

# Project 1 - FYS3150

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## I. METHOD

We're going to solve the differential equation

$$-u''(x) = f(x), \quad x \in (0, 1), \quad u(0) = u(1) = 0. \quad (1)$$

We'll approximate this differential equation by a function  $v(x) \approx u(x)$  by the approximation scheme

$$-\frac{-v_{i+1} + v_{i-1} - 2v_i}{h^2} = f_i, \quad i = 1, 2, \dots, n, \quad (2)$$

which may be rearranged into

$$2v_i - v_{i+1} - v_{i-1} = f_i h^2 \equiv \tilde{b}_i. \quad (3)$$

From (3) we can write

$$\begin{pmatrix} 2v_1 - v_2 \\ -v_1 + 2v_2 - v_3 \\ \vdots \\ 2v_n - v_{n-1} \end{pmatrix} = \begin{pmatrix} 2 & -1 & 0 & \cdots & 0 \\ -1 & 2 & -1 & \cdots & 0 \\ \vdots & & & & \\ 0 & \cdots & 0 & -1 & 2 \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{pmatrix} = \begin{pmatrix} \tilde{b}_1 \\ \tilde{b}_2 \\ \vdots \\ \tilde{b}_n \end{pmatrix} \quad (4)$$

To this end we will develop an algorithm based on the LU-decomposition  $A = LU$ :

$$A = \begin{pmatrix} b_1 & c_1 & 0 & \cdots & \cdots & \cdots \\ a_1 & b_2 & c_2 & 0 & \cdots & \cdots \\ 0 & a_2 & b_3 & 0 & \cdots & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & a_{n-2} & b_{n-1} & c_{n-1} \\ 0 & 0 & \cdots & 0 & a_{n-1} & b_n \end{pmatrix} = \begin{pmatrix} 1 & 0 & \cdots & \cdots & \cdots & 0 \\ \ell_2 & 1 & \cdots & \cdots & \cdots & 0 \\ 0 & \ell_3 & 1 & \cdots & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \\ 0 & 0 & \cdots & \ell_{n-1} & 1 & 0 \\ 0 & 0 & \cdots & \cdots & \ell_n & 1 \end{pmatrix} \begin{pmatrix} d_1 & u_1 & \cdots & \cdots & \cdots & 0 \\ 0 & d_2 & u_2 & \cdots & \cdots & 0 \\ 0 & 0 & d_3 & u_3 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & \cdots & d_{n-1} & u_{n-1} \\ 0 & 0 & \cdots & \cdots & 0 & d_n \end{pmatrix} = LU, \quad (5)$$

and performing matrix multiplication we get

$$LU = \begin{pmatrix} d_1 & u_1 & \cdots & \cdots & \cdots & 0 \\ \ell_2 d_1 & \ell_2 u_1 + d_2 & u_2 & \cdots & \cdots & 0 \\ 0 & \ell_3 d_2 & \ell_3 u_2 + d_3 & u_3 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & \ell_{n-1} d_{n-2} & \ell_{n-1} u_{n-2} + d_{n-1} & u_{n-1} \\ 0 & 0 & \cdots & \cdots & \ell_n d_{n-1} & \ell_n u_{n-1} + d_n \end{pmatrix}, \quad (6)$$

which yields the following general relations:

$$b_i = d_i, \quad c_i = u_i, \quad \text{for } i = 1, \quad (7)$$

$$\ell_i = \frac{a_{i-1}}{d_{i-1}}, \quad \text{for } 1 < i < n, \quad (8)$$

$$d_i = b_i - \ell_i u_{i-1}, \quad \text{for } 1 < i < n, \quad (9)$$

$$\ell_n = \frac{a_{n-1}}{d_{n-1}}, \quad d_n = b_n - \ell_n u_{n-1}, \quad \text{for } i = n. \quad (10)$$

requiring  $2n$  multiplications and  $n$  additions. In other words, the total floating point operations involved in finding  $LU$  is  $3n$ .

We can then write  $A\mathbf{v} = LU\mathbf{v} = L\mathbf{y} = \tilde{\mathbf{b}}$  where  $\mathbf{y} \equiv U\mathbf{v}$ . Explicitly, we can write this as

$$L\mathbf{y} = \begin{pmatrix} 1 & 0 & \cdots & \cdots & \cdots & 0 \\ \ell_2 & 1 & \cdots & \cdots & \cdots & 0 \\ 0 & \ell_3 & 1 & \cdots & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & \ell_{n-1} & 1 & 0 \\ 0 & 0 & \cdots & \cdots & \ell_n & 1 \end{pmatrix} \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} = \begin{pmatrix} y_1 \\ \ell_2 y_1 + y_2 \\ \ell_3 y_2 + y_3 \\ \vdots \\ \ell_{n-1} y_{n-2} + y_{n-1} \\ \ell_n y_{n-1} + y_n \end{pmatrix} = \begin{pmatrix} \tilde{b}_1 \\ \tilde{b}_2 \\ \vdots \\ \tilde{b}_n \end{pmatrix} \quad (11)$$

which yields the following procedure:

$$y_1 = \tilde{b}_1, \quad (12)$$

$$y_i = \tilde{b}_i - \ell_i y_{i-1}, \quad \text{for } i = 2, 3, \dots, n. \quad (13)$$

giving  $n - 1$  multiplications and  $n - 1$  additions. Thus the added computational cost is  $2(n - 1)$ .

Finally, to determine  $\mathbf{v}$ , we perform back-substitution by solving  $U\mathbf{v} = \mathbf{y}$ . Writing it out explicitly yields

$$\begin{pmatrix} d_1 & u_1 & \cdots & \cdots & \cdots & 0 \\ 0 & d_2 & u_2 & \cdots & \cdots & 0 \\ 0 & 0 & d_3 & u_3 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & \cdots & d_{n-1} & u_{n-1} \\ 0 & 0 & \cdots & \cdots & 0 & d_n \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{pmatrix} = \begin{pmatrix} d_1 v_1 + u_1 v_2 \\ d_2 v_2 + u_2 v_3 \\ \vdots \\ d_{n-1} v_{n-1} + u_{n-1} v_n \\ d_n v_n \end{pmatrix} = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_{n-1} \\ y_n \end{pmatrix}, \quad (14)$$

which yields the following procedure:

$$v_n = \frac{y_n}{d_n}, \quad (15)$$

$$v_i = \frac{y_i - u_i v_{i+1}}{d_i}, \quad \text{for } i = n - 1, n - 2, \dots, 1. \quad (16)$$

Here we got  $2n - 1$  multiplications and  $n - 1$  additions, so the number of floating point operations are  $3n - 2$ . Putting all of these together we get  $4(2n - 1) \approx 8n$  floating point operations.

Now, assuming that  $b_1 = b_2 = \cdots = b_n$  and  $a_1 = c_1, a_2 = c_2, \dots, a_{n-1} = c_{n-1}$ , we can simplify the relations for the LU-decomposition as

$$d_1 = b_1, \quad u_1 = c_1, \quad (17)$$

$$u_i = c_i = c_1, \quad \text{for } 1 < i \leq n, \quad (18)$$

$$\ell_i = \frac{a_{i-1}}{d_{i-1}} = \frac{a_1}{d_{i-1}}, \quad \text{for } 1 < i \leq n, \quad (19)$$

$$d_i = b_i - \ell_i u_i = b_1 - \ell_i u_1 \quad \text{for } 1 < i \leq n, \quad (20)$$