



Four Fundamental Subspaces

Quiz



1) Obtain P , L , U matrices from A , using $PA = LU$ factorization.

$$A = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 5 & 6 & 7 & 8 \\ 9 & 10 & 11 & 12 \end{bmatrix} \quad (1)$$

$$A = \begin{bmatrix} 1 & 4 & 0 & 0 \\ 3 & 12 & 1 & 5 \\ 2 & 8 & 1 & 5 \\ 0 & 2 & 2 & 3 \end{bmatrix} \quad (2)$$

2) For

$$\begin{bmatrix} 1 & 2 & 3 & 5 \\ 2 & 4 & 8 & 12 \\ 3 & 6 & 7 & 13 \end{bmatrix} x = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}$$

for 5th point

$$Ax = [0, 6, -6]$$

1. Reduce $Ax = b$ to $Ux = c$, to reach a triangular system.
2. Find the condition on b_1, b_2, b_3 to have a solution.
3. Describe the column space of A . Find the basis of the column space.
4. Describe the nullspace of A . Declare free variables.
5. Find a particular solution and the complete solution $x_p + x_n$

Quiz

Answers (1)



$$P = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad A = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 5 & 6 & 7 & 8 \\ 9 & 10 & 11 & 12 \end{bmatrix} \quad L = \begin{bmatrix} 1 & 0 & 0 \\ 5 & 1 & 0 \\ 9 & 2 & 1 \end{bmatrix} \quad U = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 0 & -4 & -8 & -12 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (1)$$

$$P = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \quad A = \begin{bmatrix} 1 & 4 & 0 & 0 \\ 3 & 12 & 1 & 5 \\ 2 & 8 & 1 & 5 \\ 0 & 2 & 2 & 3 \end{bmatrix} \quad L = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ \frac{2}{3} & 0 & 1 & 0 \\ \frac{1}{3} & 0 & -1 & 1 \end{bmatrix} \quad U = \begin{bmatrix} 3 & 12 & 1 & 5 \\ 0 & 2 & 2 & 3 \\ 0 & 0 & \frac{1}{3} & \frac{5}{3} \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (2)$$

Quiz

Answers (2)



1. The multipliers in elimination are 2 and 3 and -1 , taking $[A \ b]$ to $[U \ c]$.

$$\left[\begin{array}{cccc|c} 1 & 2 & 3 & 5 & b_1 \\ 2 & 4 & 8 & 12 & b_2 \\ 3 & 6 & 7 & 13 & b_3 \end{array} \right] \rightarrow \left[\begin{array}{cccc|c} 1 & 2 & 3 & 5 & b_1 \\ 0 & 0 & 2 & 2 & b_2 - 2b_1 \\ 0 & 0 & -2 & -2 & b_3 - 3b_1 \end{array} \right] \rightarrow \left[\begin{array}{cccc|c} 1 & 2 & 3 & 5 & b_1 \\ 0 & 0 & 2 & 2 & b_2 - 2b_1 \\ 0 & 0 & 0 & 0 & b_3 + b_2 - 5b_1 \end{array} \right].$$

2. The last equation shows the solvability condition $b_3 + b_2 - 5b_1 = 0$. Then $0 = 0$.
3. The column space of A is the plane containing all combinations of the pivot columns $(1, 2, 3)$ and $(3, 8, 7)$.

Second description: The column space contains all vectors with $b_3 + b_2 - 5b_1 = 0$. That makes $Ax = b$ solvable, so b is in the column space. *All columns of A pass this test $b_3 + b_2 - 5b_1 = 0$. This is the equation for the plane (in the first description of the column space).*

Quiz

Answers (3)



4. The special solutions in N have free variables $x_2 = 1, x_4 = 0$ and $x_2 = 0, x_4 = 1$:

Nullspace matrix

Special solutions to $Ax = 0$

Back-substitution in $Ux = 0$

Just switch signs in $Rx = 0$

$$N = \begin{bmatrix} -2 & -2 \\ 1 & 0 \\ 0 & -1 \\ 0 & 1 \end{bmatrix}.$$

5. Choose $b = (0, 6, -6)$, which has $b_3 + b_2 - 5b_1 = 0$. Elimination takes $Ax = b$ to $Ux = c = (0, 6, 0)$. Back-substitute with free variables = 0:

$$\text{Particular solution to } Ax_p = (0, 6, -6) \quad x_p = \begin{bmatrix} -9 \\ 0 \\ 3 \\ 0 \end{bmatrix} \begin{matrix} \text{free} \\ \\ \text{free} \end{matrix}$$

The complete solution to $Ax = (0, 6, -6)$ is (this x_p) + (all x_n).

Reference material



- Lecture 9 and 10
- "*Linear Algebra and Applications*", pdf pages 139–149
The application of four fundamental subspaces in CS
- [Matrix Transpose and the Four Fundamental Subspaces](#)
Video is about how A transpose appeared
- [Matrix online calculator](#)(russian)

Problem 1

Show that v_1, v_2, v_3 are independent but v_1, v_2, v_3, v_4 are dependent:

$$v_1 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad v_2 = \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} \quad v_3 = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \quad v_4 = \begin{bmatrix} 2 \\ 3 \\ 4 \end{bmatrix}.$$

Solve $c_1 v_1 + \cdots + c_4 v_4 = 0$ or $Ac = 0$. The v 's go in the columns of A .

Problem 1 (sol.)

Let $c_1 v_1 + c_2 v_2 + c_3 v_3 = 0$

$$\Rightarrow c_1 \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} + c_2 \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} + c_3 \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\Rightarrow \begin{bmatrix} c_1 + c_2 + c_3 \\ c_2 + c_3 \\ c_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

i.e. $c_3 = 0$

Plug this in the following equation.

$$c_2 + c_3 = 0$$

$$\Rightarrow c_2 = 0$$

Plug these values in the following equation.

$$c_1 + c_2 + c_3 = 0$$

$$\Rightarrow c_1 = 0$$

Therefore, $\boxed{c_1 = c_2 = c_3 = 0}$

Problem 1 (sol.)

Now,

$$\text{let } c_1 v_1 + c_2 v_2 + c_3 v_3 + c_4 v_4 = 0$$

$$\Rightarrow c_1 \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} + c_2 \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} + c_3 \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} + c_4 \begin{bmatrix} 2 \\ 3 \\ 4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\Rightarrow \begin{bmatrix} c_1 + c_2 + c_3 + 2c_4 \\ c_2 + c_3 + 3c_4 \\ c_3 + 4c_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\text{i.e. } c_3 + 4c_4 = 0$$

$$\Rightarrow c_3 = -4c_4$$

Plug this value in the following equation.

$$c_2 + c_3 + 3c_4 = 0$$

$$c_2 = -c_3 - 3c_4$$

$$= +4c_4 - 3c_4$$

$$= c_4$$

Plug this value in the following equation.

$$c_1 + c_2 + c_3 + 2c_4$$

$$c_1 = -c_2 - c_3 - 2c_4$$

$$= -c_4 + 4c_4 - 2c_4$$

$$c_1 = c_4$$

If $c_4 = 1$, then $c_1 = 1, c_2 = 1, c_3 = -4$

$$v_1 + v_2 - 4v_3 + v_4 = 0$$

Therefore, $\boxed{v_1 + v_2 - 4v_3 + v_4 = 0}$

$\Rightarrow v_1, v_2, v_3, v_4$ are linearly dependent

Problem 2

Find the largest possible number of independent vectors among

$$v_1 = \begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \end{bmatrix} \quad v_2 = \begin{bmatrix} 1 \\ 0 \\ -1 \\ 0 \end{bmatrix} \quad v_3 = \begin{bmatrix} 1 \\ 0 \\ 0 \\ -1 \end{bmatrix} \quad v_4 = \begin{bmatrix} 0 \\ 1 \\ -1 \\ 0 \end{bmatrix} \quad v_5 = \begin{bmatrix} 0 \\ 1 \\ 0 \\ -1 \end{bmatrix} \quad v_6 = \begin{bmatrix} 0 \\ 0 \\ 1 \\ -1 \end{bmatrix}.$$

This number is the _____ of the space spanned by the v 's.

Problem 2 (sol.)

Let,

$$c_1 v_1 + c_2 v_2 + c_3 v_3 + c_4 v_4 = 0$$

This implies;

$$c_1 \begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \end{bmatrix} + c_2 \begin{bmatrix} 1 \\ 0 \\ -1 \\ 0 \end{bmatrix} + c_3 \begin{bmatrix} 1 \\ 0 \\ 0 \\ -1 \end{bmatrix} + c_4 \begin{bmatrix} 0 \\ 1 \\ -1 \\ 0 \end{bmatrix} = 0$$

$$\begin{bmatrix} c_1 + c_2 + c_3 \\ -c_1 + c_4 \\ -c_2 - c_4 \\ -c_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

That is;

$$c_1 + c_2 + c_3 = 0$$

$$-c_1 = 0$$

$$-c_2 = 0$$

$$-c_3 = 0$$

This implies,

$$c_1 + c_2 + c_3 = 0$$

$$-c_1 + c_4 = 0$$

$$-c_2 - c_4 = 0$$

$$-c_4 = 0$$

Thus,

$$c_4 = 0$$

$$c_2 = 0$$

$$c_1 = 0$$

$$c_3 = 0$$

Therefore, v_1, v_2, v_3, v_4 are linearly independent.

Therefore, v_1, v_2, v_3 are linearly independent.

Problem 2 (sol.)

Now,

Let $c_1 v_1 + c_2 v_2 + c_3 v_3 + c_4 v_4 + c_5 v_5 = 0$

$$c_1 \begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \end{bmatrix} + c_2 \begin{bmatrix} 1 \\ 0 \\ -1 \\ 0 \end{bmatrix} + c_3 \begin{bmatrix} 1 \\ 0 \\ 0 \\ -1 \end{bmatrix} + c_4 \begin{bmatrix} 0 \\ 1 \\ -1 \\ 0 \end{bmatrix} + c_5 \begin{bmatrix} 0 \\ 1 \\ 0 \\ -1 \end{bmatrix} = 0$$
$$\begin{bmatrix} c_1 + c_2 + c_3 \\ -c_1 + c_4 + c_5 \\ -c_2 - c_4 \\ -c_3 - c_5 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

That is;

$$c_1 + c_2 + c_3 = 0$$

$$-c_1 + c_4 + c_5 = 0$$

$$-c_2 - c_4 = 0$$

$$-c_3 - c_5 = 0$$

This implies,

$$c_3 = -c_5$$

$$c_2 = -c_4$$

$$c_1 = -c_2 - c_3$$

$$= c_4 + c_5$$

Thus,

$$(c_4 + c_5)v_1 + (-c_4)v_2 + (-c_5)v_3 + c_4 v_4 + c_5 v_5 = 0$$

Therefore v_1, v_2, v_3, v_4, v_5 are linearly dependent.

Similarly, $v_1, v_2, v_3, v_4, v_5, v_6$ are linearly dependent. Here the largest possible number is 4 of independent vectors. This number four of the space spanned by v 's is the dimension of the space spanned by the v 's.

Therefore, This number four of the space spanned by v 's

Problem 4

If w_1, w_2, w_3 are independent vectors, show that the differences $v_1 = w_2 - w_3$, $v_2 = w_1 - w_3$, and $v_3 = w_1 - w_2$ are *dependent*. Find a combination of the v 's that gives zero.

Problem 4 (sol.)

$$\text{Let } c_1 v_1 + c_2 v_2 + c_3 v_3 = 0$$

$$\Rightarrow c_1 (w_2 - w_3) + c_2 (w_1 - w_3) + c_3 (w_1 - w_2) = 0$$

$$\Rightarrow (c_2 + c_3) w_1 + (c_1 - c_3) w_2 + (-c_1 - c_2) w_3 = 0$$

So,

$$\Rightarrow c_2 + c_3 = 0$$

$$c_1 - c_3 = 0$$

$$-c_1 - c_2 = 0 \quad (\text{since } w_1, w_2, w_3 \text{ are linearly independent})$$

But,

$$-c_1 - c_2 = 0$$

$$\Rightarrow c_1 = -c_2$$

And,

$$c_1 - c_3 = 0$$

$$\Rightarrow c_3 = c_1$$

Therefore, $c_3 = c_1 = -c_2$

So,

$$c_1 v_1 + c_2 v_2 + c_3 v_3 = 0$$

$$c_1 v_1 - c_1 v_2 + c_1 v_3 = 0$$

Let $c_1 = 1, v_1 - v_2 + v_3 = 0$, therefore v_1, v_2, v_3 are linear dependent

Therefore, the sum $\boxed{v_1 - v_2 + v_3 = 0}$

Problem 6

To decide whether b is in the subspace spanned by w_1, \dots, w_n , let the vectors w be the columns of A and try to solve $Ax = b$. What is the result for

- (a) $w_1 = (1, 1, 0)$, $w_2 = (2, 2, 1)$, $w_3 = (0, 0, 2)$, $b = (3, 4, 5)$?
- (b) $w_1 = (1, 2, 0)$, $w_2 = (2, 5, 0)$, $w_3 = (0, 0, 2)$, $w_4 = (0, 0, 0)$, and any b ?

Problem 6 (sol.)

(a) Suppose the vectors w be the columns of A and consider $w_1 = (1, 1, 0)$, $w_2 = (2, 2, 1)$, $w_3 = (0, 0, 2)$, and $b = (3, 4, 5)$.

So we have,

$$Ax = b$$

$$\begin{bmatrix} 1 & 2 & 0 \\ 1 & 2 & 0 \\ 0 & 1 & 2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 3 \\ 4 \\ 5 \end{bmatrix}$$

To solve for $Ax = b$, use Gaussian elimination.

$$\left[\begin{array}{ccc|c} 1 & 2 & 0 & 3 \\ 1 & 2 & 0 & 4 \\ 0 & 1 & 2 & 5 \end{array} \right]$$

By using $R_2 \rightarrow R_2 - R_1$, we get:

$$\left[\begin{array}{ccc|c} 1 & 2 & 0 & 3 \\ 0 & 0 & 0 & 1 \\ 0 & 1 & 2 & 5 \end{array} \right]$$

Second row represents the equation,

$$0x_1 + 0x_2 + 0x_3 = 1$$

By solving the equation $0x_1 + 0x_2 + 0x_3 = 1$, we get

$$0 = 1$$

As we know $0 \neq 1$, therefore, $Ax = b$ has **no solution** and b **is not in it**.

Problem 6 (sol.)

(b) Suppose the vectors w be the columns of A and consider $w_1 = (1, 2, 0)$, $w_2 = (2, 5, 1)$,
 $w_3 = (0, 0, 2)$, and $w_4 = (0, 0, 0)$.

We know that the system of equation $Ax = b$ has a solution if and only if the vector b can be expressed as a combination of the columns of A . Then b is in the column space.

Let

$$A = \begin{bmatrix} 1 & 2 & 0 & 0 \\ 2 & 5 & 0 & 0 \\ 0 & 0 & 2 & 0 \end{bmatrix}$$

And

$$b = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}$$

To solve $Ax = b$, use Gaussian elimination.

$$\left[\begin{array}{cccc|c} 1 & 2 & 0 & 0 & b_1 \\ 2 & 5 & 0 & 0 & b_2 \\ 0 & 0 & 2 & 0 & b_3 \end{array} \right] \rightarrow \left[\begin{array}{cccc|c} 1 & 0 & 0 & 0 & 5b_1 - 2b_2 \\ 0 & 1 & 0 & 0 & b_2 - 2b_1 \\ 0 & 0 & 1 & 0 & b_3/2 \end{array} \right]$$

Therefore, yes there is a b in it.

Problem 8

U comes from A by subtracting row 1 from row 3:

$$A = \begin{bmatrix} 1 & 3 & 2 \\ 0 & 1 & 1 \\ 1 & 3 & 2 \end{bmatrix} \quad \text{and} \quad U = \begin{bmatrix} 1 & 3 & 2 \\ 0 & 1 & 1 \\ 0 & 0 & 0 \end{bmatrix}.$$

Find bases for the two column spaces. Find bases for the two row spaces. Find bases for the two nullspaces.

Problem 8 (sol.)

Consider the matrices,

$$A = \begin{bmatrix} 1 & 3 & 2 \\ 0 & 1 & 1 \\ 1 & 3 & 2 \end{bmatrix} \text{ and } U = \begin{bmatrix} 1 & 3 & 2 \\ 0 & 1 & 1 \\ 0 & 0 & 0 \end{bmatrix}.$$

Here, the matrix U is obtained from A by subtracting row 1 from row 3.

The objective is to find the bases for the column spaces of A and U , the bases for the row spaces of A and U and the bases for the null spaces of A and U .

Reduce the matrix A to the reduced row echelon form.

$$\begin{aligned} & \begin{bmatrix} 1 & 3 & 2 \\ 0 & 1 & 1 \\ 1 & 3 & 2 \end{bmatrix} \\ \xrightarrow{R_3 - R_1} & \begin{bmatrix} 1 & 3 & 2 \\ 0 & 1 & 1 \\ 0 & 0 & 0 \end{bmatrix} \\ \xrightarrow{R_1 - 3R_2} & \begin{bmatrix} 1 & 0 & -1 \\ 0 & 1 & 1 \\ 0 & 0 & 0 \end{bmatrix} \end{aligned}$$

Problem 8 (sol.)

$$\begin{bmatrix} 1 & 3 & 2 \\ 0 & 1 & 1 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\xrightarrow{R_1 - 3R_2} \begin{bmatrix} 1 & 0 & -1 \\ 0 & 1 & 1 \\ 0 & 0 & 0 \end{bmatrix}$$

The reduced row echelon forms of the matrices A and U represent the same matrix

$$\begin{bmatrix} 1 & 0 & -1 \\ 0 & 1 & 1 \\ 0 & 0 & 0 \end{bmatrix}.$$

Observe that the pivot positions in the reduced row echelon form of the matrix A are in the first and second columns.

Therefore, the corresponding columns in the matrix A form a basis for the column space of A .

Hence, the basis for the column space of the matrix A is $\left\{ \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 3 \\ 1 \\ 3 \end{bmatrix} \right\}.$

The pivot positions in the matrix U are in the first and second columns. Therefore, the corresponding columns in the matrix U form a basis for the column space of U .

Therefore, the basis for the column space of the matrix U is $\left\{ \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 3 \\ 1 \\ 0 \end{bmatrix} \right\}.$

Problem 8 (sol.)

Observe that the pivot positions in the reduced row echelon form of the matrix A are in the first and second rows.

Therefore, the basis for the row space of the matrix A is $\boxed{\{(1, 0, -1), (0, 1, 1)\}}$.

The pivot positions in the reduced row echelon form of the matrix U are in the first and second rows.

Therefore, the basis for the row space of the matrix U is $\boxed{\{(1, 0, -1), (0, 1, 1)\}}$.

Problem 8 (sol.)

Now find the bases for the null spaces of the A and U .

From the first and second rows of the reduced row echelon form, the obtained equations are,

$$x_1 - x_3 = 0 \text{ and } x_2 + x_3 = 0.$$

Here, x_3 is a free variable.

So choose $x_3 = t$, where t is a parameter.

Then $x_1 = t$, $x_2 = -t$.

Therefore, the vector $\mathbf{x} = (x_1, x_2, x_3)$ can be written as,

$$\begin{aligned}\mathbf{x} &= (x_1, x_2, x_3) \\ &= (t, -t, t) \\ &= t(1, -1, 1)\end{aligned}$$

Hence, the basis for the null spaces of the matrices A and U is $\boxed{\{(1, -1, 1)\}}$.

Problem 9

Find the dimension and a basis for the four fundamental subspaces for

$$A = \begin{bmatrix} 1 & 2 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 2 & 0 & 1 \end{bmatrix} \quad \text{and} \quad U = \begin{bmatrix} 1 & 2 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}.$$

Problem 9 (sol.)

Consider the matrix:

$$A = \begin{bmatrix} 1 & 2 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 2 & 0 & 1 \end{bmatrix}$$

Reduce the matrix by taking the elementary operations to form matrix U .

$$A = \begin{bmatrix} 1 & 2 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 2 & 0 & 1 \end{bmatrix}$$

$$\begin{matrix} R_3 - R_1 \\ \vdots \end{matrix} \begin{bmatrix} 1 & 2 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} = U$$

$$\begin{matrix} R_1 - 2R_2 \\ \vdots \end{matrix} \begin{bmatrix} 1 & 0 & -2 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Here, columns 1, 2 are pivot columns.

Therefore, columns space of $A = \left\{ s \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} + t \begin{bmatrix} 2 \\ 1 \\ 2 \end{bmatrix} / s, t \in \mathbb{R} \right\}$.

And $\left\{ \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 2 \\ 1 \\ 2 \end{bmatrix} \right\}$ is basis for column space of A .

Dimension of columns space of A , $r = \boxed{2}$.

Problem 9 (sol.)

To calculate the dimension of null space of A ;

$$\begin{aligned} n-r &= 4-2 \\ &= 2 \end{aligned}$$

$$\text{The null space of } A = \left\{ \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} / a \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \right\}$$

$$\text{Now, } \begin{bmatrix} 1 & 2 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 2 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$x_1 + 2x_2 + x_4 = 0$$

$$x_2 + x_3 = 0$$

$$x_1 = -2x_2 - x_4$$

$$x_3 = -x_2$$

The null space of A is written as below:

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} -2x_2 - x_4 \\ x_2 \\ -x_2 \\ x_4 \end{bmatrix}$$

$$= x_2 \begin{bmatrix} -2 \\ 1 \\ -1 \\ 0 \end{bmatrix} + x_4 \begin{bmatrix} -1 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

Hence, the null space of A ;

$$\text{Null space of } A = \left\{ s \begin{bmatrix} -2 \\ 1 \\ -1 \\ 0 \end{bmatrix} + t \begin{bmatrix} -1 \\ 0 \\ 0 \\ 1 \end{bmatrix} / s, t \in R \right\}$$

$$\text{Here } \left\{ \begin{bmatrix} -2 \\ 1 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} -1 \\ 0 \\ 0 \\ 1 \end{bmatrix} \right\} \text{ is a basis for null space of } A.$$

$$\dim \text{Null } A = \dim \text{null } U = 2$$

Here 1, 2 columns are pivot columns of U .

$$\text{Column space of } U = \left\{ s \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} + t \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} / s, t \in R \right\}$$

$$\text{And } \left\{ \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \right\} \text{ is a basis for } U.$$

$$\text{Dimension of columns space of } U = \boxed{2}$$

Problem 9 (sol.)

To calculate the dimension of null space of U ;

$$n-r=4-2$$

$$=2$$

The null space of $U = \left\{ \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} / a \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \right\}$

Now, $\begin{bmatrix} 1 & 0 & -2 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$

$$x_1 - 2x_3 + x_4 = 0$$

$$x_2 + x_3 = 0$$

$$x_1 = 2x_3 - x_4$$

$$x_2 = -x_3$$

The null space of U is written as below:

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} 2x_3 - x_4 \\ -x_3 \\ x_3 \\ x_4 \end{bmatrix}$$

$$= x_3 \begin{bmatrix} 2 \\ -1 \\ 1 \\ 0 \end{bmatrix} + x_4 \begin{bmatrix} -1 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

Here $\left\{ \begin{bmatrix} 2 \\ -1 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} -1 \\ 0 \\ 0 \\ 1 \end{bmatrix} \right\}$ is a basis for null space of U

Now, to find the transpose of matrix A .

Transpose matrix is obtained to interchange the rows and columns.

$$A^T = \begin{bmatrix} 1 & 0 & 1 \\ 2 & 1 & 2 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix} \xrightarrow{R_1 \leftrightarrow R_3} \begin{bmatrix} 1 & 0 & 1 \\ 2 & 1 & 2 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\xrightarrow{R_2 - 2R_1} \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\xrightarrow{R_3 - R_2} \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Problem 9 (sol.)

Therefore, 1, 2 columns are pivots.

$$\text{Columns space of } A^T = \left\{ r \begin{bmatrix} 1 \\ 2 \\ 0 \\ 1 \end{bmatrix} + s \begin{bmatrix} 0 \\ 1 \\ 1 \\ 0 \end{bmatrix} / r, s \in R \right\}$$

$$\text{Row space of } A^T = \{ r(1, 2, 0, 1) + s(0, 1, 1, 0) / r, s \in R \}$$

$$\text{The basis for row space of } A^T = \boxed{\{(1, 2, 0, 1), (0, 1, 1, 0)\}} \text{ dimension of row space } r = \boxed{2}.$$

The dimension of null space of A^T ,

$$\begin{aligned} m - r &= 3 - 2 \\ &= 1 \end{aligned}$$

To find null space of A^T ,

$$\begin{bmatrix} 1 & 0 & 1 \\ 2 & 1 & 2 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

Perform the elementary row operations.

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

$$x_1 + x_3 = 0$$

$$x_2 = 0$$

$$x_1 = -x_3$$

$$x_2 = 0$$

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

$$\text{Null space of } A^T = \left\{ x_3 \begin{bmatrix} -1 \\ 0 \\ 1 \end{bmatrix} / x_3 \in R \right\}$$

$$\text{The row space of } A = \{ x(-1, 0, 1) / x \in R \}$$

$$\text{Dimension of row space of } A^T = \boxed{1}.$$

$$\text{Here } \boxed{\{(-1, 0, 1)\}} \text{ is a basis for null space of } A^T.$$

Problem 9 (sol.)

Now, to find the transpose of matrix U .

$$U^T = \begin{bmatrix} 1 & 0 & 0 \\ 2 & 1 & 0 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

$$\begin{matrix} R_4 - R_1 \\ \vdots \end{matrix} \begin{bmatrix} 1 & 0 & 0 \\ 2 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\text{Null space of } U^T = \left\{ \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} / U^T \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \right\}$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 2 & 1 & 0 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$x_1 = 0$$

$$2x_1 + x_2 = 0$$

$$x_2 = 0$$

$$x_1 = 0, x_2 = 0$$

Hence,

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

$$\text{Null space of } U^T = \left\{ x_3 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} / x \in \mathbb{R} \right\}$$

$$\dim \text{ Null of } U^T = 1$$

1, 2 columns are independent.

$$\text{Column space of } U^T = \left\{ r \begin{bmatrix} 1 \\ 2 \\ 0 \\ 1 \end{bmatrix} + s \begin{bmatrix} 0 \\ 1 \\ 1 \\ 0 \end{bmatrix} / r, s \in \mathbb{R} \right\}$$

$$\text{Basis of columns space of } U^T = \left\{ \begin{bmatrix} 1 \\ 2 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 1 \\ 0 \end{bmatrix} \right\}$$

$$\text{Dimension of column space of } U^T = \underline{2}.$$

$$\text{Here } \left\{ \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right\} \text{ is a basis for null space of } U^T, \dim \text{ null } U^T = \underline{1}.$$

Deserve "A" grade!

– Oleg Bulichev

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📍 @Lupasic

🏢 Room 105 (Underground robotics lab)