

# NUMERICAL METHODS

C / KAPPA EXAM 12 / 11/19 / 2022 [20.00]

### LEAST SQUARES REGRESSION

Goal: minimize the sum of the squares of the residual errors.

Residuals are the vertical distances between the data points and the fitted line.

$$S_r = \sum_{i=1}^n d_i = \sum_{i=1}^n (y_i - a_0 - a_1 x_i)$$

$$S_r^2 = \sum_{i=1}^n (y_i - a_0 - a_1 x_i)^2$$

Minimize  $S_r^2$  by setting  $\frac{\partial S_r^2}{\partial a_0} = 0$  and  $\frac{\partial S_r^2}{\partial a_1} = 0$ .

$$a_0 = \frac{\sum y_i}{n} - a_1 \frac{\sum x_i}{n}$$

$$a_1 = \frac{\sum x_i y_i - \frac{(\sum x_i)(\sum y_i)}{n}}{\sum x_i^2 - \frac{(\sum x_i)^2}{n}}$$

### STANDARD ERROR:

$$S_{y_1} = \sqrt{\frac{S_r}{n-2}}$$

$$S_{y_2} = \sqrt{\frac{S_r (1 - r^2)}{n-2}}$$

### STANDARD DEVIATION:

$$S_y = \sqrt{\frac{S_r}{n-1}}$$

$$S_x = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}}$$

$a_0 = \bar{y} - a_1 \bar{x}$   
 $y = a_0 + a_1 x$

### INTERPOLATION

Use a 4th order polynomial

Order	Nodes	Degree	Nodes	Degree
1st	2	1	2	1
2nd	3	2	3	2
3rd	4	3	4	3
4th	5	4	5	4

$P_n(x) = a_0 + a_1 x + a_2 x^2 + \dots + a_n x^n$   
 Order:  $n=1, 2, 3, 4, 5$   
 Turns:  $0, 1, 2, 3, 4$

### SPINES:

$$P_n = \frac{f(x_{i+1}) - f(x_i)}{x_{i+1} - x_i}$$

### POLYNOMIAL QUADRATIC REGRESSION:

Goal: minimize the sum of the squares of the residual errors.

$$S_r = \sum_{i=1}^n (y_i - a_0 - a_1 x_i - a_2 x_i^2)^2$$

Take derivatives of  $S_r$  to find the minimum.

$$\frac{\partial S_r}{\partial a_0} = -2 \sum (y_i - a_0 - a_1 x_i - a_2 x_i^2) = 0$$

$$\frac{\partial S_r}{\partial a_1} = -2 \sum (x_i (y_i - a_0 - a_1 x_i - a_2 x_i^2)) = 0$$

$$\frac{\partial S_r}{\partial a_2} = -2 \sum (x_i^2 (y_i - a_0 - a_1 x_i - a_2 x_i^2)) = 0$$

Matrix form:  $[X][X]^T [a] = [X][Y]$

### ODE'S

#### Runge-Kutta Method

$$y_{i+1} = y_i + f(x_i, y_i) \Delta x$$

#### Heun's Method

$$y_{i+1} = y_i + f(x_i, y_i) \Delta x + \frac{f(x_{i+1}, y_{i+1}) - f(x_i, y_i)}{2} \Delta x$$

$\frac{dy}{dx} = f(x, y)$   
 $y' = \frac{y^2 + 2x}{2} = f(x, y)$   
 $y_1 = 1, x_1 = 0$   
 $y_2 = 1.1, x_2 = 0.1$   
 $y_3 = 1.2, x_3 = 0.2$

### Taylor Series

$$y(x+\Delta x) = y(x) + \Delta x y'(x) + \frac{\Delta x^2}{2} y''(x) + \dots$$

### Classic 4th order Runge-Kutta

$$y_{i+1} = y_i + \frac{\Delta x}{4} (k_1 + 2k_2 + 2k_3 + k_4)$$

$k_1 = f(x_i, y_i)$   
 $k_2 = f(x_i + \frac{1}{2}\Delta x, y_i + \frac{1}{2}\Delta x k_1)$   
 $k_3 = f(x_i + \frac{1}{2}\Delta x, y_i + \Delta x k_2)$   
 $k_4 = f(x_i + \Delta x, y_i + \Delta x k_3)$

### PDE'S

#### Finite Difference Method

- Central Difference:  $\frac{\partial^2 u}{\partial x^2} \approx \frac{u_{i+1} - 2u_i + u_{i-1}}{\Delta x^2}$   
 - Forward Difference:  $\frac{\partial u}{\partial x} \approx \frac{u_i - u_{i-1}}{\Delta x}$   
 - Backward Difference:  $\frac{\partial u}{\partial x} \approx \frac{u_{i+1} - u_i}{\Delta x}$

#### Heat Conduction

$u_x = 0$  at  $x=0$  (Insulated)  
 $u = 0$  at  $x=L$  (Cooling)

### EIGEN VALUES

$\lambda = \text{Eigen Value}$

Example:  $A = \begin{bmatrix} 1 & 2 \\ 2 & 1 \end{bmatrix}$

$$|A - \lambda I| = \begin{vmatrix} 1-\lambda & 2 \\ 2 & 1-\lambda \end{vmatrix} = (1-\lambda)^2 - 4 = 0$$

$$\lambda^2 - 2\lambda - 3 = 0 \Rightarrow \lambda = 3, -1$$

### Single 2x2

$$A = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$$

$$|A - \lambda I| = \begin{vmatrix} a-\lambda & b \\ c & d-\lambda \end{vmatrix} = (a-\lambda)(d-\lambda) - bc = 0$$

$$\lambda^2 - (a+d)\lambda + (ad-bc) = 0$$

### 3x3 Matrix

$$\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$x_1 + x_2 + x_3 = 0$   
 $x_1 = -x_2 - x_3$

### 3x3 Matrix

$$\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$-x_2 + x_3 = 0 \Rightarrow x_2 = x_3$   
 $x_1 + x_2 + x_3 = 0 \Rightarrow x_1 + 2x_3 = 0 \Rightarrow x_1 = -2x_3$

### Heat Conduction

- Central Difference:  $\frac{\partial^2 u}{\partial x^2} \approx \frac{u_{i+1} - 2u_i + u_{i-1}}{\Delta x^2}$   
 - Forward Difference:  $\frac{\partial u}{\partial x} \approx \frac{u_i - u_{i-1}}{\Delta x}$   
 - Backward Difference:  $\frac{\partial u}{\partial x} \approx \frac{u_{i+1} - u_i}{\Delta x}$

- Right Boundary B.C.:  $\frac{\partial u}{\partial x} = 0$  at  $x=L$   
 $u_{i+1} - u_i = 0$   
 $u_{i+1} = u_i$

### Heat Conduction

- Central Difference:  $\frac{\partial^2 u}{\partial x^2} \approx \frac{u_{i+1} - 2u_i + u_{i-1}}{\Delta x^2}$   
 - Forward Difference:  $\frac{\partial u}{\partial x} \approx \frac{u_i - u_{i-1}}{\Delta x}$   
 - Backward Difference:  $\frac{\partial u}{\partial x} \approx \frac{u_{i+1} - u_i}{\Delta x}$

- Bottom Boundary B.C.:  $\frac{\partial u}{\partial x} = 0$  at  $x=0$   
 $u_{i+1} - u_i = 0$   
 $u_{i+1} = u_i$

### 5th Row of A Matrix

$[0 \ 1 \ 0 \ -1 \ 1 \ -1 \ 0 \ -1 \ 0] [u] = 0$

- Top Boundary B.C.:  $\frac{\partial u}{\partial x} = 0$  at  $x=L$   
 $u_{i+1} - u_i = 0$   
 $u_{i+1} = u_i$

- Left Boundary B.C.:  $u_{i-1} = u_i - 2\Delta x G_0$

### [A] MATRIX

$u_{i,j+1} - u_{i,j} = 4u_{i,j} - u_{i,j-1} - u_{i,j+1} = 2\Delta x G_0$   
 $-2u_{i,j} + 4u_{i,j} - u_{i,j-1} - u_{i,j+1} = -2\Delta x G_0$   
 $2u_{i,j} - u_{i,j-1} - u_{i,j+1} = -2\Delta x G_0$   
 $-u_{i,j} - u_{i,j+1} + 4u_{i,j} - 2u_{i,j-1} = -2\Delta x G_0$   
 $-u_{i,j} - u_{i,j+1} + 4u_{i,j} - 2u_{i,j-1} = -2\Delta x G_0$

### Finite Elements

- Centred Finite-Difference Formula:  
 $f(x) = \frac{f(x_1) - f(x_2)}{2\Delta x}$   
 $f(x) = \frac{f(x_1) - 3f(x_2) + 3f(x_3) - f(x_4)}{12\Delta x}$

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**R. Glowinski, J.L. Lions**



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