

Computational Fluid Dynamics  
SG2212 Project Report

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## Question 1

The kronecker operator (**kron**) is an operator for tensor product, which falls convinient when doing finite differences in higher dimensions than the 1D case. As we study the 2D case in this lid-driven cavity project the 5 point stencil is considered:

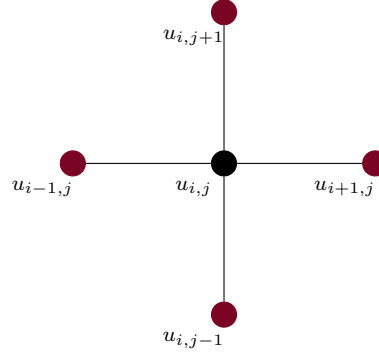


Figure 1: The five point stencil in 2D.

If we construct a finite difference scheme for the laplace operator we get:

$$\nabla^2 u = \frac{u_{i+1,j} - 2u_{i,j} + u_{i-1,j}}{h_x^2} + \frac{u_{i,j+1} - 2u_{i,j} + u_{i,j-1}}{h_y^2} \quad (1)$$

$$\left\{ \text{and if } h_x = h_y = h \implies \frac{u_{i+1,j} + u_{i-1,j} - 4u_{i,j} + u_{i,j+1} + u_{i,j-1}}{h^2} \right\} \quad (2)$$

The above expression we can transform into a vector form in size  $(N_x, N_y) \mapsto N_x \cdot N_y$ , using the indexing that one step in  $y$ -direction is equivalent to one row in the matrix *i.e.*  $+N_x$  steps.

We can now define the second partial derivative in the separate directions:

$$S_x = \frac{1}{h_x^2} \begin{bmatrix} -1 & 1 & & & \\ 1 & -2 & 1 & & \\ & 1 & -2 & \ddots & \\ & & \ddots & \ddots & \\ & & & 1 & -1 \end{bmatrix} \quad S_y = \frac{1}{h_y^2} \begin{bmatrix} -1 & 1 & & & \\ 1 & -2 & 1 & & \\ & 1 & -2 & \ddots & \\ & & \ddots & \ddots & \\ & & & 1 & -1 \end{bmatrix}$$

Forming a matrix by the size  $(N_x \cdot N_y) \times (N_x \cdot N_y)$  is now done by the kronecker product.

The operation done by the kronecker product essentially does the following in this case. Consider the identity matrix in the shape  $N_y \times N_y$  ( $I_y$ ), and the  $S_x$  from above. We get:

$$\text{kron}(I_y, S_x) = I_y \otimes S_x = \begin{bmatrix} [S_x] & 0 & \dots & \\ 0 & [S_x] & 0 & \dots \\ \vdots & & \ddots & \\ & & & [S_x] \end{bmatrix} \quad \text{shape is } (N_y \cdot N_x) \times (N_y \cdot N_x)$$

and for the other term in the sum of kronecker products we have:

$$S_y \otimes I_x = \begin{bmatrix} S_y^{1,1}[I_x] & 0 & \dots & \\ 0 & S_y^{2,2}[I_x] & 0 & \dots \\ \vdots & & \ddots & \\ & & & S_y^{N_y, N_y}[I_x] \end{bmatrix} \quad \text{shape is } (N_y \cdot N_x) \times (N_y \cdot N_x)$$

We can then see that in the simplified example where  $N_x = N_y = N$  and  $h_x = h_y = h = 1$ , and no specific boundaries are set, we get:

$$I_y \otimes S_x + S_y \otimes I_x = \begin{bmatrix} -4 & 1 & \dots & 1 & \dots & \\ 1 & -4 & 1 & \dots & 1 & \dots \\ 0 & \ddots & \ddots & \ddots & & \\ & & & 1 & \dots & 1 & -4 \end{bmatrix} \quad (3)$$

which describes the case stated in Equation 2. Note that the 1's in matrix in Equation 3 are  $N_x$  values apart, with zero-values in between.

## Question 2

Experimental stability condition for  $\Delta t$  (with parameters  $N_x = N_y = 30$ ,  $L_y = L_x = 1$  and  $Re = 25$ ) was empirically found to be

$$\Delta t_{\max} \approx 0.006971$$

when integrated up to  $T = 50$ .

## Question 3

## Question 4

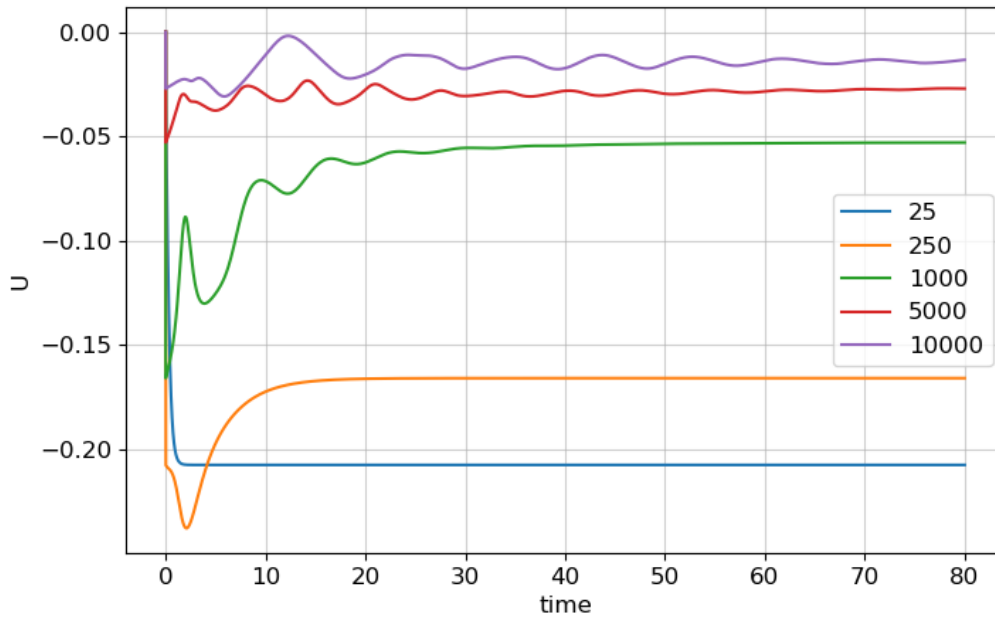


Figure 2:  $U$  in middle of domain for different  $Re$ -values

Question 5

Question 6

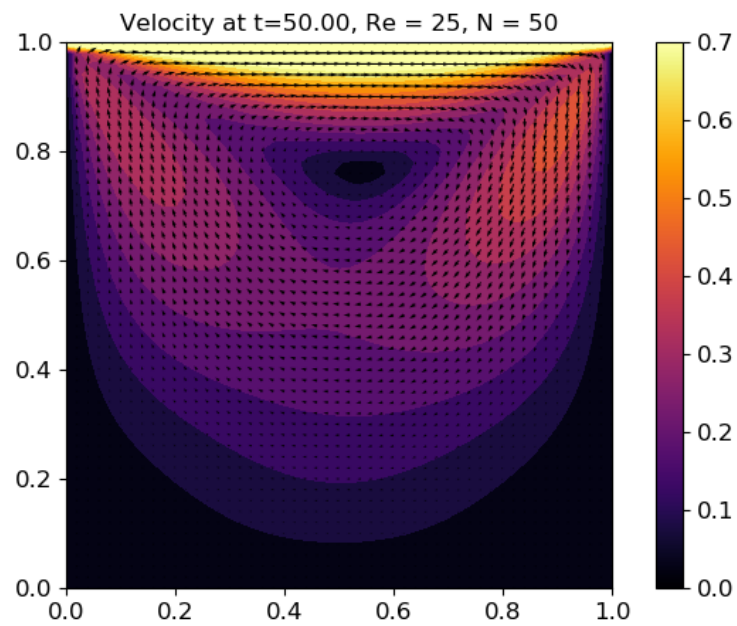


Figure 3: Case A

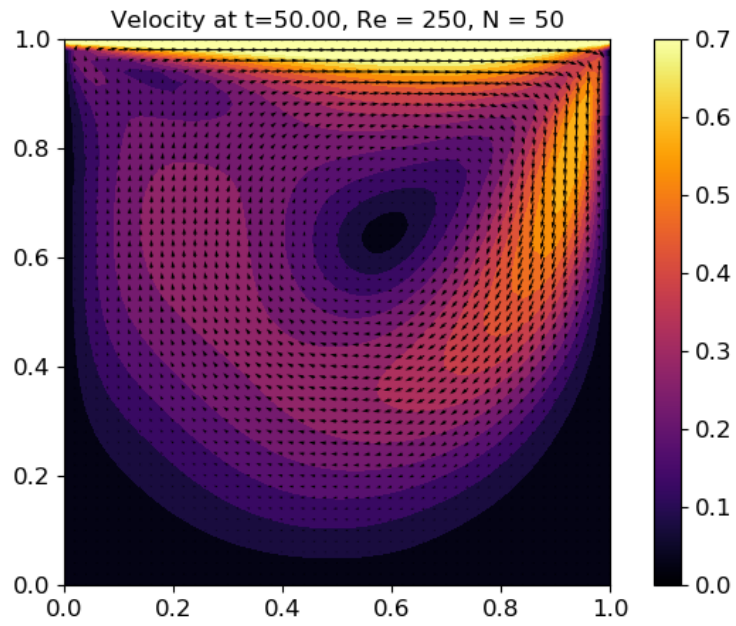


Figure 4: Case B

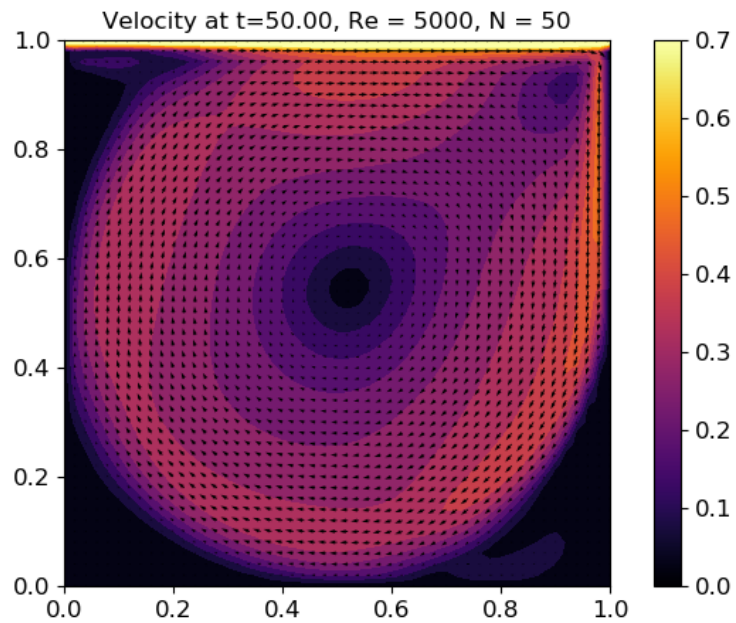


Figure 5: Case C

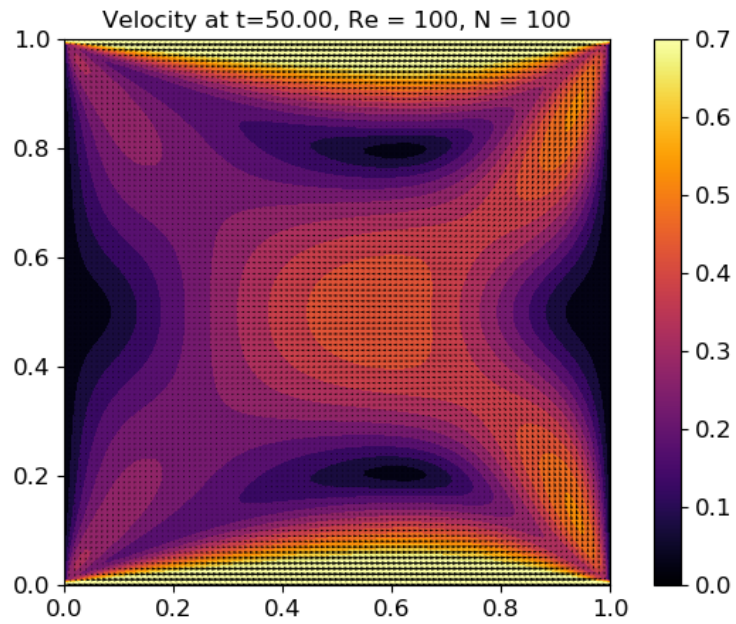
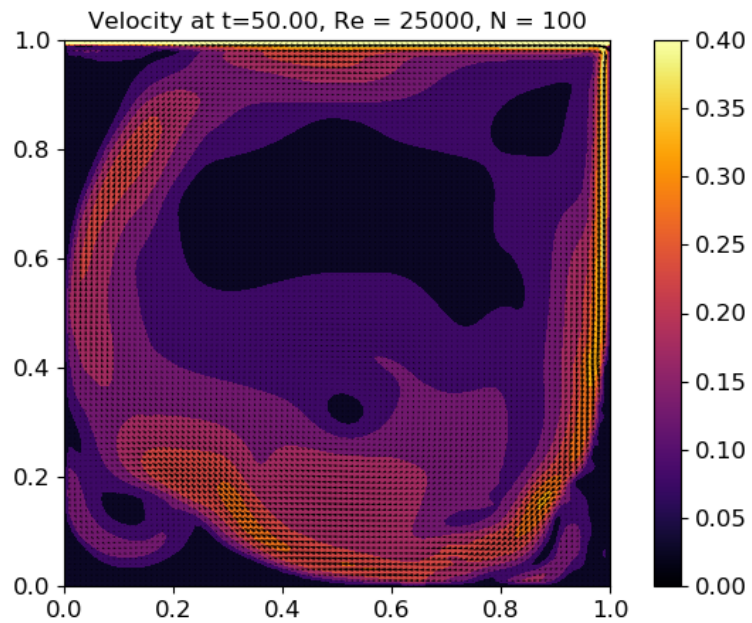


Figure 6: Case D

Figure 7: Bonus case with even higher  $Re$