MA378 Chapter 1: Interpolation

§1.3 Interpolation Error Estimates

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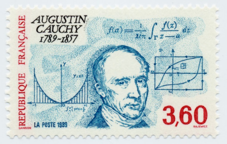

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Augustin-Louis Cauchy (1789–1857), Paris, France. He was a pioneer of analysis, in particular in introducing rigour into calculus proofs. He founded the fields of complex analysis and the study of permutation groups.

3.1 Introduction

In our last example, we wrote down the polynomial of degree $n = 2$ interpolating $f(x) = e^x$ at $x_0 = -1$, $x_1 = 0$ and $x_2 = 1$.

We now want to investigate how, in general, error in polynomial interpolation depends on

(i) the function (and its derivatives)

(ii) the number of points used (or, equivalently, degree of the polynomial used).

3.1 Introduction

The main ingredient we need to the following theorem.

Theorem 3.1 (Rolle's Theorem)

Let g be a function that is continuous and differentiable on the interval $[a, b]$. If $g(a) = g(b)$, then there is at least one point c in (a, b) where $g'(c) = 0$.

Our "proof" is by picture:[1]

[1]One can easily deduce Rolle's Theorem from the Mean Value Theorem (MVT). But since the standard proof of the MVT uses Rolle's Theorem, that would be cheating.

3.2 Error estimate for n=0

The simplest case is when $n = 0$, so the interpolant is a constant, i.e., it is p_0 interpolating a function f at a point x_0. Here is one way we can deduce the *interpolation error*.

3.2 Error estimate for n=0

It is important to understand what this formula is telling us:

3.3 Error estimates for $n \geq 1$

The following is the most important theorem of NA2; it is used repeatedly through-out the semester. It's often called the *Polynomial Interpolation Error Theorem*, or *Cauchy's Theorem*.

First, we need to define an important polynomial.

Definition 3.2 (Nodal Polynomial)

The **Nodal Polynomial** π_{n+1} associated with the interpolation points that $a = x_0 < x_1 < \cdots < x_n = b$ is

$$\pi_{n+1}(x) = (x - x_0)(x - x_1) \ldots (x - x_n) = \prod_{i=0}^{n} (x - x_i).$$

3.3 Error estimates for $n \geq 1$

Theorem 3.3 (Cauchy, 1840)

Suppose that $n \geq 0$ and f is a real-valued function that is continuous and defined on $[a, b]$, such that the derivative of f of order $n+1$ exists and is continuous on $[a, b]$. Let p_n be the polynomial of degree n that interpolates f at the $n+1$ points $a = x_0 < x_1 < \cdots < x_n = b$. Then, for any $x \in [a, b]$ there is a $\tau \in (a, b)$ such that

$$f(x) - p_n(x) = \frac{f^{(n+1)}(\tau)}{(n+1)!}\pi_{n+1}(x). \tag{1}$$

3.3 Error estimates for $n \geq 1$

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Example 3.4

In an earlier example, we wrote down the Lagrange form of the polynomial, p_2, that interpolates $f(x) = e^x$ at the points $\{-1, 0, 1\}$. Give a formula for $e^x - p_2(x)$.

3.3 Error estimates for $n \geq 1$

Usually (and as in the above example), we can't calculate $f(x) - p_n(x)$ exactly from Formula (1), because we have no way of finding τ. However, we are typically not so interested in what the error is at some given point, but what is the maximum error over the whole interval $[x_0, x_n]$. That is given by:

Corollary 3.5

Define

$$M_{n+1} = \max_{x_0 \leq \sigma \leq x_n} |f^{(n+1)}(\sigma)|.$$

Then

$$|f(x) - p_n(x)| \leq \frac{M_{n+1}}{(n+1)!} |\pi_{n+1}(x)|. \tag{2}$$

3.3 Error estimates for $n \geq 1$

Example 3.6

Let p_1 be the polynomial of degree 1 that interpolates a function f at distinct points x_0 and x_1. Letting $h = x_1 - x_0$, show that

$$\max_{x_0 \leq x \leq x_1} |f(x) - p_1(x)| \leq \frac{1}{8} h^2 M_2.$$

Exercise 3.1

Let p_2 be the polynomial of degree 2 that interpolates a function f at the points x_0, x_1 and x_2. If $x_1 - x_0 = x_2 - x_1 = h$, show that

$$\max_{x_0 \leq x \leq x_2} |f(x) - p_2(x)| \leq \frac{1}{6}\frac{2}{3\sqrt{3}}h^3 M_3 = \frac{1}{9\sqrt{3}}h^3 M_3.$$

Hint: simplify the calculations by taking $t = x - x_1$, writing $(x - x_0)(x - x_1)(x - x_2)$ in terms of h and t.