

# Numerical Analysis : Recitations

Aakash Jog

2015-16

## Contents

<b>1</b>	<b>Instructor Information</b>	<b>2</b>
<b>2</b>	<b>Errors</b>	<b>2</b>
2.1	Propagation of Error . . . . .	4
<b>3</b>	<b>Interpolation by Polynomials</b>	<b>5</b>



This work is licensed under the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License. To view a copy of this license, visit <http://creativecommons.org/licenses/by-nc-sa/4.0/>.

# 1 Instructor Information

Ron Levie

E-mail: ronlevie@post.tau.ac.il

## 2 Errors

**Definition 1** (Error). The absolute error in representation is defined as

$$e_x = x - \tilde{x}$$

The relative error in representation is defined as

$$\delta = \frac{x - \tilde{x}}{x}$$

### Recitation 1 – Exercise 1.

The dimensions of a field are measured. The length is measured to be  $\tilde{x} = 800\text{m}$ , with an absolute error bounded by 16. The width is measured to be  $\tilde{y} = 30\text{m}$ , with an absolute error  $e_y$ , such that  $|e_y| \leq 6$ .

1. Find the approximate bounds for  $|\delta_x|$  and  $|\delta_y|$ .
2. Find the bounds on the absolute error in the calculated area of the field.

### Recitation 1 – Solution 1.

1.

$$\begin{aligned} |\delta_x| &= \frac{|e_x|}{|x|} \\ &\leq \frac{16}{|x|} \\ &\approx \frac{16}{800} \\ &= 0.02 \\ \therefore |\delta_x| &\leq 0.02 \end{aligned}$$

$$\begin{aligned}
|\delta_y| &= \frac{|e_y|}{|y|} \\
&\leq \frac{6}{|y|} \\
&\approx \frac{6}{300} \\
&= 0.02 \\
\therefore |\delta_y| &\leq 0.02
\end{aligned}$$

2. The measured area of the field is

$$\begin{aligned}
\tilde{A} &= \tilde{x}\tilde{y} \\
&= 800 \cdot 300 \\
&= 240000
\end{aligned}$$

The maximum area of the field is

$$\begin{aligned}
A_{\max} &= (\tilde{x} + e_{x\max})(\tilde{y} + e_{y\max}) \\
&= (800 + 16)(300 + 6) \\
&= 249696
\end{aligned}$$

The minimum area of the field is

$$\begin{aligned}
A_{\min} &= (\tilde{x} + e_{x\min})(\tilde{y} + e_{y\min}) \\
&= (800 - 16)(300 - 6) \\
&= 230496
\end{aligned}$$

Therefore,

$$\begin{aligned}
|e_{xy}| &\leq (A_{\max} - A_{\min}) \\
&\leq 9696
\end{aligned}$$

3.

$$\begin{aligned}
|\delta_{xy}| &= \frac{|e_{xy}|}{|xy|} \\
&\leq \frac{9696}{|xy|} \\
&\leq \frac{9696}{230496} \\
&\approx 0.042
\end{aligned}$$

## 2.1 Propagation of Error

### Recitation 1 – Exercise 2.

Let  $\tilde{x}$ ,  $\tilde{y}$  be approximations of  $x$ ,  $y$ .

1. Find a formula for the absolute error in  $x + y$  in terms of  $e_x$  and  $e_y$ .
2. Find a formula for  $\delta_{x+y}$ ,  $\delta_{x-y}$  in terms of  $\delta_x$ ,  $\delta_y$ ,  $x$ ,  $y$ .
3. Let  $\delta = \max\{\delta_x, \delta_y\}$ . Assuming  $x, y > 0$ , show

$$|\delta_{x-y}| \leq \frac{x+y}{|x-y|} \delta$$

### Recitation 1 – Solution 2.

1.

$$\begin{aligned} e_{x+y} &= (x+y) - (\tilde{x} + \tilde{y}) \\ &= (x - \tilde{x}) + (y - \tilde{y}) \\ &= e_x + e_y \end{aligned}$$

2.

$$\begin{aligned} \delta_{x+y} &= \frac{e_{x+y}}{x+y} \\ &= \frac{e_x + e_y}{x+y} \\ &= \frac{x\delta_x + y\delta_y}{x+y} \end{aligned}$$

Similarly,

$$\begin{aligned} \delta_{x-y} &= \frac{e_{x-y}}{x-y} \\ &= \frac{e_x - e_y}{x-y} \\ &= \frac{x\delta_x - y\delta_y}{x-y} \end{aligned}$$

3.

$$\begin{aligned}
|\delta_{x-y}| &= \left| \frac{x\delta_x - y\delta_y}{x-y} \right| \\
&\leq \frac{|x||\delta_x| + |y||\delta_y|}{|x-y|} \\
&\leq \frac{x\delta + y\delta}{|x-y|} \\
&= \frac{x+y}{|x-y|} \delta
\end{aligned}$$

**Recitation 1 – Exercise 3.**

Find a formula for  $\delta_{xy}$ , in terms of  $x$ ,  $y$ ,  $\delta_x$ ,  $\delta_y$ .

**Recitation 1 – Solution 3.**

$$\begin{aligned}
\delta_a &= \frac{a - \tilde{a}}{a} \\
\therefore \tilde{a} &= a(1 - \delta_a)
\end{aligned}$$

Therefore,

$$\begin{aligned}
\tilde{x}\tilde{y} &= (x(1 - \delta_x)) (y(1 - \delta_y)) \\
&= xy(1 - \delta_x - \delta_y + \delta_x\delta_y)
\end{aligned}$$

Also,

$$\tilde{x}\tilde{y} = xy(1 - \delta_{xy})$$

Therefore,

$$\delta_{xy} = \delta_x + \delta_y - \delta_x\delta_y$$

### 3 Interpolation by Polynomials

**Theorem 1** (Existence and Uniqueness Theorem). *There exists a unique polynomial  $p_n(x)$  which approximates  $f(x)$  between the sample points, i.e.*

$$|e_n(x)| = |f(x) - p_n(x)|$$

**Recitation 2 – Exercise 1.**

Find the interpolation polynomial for the data

$x_i$	$f(x_i)$
1	3
2	2
4	1

**Recitation 2 – Solution 1.**

Let

$$p(x) = a_0 + a_1x + a_2x^2$$

be the required interpolation polynomial.

Therefore,

$$\begin{aligned}p(1) &= 3 \\ \therefore 3 &= a_0 + a_1 \cdot 1 + a_2 \cdot 1^2 \\ p(2) &= 2 \\ \therefore 2 &= a_0 + a_1 \cdot 2 + a_2 \cdot 2^2 \\ p(4) &= 1 \\ \therefore 1 &= a_0 + a_1 \cdot 4 + a_2 \cdot 4^2\end{aligned}$$

Therefore,

$$\begin{pmatrix} 1 & 1 & 1^2 \\ 1 & 2 & 2^2 \\ 1 & 4 & 4^2 \end{pmatrix} \begin{pmatrix} a_0 \\ a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} 3 \\ 2 \\ 1 \end{pmatrix}$$

Therefore, solving,

$$\begin{pmatrix} a_0 \\ a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} \frac{13}{3} \\ -\frac{3}{2} \\ \frac{1}{6} \end{pmatrix}$$

Therefore,

$$p(x) = \frac{13}{3} - \frac{3}{2}x + \frac{1}{6}x^2$$

**Definition 2.** Let the sample points be  $x_0, \dots, x_{n-1}$ .

Lagrange polynomials are  $n$  polynomials of degree  $n - 1$ , each of which is 0 at all sample points, except one, at which it is 1.

$$l_i(x) = \frac{(x - x_0) \dots (x - x_{i-1})(x - x_{i+1}) \dots (x - x_{n-1})}{(x_i - x_0) \dots (x_i - x_{i-1})(x_i - x_{i+1}) \dots (x_i - x_{n-1})}$$

**Recitation 2 – Exercise 2.**

Find the interpolation polynomial for the data

$x_i$	$f(x_i)$
1	3
2	2
4	1

using Lagrange polynomials.

**Recitation 2 – Solution 2.**

Let

$$x_0 = 1$$

$$x_1 = 2$$

$$x_3 = 4$$

Therefore,

$$\begin{aligned} l_0(x) &= \frac{(x - x_1)(x - x_2)}{(x_0 - x_1)(x_0 - x_2)} \\ &= \frac{(x - 2)(x - 4)}{(1 - 2)(1 - 4)} \\ l_1(x) &= \frac{(x - x_0)(x - x_2)}{(x_1 - x_0)(x_1 - x_2)} \\ &= \frac{(x - 1)(x - 4)}{(2 - 1)(2 - 4)} \\ l_2(x) &= \frac{(x - x_0)(x - x_1)}{(x_2 - x_0)(x_2 - x_1)} \\ &= \frac{(x - 1)(x - 2)}{(4 - 1)(4 - 2)} \end{aligned}$$

Therefore,

$$\begin{aligned} p(x) &= f(x_0)l_0(x) + f(x_1)l_1(x) + f(x_2)l_2(x) \\ &= 3l_0(x) + 2l_1(x) + l_2(x) \end{aligned}$$

### Recitation 3 – Exercise 1.

Given

$x_i$	$f(x_i)$
0	0
$\frac{\pi}{4}$	$\frac{\sqrt{2}}{2}$
$\frac{\pi}{2}$	1

Find the interpolating polynomial in Newton's form.

### Recitation 3 – Solution 1.

The interpolating polynomial is

$$p_2(x) = A_0 + A_1(x - x_0) + A_2(x - x_0)(x - x_1)$$

where

$$A_k = f[x_0, \dots, x_k]$$

Therefore,

$$\begin{aligned} \therefore f[0] &= f(0) \\ &= 0 \\ \therefore f\left[\frac{\pi}{4}\right] &= f\left(\frac{\pi}{4}\right) \\ &= \frac{\sqrt{2}}{2} \\ \therefore f\left[\frac{\pi}{2}\right] &= f\left(\frac{\pi}{2}\right) \\ &= 1 \end{aligned}$$



Therefore,

$$\begin{aligned} f\left[0, \frac{\pi}{4}\right] &= \frac{f\left[\frac{\pi}{4}\right] - f[0]}{\frac{\pi}{4} - 0} \\ &= \frac{\frac{\sqrt{2}}{2} - 0}{\frac{\pi}{4}} \\ f\left[\frac{\pi}{4}, \frac{\pi}{2}\right] &= \frac{f\left[\frac{\pi}{2}\right] - f\left[\frac{\pi}{4}\right]}{\frac{\pi}{2} - \frac{\pi}{4}} \end{aligned}$$

Therefore,

$$\begin{aligned} f\left[0, \frac{\pi}{4}, \frac{\pi}{2}\right] &= \frac{f\left[\frac{\pi}{4}, \frac{\pi}{2}\right] - f\left[0, \frac{\pi}{4}\right]}{\frac{\pi}{2} - 0} \\ &= \frac{8(1 - \sqrt{2})}{\pi^2} \end{aligned}$$

Therefore,

$$\begin{aligned} A_0 &= 0 \\ A_1 &= \frac{2\sqrt{2}}{\pi} \\ A_2 &= \frac{8(1 - \sqrt{2})}{\pi^2} \end{aligned}$$

Therefore,

$$p_2(x) = \frac{2\sqrt{2}}{\pi}x + \frac{8(1 - \sqrt{2})}{\pi^2}(x) \left(x - \frac{\pi}{4}\right)$$

### Recitation 3 – Exercise 2.

$\sin\left(\frac{\pi}{3}\right)$  was approximated using Newton's method, at sample points  $0, \frac{\pi}{4}, \frac{\pi}{2}$ , to be

$$\begin{aligned} p_2\left(\frac{\pi}{3}\right) &= \frac{2\sqrt{2}}{3} + \frac{8(1 - \sqrt{2})}{36} \\ &= 0.8507 \end{aligned}$$

Find the bounds on the error in this approximation.

### Recitation 3 – Solution 2.

$$\begin{aligned} |e_n(x)| &= |f(x) - p_n(x)| \\ &\leq \left| \frac{f^{(n+1)}(c)}{(n+1)!} \prod_{j=0}^n (x - x_j) \right| \end{aligned}$$

where  $c \in [\min\{x_0, \dots, x_n, x\}, \max\{x_0, \dots, x_n, x\}]$ .

Therefore,

$$\begin{aligned} |e_2(x)| &\leq \left| \frac{\sin^{(3)}(c)}{3!} \prod_{j=0}^2 (x - x_j) \right| \\ \therefore \left| e_2\left(\frac{\pi}{3}\right) \right| &\leq \left| \frac{\sin^{(3)}(c)}{3!} \prod_{j=0}^2 \left(\frac{\pi}{3} - x_j\right) \right| \\ &\leq \left| \frac{\sin^{(3)}(c)}{3!} \left(\frac{\pi}{3} - 0\right) \left(\frac{\pi}{3} - \frac{\pi}{4}\right) \left(\frac{\pi}{3} - \frac{\pi}{2}\right) \right| \\ &\leq \left| \frac{-\cos(c)}{6} \frac{\pi^3}{(3)(12)(6)} \right| \\ &\leq \left| \frac{-\cos(c)\pi^3}{1296} \right| \end{aligned}$$

Therefore, as  $|\cos(c)|$  is bounded by 0 and 1,

$$\begin{aligned} \left| e_2\left(\frac{\pi}{3}\right) \right| &\leq \left| \frac{\pi^3}{1296} \right| \\ &< 0.0242 \end{aligned}$$

### Recitation 4 – Exercise 1.

Find Hermite's interpolating polynomial for the sample points 1, 1,  $e$ , for the function  $f(x) = \ln(x)$ .

### Recitation 4 – Solution 1.

$$f[x_0, \dots, x_k] = \begin{cases} \frac{f[x_1, \dots, x_k] - f[x_0, \dots, x_{k-1}]}{x_k - x_0} & ; \quad x_k \neq x_0 \\ \frac{f^{(k)}(x_0)}{k!} & ; \quad x_k = x_0 \end{cases}$$

Therefore,

$$\begin{aligned} f[1] &= 0 \\ f[1] &= 0 \\ f[e] &= 1 \end{aligned}$$

Therefore,

$$\begin{aligned}f[1, 1] &= \frac{f'(1)}{1!} \\&= \frac{1}{x} \Big|_{x=1} \\&= 1 \\f[1, e] &= \frac{1-0}{e-1} \\&= \frac{1}{e-1}\end{aligned}$$

Therefore,

$$\begin{aligned}f[1, 1, e] &= \frac{\frac{1}{e-1} - 1}{e-1} \\&= \frac{2-e}{(e-1)^2}\end{aligned}$$

Therefore,

$$\begin{aligned}p_2(x) &= f[1] + f[e](x-1) + \frac{2-e}{(e-1)^2}(x-1)(x-1) \\&= 0 + 1(x-1) + \frac{2-e}{(e-1)^2}(x-1)^2\end{aligned}$$