0}$, $\forall i$.

$$\begin{aligned} \widehat{H}'_{n,j}(x) &= L_{n,j}^2(x) + 2(x - x_j)L_{n,j}(x)L'_{n,j}(x) \\ &= L_{n,j}(x) [L_{n,j}(x) + 2(x - x_j)L'_{n,j}(x)] \end{aligned}$$

If $i \neq j$: $\widehat{H}'_{n,j}(x_i) = 0$, since $L_{n,j}(x_i) = \delta_{i,j}$.

If $i = j$: $\widehat{H}'_{n,j}(x_j) = 1 \cdot [1 + 2(x_j - x_j)L'_{n,j}(x_j)] = 1$.

Hence, $\mathbf{H}'_{2n+1}(\mathbf{x}_i) = \mathbf{f}'(\mathbf{x}_i)$, $\forall i$. \square

Uniqueness Proof

Assume there is a second polynomial $G(x)$ (of degree $\leq 2n + 1$) interpolating the same data.

Define $R(x) = H_{2n+1}(x) - G(x)$.

Then by construction $R(x_i) = R'(x_i) = 0$, i.e. all the x_i 's are zeros of multiplicity at least 2.

This can only be true if $R(x) = q(x) \prod_{i=0}^n (x - x_i)^2$, for some $q(x)$.

If $q(x) \not\equiv 0$ then the degree of $R(x)$ is $\geq 2n + 2$, which is a contradiction.

Hence $q(x) \equiv 0 \Rightarrow R(x) \equiv 0 \Rightarrow H_{2n+1}(x)$ is unique. \square

Main Use of Hermite Interpolatory Polynomials

One of the primary applications of Hermite Interpolatory Polynomials is the development of **Gaussian quadrature** for numerical integration. (To be revisited later this semester.)

The most commonly seen Hermite interpolatory polynomial is the cubic one, which satisfies

$$H_3(x_0) = f(x_0), \quad H_3'(x_0) = f'(x_0)$$

$$H_3(x_1) = f(x_1), \quad H_3'(x_1) = f'(x_1).$$

it can be written explicitly as

$$H_3(x) = \left[1 + 2 \frac{x-x_0}{x_1-x_0} \right] \left[\frac{x_1-x}{x_1-x_0} \right]^2 f(x_0) + (x-x_0) \left[\frac{x_1-x}{x_1-x_0} \right] f'(x_0)$$

$$+ \left[1 + 2 \frac{x_1-x}{x_1-x_0} \right] \left[\frac{x-x_0}{x_1-x_0} \right]^2 f(x_1) + (x-x_1) \left[\frac{x-x_0}{x_1-x_0} \right] f'(x_1).$$

It appears in some optimization algorithms (see **Math 693a, line-search algorithms**.)

Computing from the Definition is Tedious!

However, there is good news: we can re-use the algorithm for **Newton's Interpolatory Divided Difference Formula** with some modifications in the initialization.

We double the number of points, *i.e.* let

$$\{y_0, y_1, \dots, y_{2n+1}\} = \{x_0, x_0 + \epsilon, x_1, x_1 + \epsilon, \dots, x_n, x_n + \epsilon\}$$

Set up the divided difference table (up to the first divided differences), and let $\epsilon \rightarrow 0$ (formally), and identify:

$$f'(x_i) = \lim_{\epsilon \rightarrow 0} \frac{f[x_i + \epsilon] - f[x_i]}{\epsilon},$$

to get the table [*next slide*]...

Hermite Interpolatory Polynomial using Modified Newton Divided Differences

y	f(x)	1st Div. Diff.	2nd Div. Diff.	3rd Div. Diff.
$y_0 = x_0$	$f[y_0]$	$f[y_0, y_1] = f'(y_0)$		
$y_1 = x_0$	$f[y_1]$	$f[y_1, y_2]$	$f[y_0, y_1, y_2]$	$f[y_0, y_1, y_2, y_3]$
$y_2 = x_1$	$f[y_2]$	$f[y_2, y_3] = f'(y_2)$	$f[y_1, y_2, y_3]$	$f[y_1, y_2, y_3, y_4]$
$y_3 = x_1$	$f[y_3]$	$f[y_3, y_4]$	$f[y_2, y_3, y_4]$	$f[y_2, y_3, y_4, y_5]$
$y_4 = x_2$	$f[y_4]$	$f[y_4, y_5] = f'(y_4)$	$f[y_3, y_4, y_5]$	$f[y_3, y_4, y_5, y_6]$
$y_5 = x_2$	$f[y_5]$	$f[y_5, y_6]$	$f[y_4, y_5, y_6]$	$f[y_4, y_5, y_6, y_7]$
$y_6 = x_3$	$f[y_6]$	$f[y_6, y_7] = f'(y_6)$	$f[y_5, y_6, y_7]$	$f[y_5, y_6, y_7, y_8]$
$y_7 = x_3$	$f[y_7]$	$f[y_7, y_8]$	$f[y_6, y_7, y_8]$	$f[y_6, y_7, y_8, y_9]$
$y_8 = x_4$	$f[y_8]$	$f[y_8, y_9] = f'(y_8)$	$f[y_7, y_8, y_9]$	
$y_9 = x_4$	$f[y_9]$			

$H_3(x)$ revisited...

Old notation

$$H_3(x) = \left[1 + 2 \frac{x-x_0}{x_1-x_0} \right] \left[\frac{x_1-x}{x_1-x_0} \right]^2 f(x_0)$$

$$+ \left[1 + 2 \frac{x_1-x}{x_1-x_0} \right] \left[\frac{x-x_0}{x_1-x_0} \right]^2 f(x_1)$$

$$+ (x-x_0) \left[\frac{x_1-x}{x_1-x_0} \right] f'(x_0)$$

$$+ (x-x_1) \left[\frac{x-x_0}{x_1-x_0} \right] f'(x_1).$$

Divided difference notation

$$H_3(x) = f(x_0) + f'(x_0)(x-x_0) + f[x_0, x_0, x_1](x-x_0)^2$$

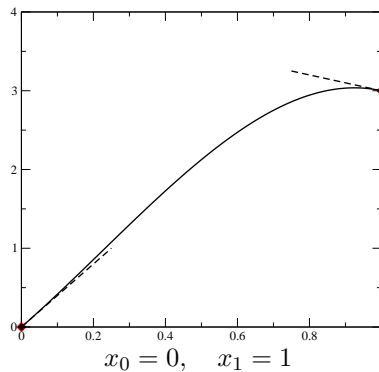
$$+ f[x_0, x_0, x_1, x_1](x-x_0)^2(x-x_1).$$

Or with the y 's...

$$H_3(x) = f(y_0) + f'(y_0)(x-y_0) + f[y_0, y_1, y_2](x-y_0)(x-y_1)$$

$$+ f[y_0, y_1, y_2, y_3](x-y_1)(x-y_2)(x-y_3).$$

$H_3(x)$ Example



$$f(x_0) = 0, \quad f'(x_0) = 4, \quad f(x_1) = 3, \quad f'(x_1) = -1$$

$$H_3(x) = 4x - x^2 - 3x^2(x-1)$$

$H_3(x)$ Example — Not Very Pretty Computations

```

x0 = 0; x1 = 1;           % This is the data
fv0 = 0; fpv0 = 4;
fv1 = 3; fpv1 = -1;

y0 = x0; f0=fv0;         % Initializing the table
y1 = x0; f1=fv0;
y2 = x1; f2=fv1;
y3 = x1; f3=fv1;

f01 = fpv0;              % First divided differences
f12 = (f2-f1)/(y2-y1);
f23 = fpv1;

f012 = (f12-f01)/(y2-y0); % Second divided differences
f123 = (f23-f12)/(y3-y1);

f0123 = (f123-f012)/(y3-y0); % Third divided difference

x=(0:0.01:1)';

H3 = f0 + f01*(x-y0) + f012*(x-y0).*(x-y1) + ...
     f0123*(x-y0).*(x-y1).*(x-y2);

```

Algorithm: Hermite Interpolation

Given the data points $(x_i, f(x_i), f'(x_i))$, $i = 0, \dots, n$.

Step 1: FOR $i=0:n$

$$y_{2i} = x_i, \quad Q_{2i,0} = f(x_i), \quad y_{2i+1} = x_i, \quad Q_{2i+1,0} = f(x_i)$$

$$Q_{2i+1,1} = f'(x_i)$$

IF $i > 0$

$$Q_{2i,1} = \frac{Q_{i,0} - Q_{i-1,0}}{y_{2i} - y_{2i-1}}$$

END

END

Step 2: FOR $i = 2 : (2n + 1)$

FOR $j = 2 : i$

$$Q_{i,j} = \frac{Q_{i,j-1} - Q_{i-1,j-1}}{y_i - y_{i-j}}$$

END

END

Result: $q_i = Q_{i,i}$, $i = 0, \dots, 2n + 1$ now contains the coefficients for

$$H_{2n+1}(x) = q_0 + \sum_{k=1}^{2n+1} \left[q_k \prod_{j=0}^{k-1} (x - y_j) \right].$$

Higher Order Osculating Polynomials

1 of 3

So far we have seen the osculating polynomials of order 0 — the Lagrange polynomial, and of order 1 — the Hermite interpolatory polynomial.

It turns out that generating osculating polynomials of higher order is fairly straight-forward; — and we use Newton's divided differences to generate those as well.

Given a set of points $\{x_k\}_{k=0}^n$, and $\{f^{(\ell)}(x_k)\}_{k=0, \ell=0}^{n, \ell_k}$; i.e. the function values, as well as the first ℓ_k derivatives of f in x_k . (Note that we can specify a different number of derivatives in each point.)

Set up the Newton-divided-difference table, and put in $(\ell_k + 1)$ duplicate entries of each point x_k , as well as its function value $f(x_k)$.

Run the computation of Newton's divided differences as usual; with the following exception:

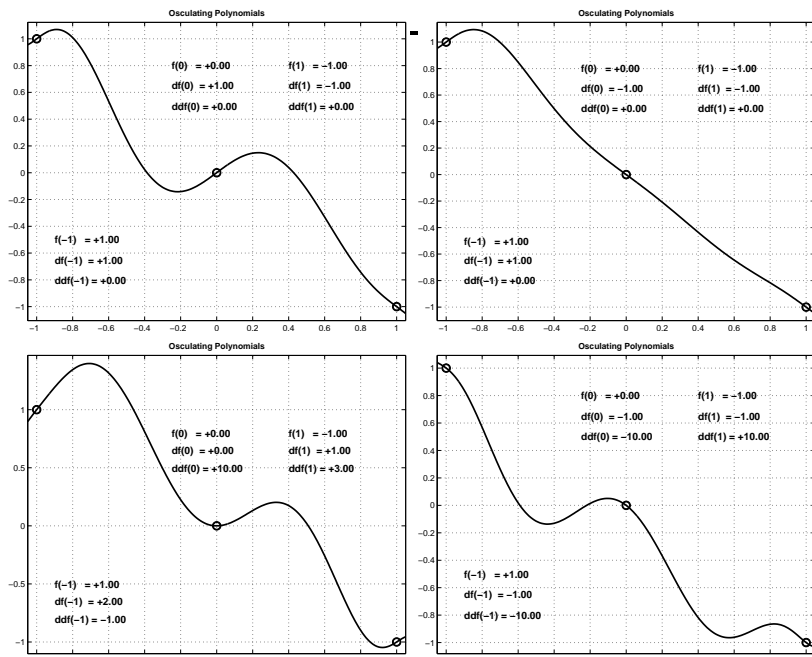
Whenever a zero-denominator is encountered — *i.e.* the divided difference for that entry cannot be computed due to duplication of a point — use a derivative instead. For m^{th} divided differences, use $\frac{1}{m!}f^{(m)}(x_k)$.

On the next slide we see the setup for two point in which two derivatives are prescribed.

y	f(x)	1st Div. Diff.	2nd Div. Diff.	3rd Div. Diff.
$y_0 = x_0$	$f[y_0]$	$f[y_0, y_1] = f'(x_0)$		
$y_1 = x_0$	$f[y_1]$	$f[y_1, y_2] = f'(x_0)$	$f[y_0, y_1, y_2] = \frac{1}{2}f''(x_0)$	$f[y_0, y_1, y_2, y_3]$
$y_2 = x_0$	$f[y_2]$	$f[y_2, y_3]$	$f[y_1, y_2, y_3]$	$f[y_1, y_2, y_3, y_4]$
$y_3 = x_1$	$f[y_3]$	$f[y_3, y_4] = f'(x_1)$	$f[y_2, y_3, y_4]$	$f[y_2, y_3, y_4, y_5]$
$y_4 = x_1$	$f[y_4]$	$f[y_4, y_5] = f'(x_1)$	$f[y_3, y_4, y_5] = \frac{1}{2}f''(x_1)$	
$y_5 = x_1$	$f[y_5]$			

3rd and higher order divided differences are computed “as usual” in this case.

On the next slide we see four examples of 2nd order osculating polynomials.



We have encountered methods by these fellows

Sir Isaac Newton, 4 Jan 1643 (Woolsthorpe, Lincolnshire, England) — 31 March 1727.

Joseph-Louis Lagrange, 25 Jan 1736 (Turin, Sardinia-Piedmont (now Italy)) — 10 April 1813.

Johann Carl Friedrich Gauss, 30 April 1777 (Brunswick, Duchy of Brunswick (now Germany)) — 23 Feb 1855.

Charles Hermite, 24 Dec 1822 (Dieuze, Lorraine, France) — 14 Jan 1901.

The class website contains links to short bios for these (and other) mathematicians, click on **Mathematics Personae**, who have contributed to the material covered in this class. It makes for interesting reading and puts mathematics into a historical and political context.