

## ***Solution***      **Section 1.1 – Introduction to System of Linear Equations**

### ***Exercise***

Find a solution for  $x$ ,  $y$ ,  $z$  to the system of equations

$$\begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} 3e + 2\sqrt{2} + \pi \\ 6e + 5\sqrt{2} + 4\pi \\ 9e + 8\sqrt{2} + 7\pi \end{pmatrix}$$

### **Solution**

$$\begin{pmatrix} x + 2y + 3z \\ 4x + 5y + 6z \\ 7x + 8y + 9z \end{pmatrix} = \begin{pmatrix} 3e + 2\sqrt{2} + \pi \\ 6e + 5\sqrt{2} + 4\pi \\ 9e + 8\sqrt{2} + 7\pi \end{pmatrix}$$

$$\Rightarrow \begin{cases} x + 2y + 3z = \pi + 2\sqrt{2} + 3e \\ 4x + 5y + 6z = 4\pi + 5\sqrt{2} + 6e \\ 7x + 8y + 9z = 7\pi + 8\sqrt{2} + 9e \end{cases}$$

$$\text{Solution: } \underline{x = \pi \quad y = \sqrt{2} \quad z = e}$$

### ***Exercise***

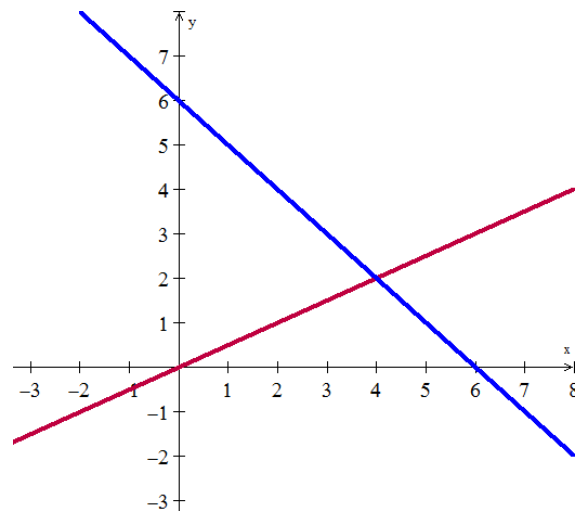
Draw the two pictures in two planes for the equations:  $x - 2y = 0$ ,     $x + y = 6$

### **Solution**

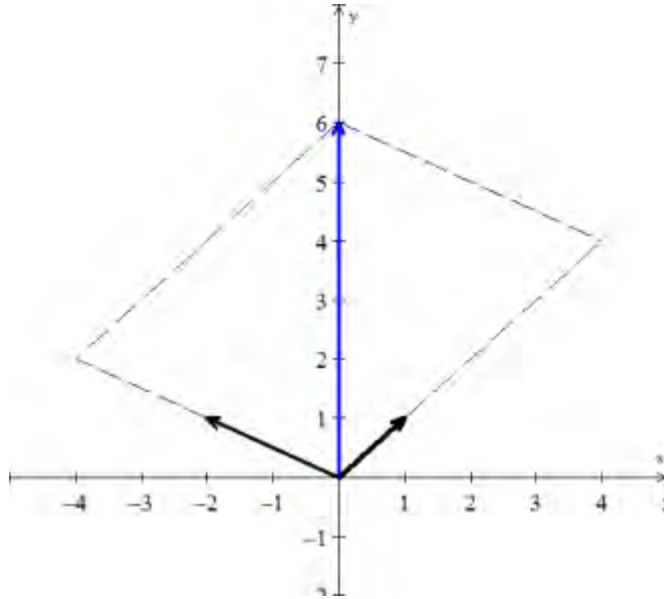
The matrix form of the 2 equations:

$$\begin{pmatrix} 1 & -2 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} 0 \\ 6 \end{pmatrix}$$

**Row picture** is the 2 lines from the given equations and their intersection is the point  $(4, 2)$  which is the solution for the system.



**Column Picture** is the column vectors  $\begin{pmatrix} 1 \\ 1 \end{pmatrix}$  and  $\begin{pmatrix} -2 \\ 1 \end{pmatrix}$



$$x \begin{pmatrix} 1 \\ 1 \end{pmatrix} + y \begin{pmatrix} -2 \\ 1 \end{pmatrix} = 4 \begin{pmatrix} 1 \\ 1 \end{pmatrix} + 2 \begin{pmatrix} -2 \\ 1 \end{pmatrix} = \begin{pmatrix} 0 \\ 6 \end{pmatrix}$$

The parallelogram shows how the solution vector  $\begin{pmatrix} 0 \\ 6 \end{pmatrix}$  can be written as the linear combination of the column vectors.

### ***Exercise***

Normally 4 planes in 4-dimensional space meet at a \_\_\_\_\_. Normally 4 column vectors in 4-dimensional space can combine to produce  $b$ . what combinations of

$\begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 \\ 1 \\ 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}$  produces  $b = \begin{pmatrix} 3 \\ 3 \\ 3 \\ 2 \end{pmatrix}$ ?

What 4 equations for  $x, y, z, w$  are you solving?

### **Solution**

Normally 4 planes in 4-dimensional space meet at a ***point***.

The combination of the vectors producing  $b$  is:

$$0 \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} + 0 \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix} + 1 \begin{pmatrix} 1 \\ 1 \\ 1 \\ 0 \end{pmatrix} + 2 \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 3 \\ 3 \\ 3 \\ 2 \end{pmatrix}$$

$$1 \begin{pmatrix} 1 \\ 1 \\ 1 \\ 0 \end{pmatrix} + 2 \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 3 \\ 3 \\ 3 \\ 2 \end{pmatrix}$$

The system of equations that satisfies the given vectors is:

$$\begin{cases} x + y + z + w = 3 \\ y + z + w = 3 \\ z + w = 3 \\ w = 2 \end{cases}$$

### Exercise

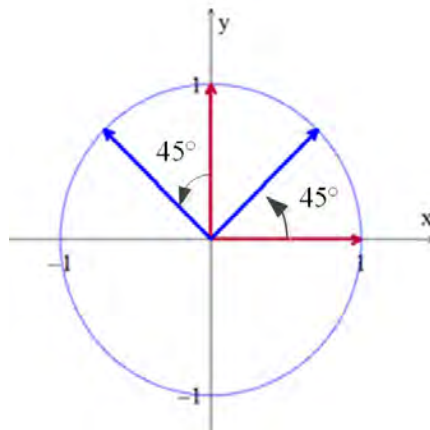
What 2 by 2 matrix  $A$  rotates every vector through  $45^\circ$  ?

The vector  $(1, 0)$  goes to  $\left(\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}\right)$ . The vector  $(0, 1)$  goes to  $\left(-\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}\right)$ .

Those determine the matrix. Draw these particular vectors in the  $xy$ -plane and find  $A$ .

### Solution

$$A = \begin{pmatrix} \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{pmatrix}$$



### Exercise

What two vectors are obtained by rotating the plane vectors  $\begin{bmatrix} 1 \\ 0 \end{bmatrix}$  and  $\begin{bmatrix} 0 \\ 1 \end{bmatrix}$  by  $30^\circ$  (cw) ?

Write a matrix  $A$  such that for every vector  $v$  in the plane,  $Av$  is the vector obtained by rotating  $v$  clockwise by  $30^\circ$ .

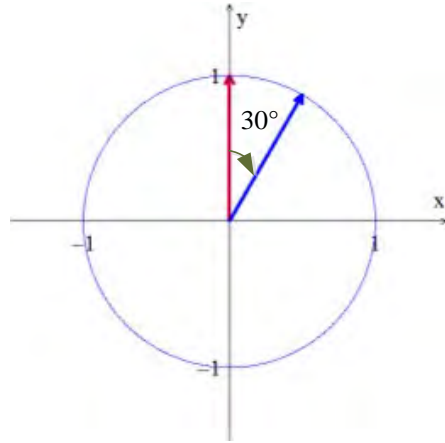
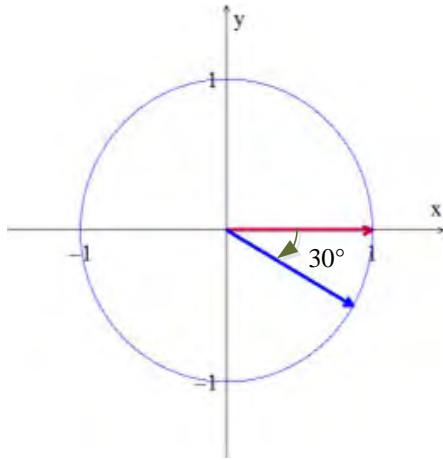
Find a matrix  $B$  such that for every 3-dimensional vector  $v$ , the vector  $Bv$  is the reflection of  $v$  through the plane  $x + y + z = 0$ . *Hint* :  $v = (1, 0, 0)$

### Solution

Rotating the vectors by  $30^\circ$  (cw) yields:

$$\text{For the vector } \begin{bmatrix} 1 \\ 0 \end{bmatrix} \text{ yields to } \begin{pmatrix} \cos(-30^\circ) \\ \sin(-30^\circ) \end{pmatrix} = \begin{pmatrix} \frac{\sqrt{3}}{2} \\ -\frac{1}{2} \end{pmatrix}$$

And for the vector  $\begin{bmatrix} 0 \\ 1 \end{bmatrix}$  yields to  $\begin{pmatrix} \sin(30^\circ) \\ \cos(30^\circ) \end{pmatrix} = \begin{pmatrix} \frac{1}{2} \\ \frac{\sqrt{3}}{2} \end{pmatrix}$



The desired matrix is:  $A = \begin{pmatrix} \frac{\sqrt{3}}{2} & \frac{1}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{pmatrix}$

To get 1 from  $\frac{\sqrt{3}}{2}$  is to multiply by  $\frac{2}{\sqrt{3}} = 2\frac{1}{\sqrt{3}}$

The unit vector to the plane  $x + y + z = 0$  is  $\hat{u} = \left( \frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}} \right)$

$$\begin{aligned} Bv &= B \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \\ &= \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} - \frac{2}{\sqrt{3}} \hat{u} \\ &= \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} - \frac{2}{\sqrt{3}} \begin{pmatrix} 1/\sqrt{3} \\ 1/\sqrt{3} \\ 1/\sqrt{3} \end{pmatrix} \\ &= \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} - \begin{pmatrix} \frac{2}{3} \\ \frac{2}{3} \\ \frac{2}{3} \end{pmatrix} \end{aligned}$$

$$\begin{aligned}
B \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} &= \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} - \frac{2}{\sqrt{3}} \hat{u} \\
&= \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} - \begin{pmatrix} \frac{2}{3} \\ \frac{2}{3} \\ \frac{2}{3} \end{pmatrix} \\
&= \begin{pmatrix} \frac{1}{3} \\ -\frac{2}{3} \\ -\frac{2}{3} \end{pmatrix}
\end{aligned}$$

$$\begin{aligned}
B \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} &= \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} - \frac{2}{\sqrt{3}} \hat{u} \\
&= \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} - \begin{pmatrix} \frac{2}{3} \\ \frac{2}{3} \\ \frac{2}{3} \end{pmatrix} \\
&= \begin{pmatrix} -\frac{2}{3} \\ \frac{1}{3} \\ -\frac{2}{3} \end{pmatrix} \\
&= \begin{pmatrix} -\frac{2}{3} \\ -\frac{2}{3} \\ \frac{1}{3} \end{pmatrix}
\end{aligned}$$

The solution:  $\begin{pmatrix} \frac{1}{3} & -\frac{2}{3} & -\frac{2}{3} \\ -\frac{2}{3} & \frac{1}{3} & -\frac{2}{3} \\ -\frac{2}{3} & -\frac{2}{3} & \frac{1}{3} \end{pmatrix}$

### ***Exercise***

Find a system of linear equation corresponding to the given augmented matrix

$$\begin{bmatrix} 0 & 3 & -1 & -1 & -1 \\ 5 & 2 & 0 & -3 & -6 \end{bmatrix}$$

### **Solution**

$$\begin{cases} 3x_2 - x_3 - x_4 = -1 \\ 5x_1 + 2x_2 - 3x_4 = -6 \end{cases}$$

### ***Exercise***

Find a system of linear equation corresponding to the given augmented matrix

$$\begin{bmatrix} 1 & 2 & 3 & 4 \\ -4 & -3 & -2 & -1 \\ 5 & -6 & 1 & 1 \\ -8 & 0 & 0 & 3 \end{bmatrix}$$

### **Solution**

$$\begin{cases} x_1 + 2x_2 + 3x_3 = 4 \\ -4x_1 - 3x_2 - 2x_3 = -1 \\ 5x_1 - 6x_2 + x_3 = 1 \\ -8x_1 = 3 \end{cases}$$

### ***Exercise***

Find the augmented matrix for the given system of linear equations.

$$\begin{cases} -2x_1 = 6 \\ 3x_1 = 8 \\ 9x_1 = -3 \end{cases}$$

### **Solution**

$$\left[ \begin{array}{c|c} -2 & 6 \\ 3 & 8 \\ 9 & -3 \end{array} \right]$$

***Exercise***

Find the augmented matrix for the given system of linear equations.

$$\begin{cases} 3x_1 - 2x_2 = -1 \\ 4x_1 + 5x_2 = 3 \\ 7x_1 + 3x_2 = 2 \end{cases}$$

***Solution***

$$\left[ \begin{array}{cc|c} 3 & -2 & -1 \\ 4 & 5 & 3 \\ 7 & 3 & 2 \end{array} \right]$$

***Exercise***

Find the augmented matrix for the given system of linear equations.

$$\begin{cases} 2x_1 + 2x_3 = 1 \\ 3x_1 - x_2 + 4x_3 = 7 \\ 6x_1 + x_2 - x_3 = 0 \end{cases}$$

***Solution***

$$\left[ \begin{array}{ccc|c} 2 & 0 & 2 & 1 \\ 3 & -1 & 4 & 7 \\ 6 & 1 & -1 & 0 \end{array} \right]$$

## ***Solution***      **Section 1.2 – Gaussian Elimination**

### ***Exercise***

When elimination is applied to the matrix  $A = \begin{bmatrix} 3 & 1 & 0 \\ 6 & 9 & 2 \\ 0 & 1 & 5 \end{bmatrix}$

- a) What are the first and second pivots?
- b) What is the multiplier  $l_{21}$  in the first step ( $l_{21}$  times row 1 is subtracted from row 2)?
- c) What entry in the 2, 2 position (instead of 9) would force an exchange of rows 2 and 3?
- d) What is the multiplier  $l_{31} = 0$ , subtracting 0 times row 1 from row 3?

### **Solution**

- a) The first pivot is 3 and when 2 times row 1 is subtracted from row 2, the second pivot is revealed as 7.

$$\begin{bmatrix} 3 & 1 & 0 \\ 6 & 9 & 2 \\ 0 & 1 & 5 \end{bmatrix} \begin{array}{l} \text{subtract 2 times row.1} \\ \text{from row.2} \end{array} \begin{bmatrix} 3 & 1 & 0 \\ 0 & \boxed{7} & 2 \\ 0 & 1 & 5 \end{bmatrix}$$

- b) The multiplier  $l_{21}$  in the first step is  $\frac{6}{3} = 2$ .
- c) If we reduce the entry 9 to 2, that drop of 7 in the  $a_{22}$  position would force a row exchange.

$$\begin{bmatrix} 3 & 1 & 0 \\ 6 & 9 & 2 \\ 0 & 1 & 5 \end{bmatrix} \begin{array}{l} \text{subtract 7 times row.1} \\ \text{from row.2} \end{array} \begin{bmatrix} 3 & 1 & 0 \\ -15 & \boxed{2} & 2 \\ 0 & 1 & 5 \end{bmatrix}$$

- d) The multiplier  $l_{31}$  is already zero because  $a_{31} = 0$  and no needs row elimination.

### ***Exercise***

Use elimination to reach upper triangular matrices  $U$ . Solve by back substitution or explain why this impossible. What are the pivots (never zero)? Exchange equations when necessary. The only difference is the  $-x$  in equation (3).

$$\begin{cases} x + y + z = 7 \\ x + y - z = 5 \\ x - y + z = 3 \end{cases} \quad \begin{cases} x + y + z = 7 \\ x + y - z = 5 \\ -x - y + z = 3 \end{cases}$$

### **Solution**

For the *first* system:



$$\begin{array}{lll}
 x + y + z = 7 & \text{subtract eqn.1} & x + y + z = 7 \\
 x + y - z = 5 & \text{from eqn.2} & 0y - 2z = -2 \\
 x - y + z = 3 & \text{from eqn.3} & -2y - 0z = -4
 \end{array}$$

$$\begin{array}{lll}
 x + y + z = 7 & & 1x + y + z = 7 \\
 x + y - z = 5 & \text{Exchange eqn.2} & -2y - 0z = -4 \\
 x - y + z = 3 & \text{and eqn.3} & -2z = -2
 \end{array}$$

The solutions are:  $z = 1$   $y = 2$   $x = 4$  and the pivots are 1, -2, -2.

For the *second* system:

$$\begin{array}{lll}
 x + y + z = 7 & \text{Subtract eqn.1} & x + y + z = 7 \\
 x + y - z = 5 & \text{from eqn.2} & 0y - 2z = -2 \\
 -x - y + z = 3 & \text{Add eqn.1} & 0y + 2z = 10 \\
 & \text{to eqn.3} &
 \end{array}$$

$$\begin{array}{lll}
 x + y + z = 7 & & x + y + z = 7 \\
 0y - 2z = -2 & \text{Add eqn.2} & 0y - 2z = -2 \\
 0y + 2z = 10 & \text{to eqn.3} & \boxed{0z = 8}
 \end{array}$$

The three planes don't meet. But if we change '3' in the last equation to '-5'

$$\begin{array}{lll}
 x + y + z = 7 & \text{Subtract eqn.1} & x + y + z = 7 \\
 x + y - z = 5 & \text{from eqn.2} & 0y - 2z = -2 \\
 -x - y + z = -5 & \text{Add eqn.1} & 0y + 2z = 2 \\
 & \text{to eqn.3} &
 \end{array}$$

$$\begin{array}{lll}
 x + y + z = 7 & x + y = 6 & \\
 0y - 2z = -2 & & \text{There are unique infinite many solutions!} \\
 0y + 2z = 10 & z = 1 &
 \end{array}$$

The three planes now meet along a whole line.

## Exercise

For which numbers  $a$  does the elimination break down (1) permanently (2) temporarily

$$\begin{array}{l}
 ax + 3y = -3 \\
 4x + 6y = 6
 \end{array}$$

Solve for  $x$  and  $y$  after fixing the second breakdown by a row change.

## Solution

The matrix form is:  $\begin{pmatrix} a & 3 \\ 4 & 6 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} -3 \\ 6 \end{pmatrix}$

If  $a = 0$ , the elimination brakes down temporarily.

$$\begin{pmatrix} 4 & 6 \\ 0 & \boxed{3} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} 6 \\ -3 \end{pmatrix}$$

The system is in upper triangular form and entry row 2 column 2 is not equal to zero, therefore the system has a solution.

If  $a \neq 0$ ,

$$\begin{pmatrix} a & 3 \\ 4 & 6 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} -3 \\ 6 \end{pmatrix} \quad R_2 - \frac{4}{a}R_1$$

$$\begin{pmatrix} a & 3 \\ 0 & 6 - \frac{12}{a} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} -3 \\ 6 + \frac{12}{a} \end{pmatrix}$$

$$6 - \frac{12}{a} = 0$$

$$\frac{12}{a} = 6$$

$$a = \frac{12}{6} = \underline{2}$$

If  $a = 2$ ,

$$\begin{pmatrix} 2 & 3 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} -3 \\ 12 \end{pmatrix}, \text{ the system will fail and has no solution.}$$

If  $a \neq 2$ ;

$$\begin{pmatrix} a & 3 \\ 0 & 6 - \frac{12}{a} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} -3 \\ 6 + \frac{12}{a} \end{pmatrix}, \text{ the system has a unique solution.}$$

### Exercise

Find the pivots and the solution for these four equations:

$$\begin{aligned}2x + y &= 0 \\x + 2y + z &= 0 \\y + 2z + t &= 0 \\z + 2t &= 5\end{aligned}$$

### Solution

$$\begin{pmatrix} 2 & 1 & 0 & 0 & 0 \\ 1 & 2 & 1 & 0 & 0 \\ 0 & 1 & 2 & 1 & 0 \\ 0 & 0 & 1 & 2 & 5 \end{pmatrix} R_2 - \frac{1}{2}R_1$$

$$\begin{pmatrix} 2 & 1 & 0 & 0 & 0 \\ 0 & 1.5 & 1 & 0 & 0 \\ 0 & 1 & 2 & 1 & 0 \\ 0 & 0 & 1 & 2 & 5 \end{pmatrix} R_3 - \frac{2}{3}R_2$$

$$\begin{pmatrix} 2 & 1 & 0 & 0 & 0 \\ 0 & \frac{3}{2} & 1 & 0 & 0 \\ 0 & 0 & \frac{4}{3} & 1 & 0 \\ 0 & 0 & 1 & 2 & 5 \end{pmatrix} R_4 - \frac{3}{4}R_3$$

$$\begin{pmatrix} 2 & 1 & 0 & 0 & 0 \\ 0 & \frac{3}{2} & 1 & 0 & 0 \\ 0 & 0 & \frac{4}{3} & 1 & 0 \\ 0 & 0 & 0 & \frac{5}{4} & 5 \end{pmatrix}$$

$$\begin{pmatrix} 2 & 1 & 0 & 0 & 0 \\ 0 & \frac{3}{2} & 1 & 0 & 0 \\ 0 & 0 & \frac{4}{3} & 1 & 0 \\ 0 & 0 & 0 & \frac{5}{4} & 5 \end{pmatrix} \begin{aligned} 2x = -y &\Rightarrow \boxed{x = -2\frac{1}{2} = -1} \\ \frac{3}{2}y + z = 0 &\Rightarrow y = -z\frac{2}{3} = -(-3)\frac{2}{3} \rightarrow \boxed{y = 2} \\ \frac{4}{3}z + t = 0 &\rightarrow \frac{4}{3}z = -t \rightarrow \boxed{z = -4\frac{3}{4} = -3} \\ \frac{5}{4}t = 5 &\rightarrow \boxed{t = 4} \end{aligned}$$

The pivots are diagonal entries and the solution is:  $(-1, 2, -3, 4)$

### Exercise

Look for a matrix that has row sums 4 and 8, and column sums 2 and  $s$ .

$$A = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \quad \begin{array}{ll} a + b = 4 & a + c = 2 \\ c + d = 8 & b + d = s \end{array}$$

The four equations are solvable only if  $s = \underline{\hspace{1cm}}$ . Then find two different matrices that have the correct row and column sums.

### Solution

$$\begin{array}{r} a + b = 4 \\ + \quad c + d = 8 \\ \hline a + c + b + d = 12 \end{array}$$

$$2 + s = 12$$

$$\boxed{s = 10}$$

### Exercise

Three planes can fail to have an intersection point, even if no planes are parallel. The system is singular if row 3 of  $A$  is a \_\_\_\_\_ of the first two rows. Find a third equation that can't be solved together with  $x + y + z = 0$  and  $x - 2y - z = 1$

### Solution

The system is singular if row 3 of  $A$  is a **linear combination** of the first two rows.

There are many possible of a third equation that can't be solved together with  $x + y + z = 0$  and  $x - 2y - z = 1$ .

$$\begin{array}{r} 3 \text{ times } 1^{\text{st}} \text{ equation} \quad 3x + 3y + 3z \\ \text{minus } 2^{\text{nd}} \quad \quad \quad -x + 2y + z \\ \hline 2x + 5y + 4z = 1 \end{array}$$

## Exercise

Use the Gauss-Jordan method to solve the system

$$x - y + 5z = -6$$

$$3x + 3y - z = 10$$

$$x + 3y + 2z = 5$$

## Solution

$$\left[ \begin{array}{ccc|c} 1 & -1 & 5 & -6 \\ 3 & 3 & -1 & 10 \\ 1 & 3 & 2 & 5 \end{array} \right] \begin{array}{l} \\ R_2 - 3R_1 \\ R_3 - R_1 \end{array}$$

$$\begin{array}{ccc|c} 3 & 3 & -1 & 10 \\ -3 & 3 & -15 & 18 \\ \hline 0 & 6 & -16 & 28 \end{array} \quad \begin{array}{ccc|c} 1 & 3 & 2 & 5 \\ -1 & 1 & -5 & 6 \\ \hline 0 & 4 & -3 & 11 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & -1 & 5 & -6 \\ 0 & 6 & -16 & 28 \\ 0 & 4 & -3 & 11 \end{array} \right] \frac{1}{6}R_2$$

$$0 \quad 1 \quad -\frac{8}{3} \quad \frac{14}{3}$$

$$\left[ \begin{array}{ccc|c} 1 & -1 & 5 & -6 \\ 0 & 1 & -\frac{8}{3} & \frac{14}{3} \\ 0 & 4 & -3 & 11 \end{array} \right] \begin{array}{l} R_1 + R_2 \\ \\ R_3 - 4R_2 \end{array}$$

$$\begin{array}{ccc|c} 0 & 4 & -3 & 11 \\ 0 & -4 & \frac{32}{3} & -\frac{56}{3} \\ \hline 0 & 0 & \frac{23}{3} & -\frac{23}{3} \end{array} \quad \begin{array}{ccc|c} 1 & -1 & 5 & -6 \\ 0 & 1 & -\frac{8}{3} & \frac{14}{3} \\ \hline 1 & 0 & \frac{7}{3} & -\frac{4}{3} \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 0 & \frac{7}{3} & -\frac{4}{3} \\ 0 & 1 & -\frac{8}{3} & \frac{14}{3} \\ 0 & 0 & \frac{23}{3} & -\frac{23}{3} \end{array} \right] \frac{3}{23}R_3$$

$$0 \quad 0 \quad 1 \quad -1$$

$$\left[ \begin{array}{ccc|c} 1 & 0 & \frac{7}{3} & -\frac{4}{3} \\ 0 & 1 & -\frac{8}{3} & \frac{14}{3} \\ 0 & 0 & 1 & -1 \end{array} \right] \begin{array}{l} R_1 - \frac{7}{3}R_3 \\ R_2 + \frac{8}{3}R_3 \\ \end{array}$$

$$\begin{array}{ccc|c} 1 & 0 & \frac{7}{3} & -\frac{4}{3} \\ 0 & 0 & -\frac{7}{3} & \frac{7}{3} \\ \hline 1 & 0 & 0 & 1 \end{array} \quad \begin{array}{ccc|c} 0 & 1 & -\frac{8}{3} & \frac{14}{3} \\ 0 & 0 & \frac{8}{3} & -\frac{8}{3} \\ \hline 0 & 1 & 0 & 2 \end{array}$$

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

**Solution:** (1, 2, -1)

## Exercise

Use the Gauss-Jordan method to solve the system

$$\begin{cases} 2x - y + 4z = -3 \\ x - 2y - 10z = -6 \\ 3x \quad \quad + 4z = 7 \end{cases}$$

## Solution

$$\left[ \begin{array}{ccc|c} 2 & -1 & 4 & -3 \\ 1 & -2 & -10 & -6 \\ 3 & 0 & 4 & 7 \end{array} \right] \frac{1}{2}R_1$$

$$1 \quad -\frac{1}{2} \quad 2 \quad -\frac{3}{2}$$

$$\left[ \begin{array}{ccc|c} 1 & -\frac{1}{2} & 2 & -\frac{3}{2} \\ 1 & -2 & -10 & -6 \\ 3 & 0 & 4 & 7 \end{array} \right] \begin{array}{l} R_2 - R_1 \\ R_3 - 3R_1 \end{array}$$

$$\begin{array}{cccc|cccc} 1 & -2 & -10 & -6 & 3 & 0 & 4 & 7 \\ -1 & \frac{1}{2} & -2 & \frac{3}{2} & -3 & \frac{3}{2} & -6 & \frac{9}{2} \\ \hline 0 & -\frac{3}{2} & -12 & -\frac{9}{2} & 0 & \frac{3}{2} & -2 & \frac{23}{2} \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & -\frac{1}{2} & 2 & -\frac{3}{2} \\ 0 & -\frac{3}{2} & -12 & -\frac{9}{2} \\ 0 & \frac{3}{2} & -2 & \frac{23}{2} \end{array} \right] -\frac{2}{3}R_2$$

$$0 \quad 1 \quad 8 \quad 3$$

$$\left[ \begin{array}{ccc|c} 1 & -\frac{1}{2} & 2 & -\frac{3}{2} \\ 0 & 1 & 8 & 3 \\ 0 & \frac{3}{2} & -2 & \frac{23}{2} \end{array} \right] \begin{array}{l} R_1 + \frac{1}{2}R_2 \\ R_3 - \frac{3}{2}R_2 \end{array}$$

$$\begin{array}{cccc|cccc} 0 & \frac{3}{2} & -2 & \frac{23}{2} & 1 & -\frac{1}{2} & 2 & -\frac{3}{2} \\ 0 & -\frac{3}{2} & -12 & -\frac{9}{2} & 0 & \frac{1}{2} & 4 & \frac{3}{2} \\ \hline 0 & 0 & -14 & 7 & 1 & 0 & 6 & 0 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 0 & 6 & 0 \\ 0 & 1 & 8 & 3 \\ 0 & 0 & -14 & 7 \end{array} \right] -\frac{1}{14}R_3$$

$$0 \quad 0 \quad 1 \quad -\frac{1}{2}$$

$$\left[ \begin{array}{ccc|c} 1 & 0 & 6 & 0 \\ 0 & 1 & 8 & 3 \\ 0 & 0 & 1 & -\frac{1}{2} \end{array} \right] \begin{array}{l} R_1 - 6R_3 \\ R_2 - 8R_3 \end{array}$$

$$\begin{array}{cccc|cccc} 1 & 0 & 6 & 0 & 0 & 1 & 8 & 3 \\ 0 & 0 & -6 & 3 & 0 & 0 & -8 & 4 \\ \hline 1 & 0 & 0 & 3 & 0 & 1 & 0 & 7 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 0 & 0 & 3 \\ 0 & 1 & 0 & 7 \\ 0 & 0 & 1 & -\frac{1}{2} \end{array} \right]$$

**Solution:**  $\underline{\left( 3, 7, -\frac{1}{2} \right)}$

### Exercise

Use the Gauss-Jordan method to solve the system 
$$\begin{cases} 4x + 3y - 5z = -29 \\ 3x - 7y - z = -19 \\ 2x + 5y + 2z = -10 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} 4 & 3 & -5 & -29 \\ 3 & -7 & -1 & -19 \\ 2 & 5 & 2 & -10 \end{array} \right] \frac{1}{4}R_1$$

$$1 \quad \frac{3}{4} \quad -\frac{5}{4} \quad -\frac{29}{4}$$

$$\left[ \begin{array}{ccc|c} 1 & \frac{3}{4} & -\frac{5}{4} & -\frac{29}{4} \\ 3 & -7 & -1 & -19 \\ 2 & 5 & 2 & -10 \end{array} \right] \begin{array}{l} R_2 - 3R_1 \\ R_3 - 2R_1 \end{array}$$

$$\begin{array}{ccc|c} 3 & -7 & -1 & -19 \\ -3 & -\frac{9}{4} & \frac{15}{4} & \frac{87}{4} \\ \hline 0 & -\frac{37}{4} & \frac{11}{4} & \frac{11}{4} \end{array}$$

$$\begin{array}{ccc|c} 2 & 5 & 2 & -10 \\ -2 & -\frac{3}{2} & \frac{5}{2} & \frac{29}{2} \\ \hline 0 & \frac{7}{2} & \frac{9}{2} & \frac{9}{2} \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & \frac{3}{4} & -\frac{5}{4} & -\frac{29}{4} \\ 0 & -\frac{37}{4} & \frac{11}{4} & \frac{11}{4} \\ 0 & \frac{7}{2} & \frac{9}{2} & \frac{9}{2} \end{array} \right] -\frac{4}{37}R_2$$

$$0 \quad 1 \quad -\frac{11}{37} \quad -\frac{11}{37}$$

$$\left[ \begin{array}{ccc|c} 1 & \frac{3}{4} & -\frac{5}{4} & -\frac{29}{4} \\ 0 & 1 & -\frac{11}{37} & -\frac{11}{37} \\ 0 & \frac{7}{2} & \frac{9}{2} & \frac{9}{2} \end{array} \right] \begin{array}{l} R_1 - \frac{3}{4}R_2 \\ R_3 - \frac{7}{2}R_2 \end{array}$$

$$\begin{array}{ccc|c} 1 & \frac{3}{4} & -\frac{5}{4} & -\frac{29}{4} \\ 0 & -\frac{3}{4} & \frac{33}{148} & \frac{33}{148} \\ \hline 1 & 0 & -\frac{38}{37} & -\frac{260}{37} \end{array}$$

$$\begin{array}{ccc|c} 0 & \frac{7}{2} & \frac{9}{2} & \frac{9}{2} \\ 0 & -\frac{7}{2} & \frac{77}{72} & \frac{77}{72} \\ \hline 0 & 0 & \frac{401}{72} & \frac{401}{72} \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 0 & -\frac{38}{37} & -\frac{260}{37} \\ 0 & 1 & -\frac{11}{37} & -\frac{11}{37} \\ 0 & 0 & \frac{401}{72} & \frac{401}{72} \end{array} \right] \frac{72}{401}R_3$$

$$0 \quad 0 \quad 1 \quad 1$$

$$\left[ \begin{array}{ccc|c} 1 & 0 & -\frac{38}{37} & -\frac{260}{37} \\ 0 & 1 & -\frac{11}{37} & -\frac{11}{37} \\ 0 & 0 & 1 & 1 \end{array} \right] \begin{array}{l} R_1 + \frac{38}{37}R_3 \\ R_2 + \frac{11}{37}R_3 \end{array}$$

$$\begin{array}{ccc|c} 1 & 0 & -\frac{38}{37} & -\frac{260}{37} \\ 0 & 0 & \frac{38}{37} & \frac{38}{37} \\ \hline 1 & 0 & 0 & -6 \end{array}$$

$$\begin{array}{ccc|c} 0 & 1 & -\frac{11}{37} & -\frac{11}{37} \\ 0 & 0 & \frac{11}{37} & \frac{11}{37} \\ \hline 0 & 1 & 0 & 0 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 0 & 0 & -6 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{array} \right]$$

**Solution:**  $\underline{(-6, 0, 1)}$

### Exercise

Use the Gauss-Jordan method to solve the system 
$$\begin{cases} x + 2y - 3z = -15 \\ 2x - 3y + 4z = 18 \\ -3x + y + z = 1 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & 2 & -3 & -15 \\ 2 & -3 & 4 & 18 \\ -3 & 1 & 1 & 1 \end{array} \right]$$

$$\left[ \begin{array}{ccc|c} 1 & 2 & -3 & -15 \\ 2 & -3 & 4 & 18 \\ -3 & 1 & 1 & 1 \end{array} \right] \begin{array}{l} \\ R_2 - 2R_1 \\ R_3 + 3R_1 \end{array}$$

$$\begin{array}{cccc} -2 & -4 & 6 & 30 \\ 2 & -3 & 4 & 18 \\ \hline 0 & -7 & 10 & 48 \end{array} \quad \begin{array}{cccc} 3 & 6 & -9 & -45 \\ -3 & 1 & 1 & 1 \\ \hline 0 & 7 & -8 & -44 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 2 & -3 & -15 \\ 0 & -7 & 10 & 48 \\ 0 & 7 & -8 & -44 \end{array} \right] -\frac{1}{7}R_2$$

$$\left[ \begin{array}{ccc|c} 1 & 2 & -3 & -15 \\ 0 & 1 & -\frac{10}{7} & -\frac{48}{7} \\ 0 & 7 & -8 & -44 \end{array} \right] \begin{array}{l} R_1 - 2R_2 \\ \\ R_3 - 7R_2 \end{array}$$

$$\begin{array}{cccc} 1 & 2 & -3 & -15 \\ 0 & -2 & \frac{20}{7} & \frac{96}{7} \\ \hline 1 & 0 & -\frac{1}{7} & -\frac{9}{7} \end{array} \quad \begin{array}{cccc} 0 & -7 & 10 & 48 \\ 0 & 7 & -8 & -44 \\ \hline 0 & 0 & 2 & 4 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 0 & -\frac{1}{7} & -\frac{9}{7} \\ 0 & 1 & -\frac{10}{7} & -\frac{48}{7} \\ 0 & 0 & 2 & 4 \end{array} \right] \frac{1}{2}R_3$$

$$\left[ \begin{array}{ccc|c} 1 & 0 & -\frac{1}{7} & -\frac{9}{7} \\ 0 & 1 & -\frac{10}{7} & -\frac{48}{7} \\ 0 & 0 & 1 & 2 \end{array} \right] \begin{array}{l} R_1 + \frac{1}{7}R_3 \\ R_2 + \frac{10}{7}R_3 \\ \end{array}$$

$$\begin{array}{cccc} 1 & 0 & -\frac{1}{7} & -\frac{9}{7} \\ 0 & 0 & \frac{1}{7} & \frac{2}{7} \\ \hline 1 & 0 & 0 & -1 \end{array} \quad \begin{array}{cccc} 0 & 1 & -\frac{10}{7} & -\frac{48}{7} \\ 0 & 0 & \frac{10}{7} & \frac{20}{7} \\ \hline 0 & 1 & 0 & -4 \end{array}$$

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

**Solution:**  $\underline{(-1, -4, 2)}$



### Exercise

Use the Gauss-Jordan method to solve the system 
$$\begin{cases} x + 2y + 3z = 10 \\ 4x + 5y + 6z = 11 \\ 7x + 8y + 9z = 12 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & 2 & 3 & 10 \\ 4 & 5 & 6 & 11 \\ 7 & 8 & 9 & 12 \end{array} \right] \begin{array}{l} \\ R_2 - 4R_1 \\ R_3 - 7R_1 \end{array} \quad \begin{array}{cccc} -4 & -8 & -12 & -40 \\ 4 & 5 & 6 & 11 \\ \hline 0 & -3 & -6 & -29 \end{array} \quad \begin{array}{cccc} -7 & -14 & -21 & -70 \\ 7 & 8 & 9 & 12 \\ \hline 0 & -6 & -12 & -58 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 2 & 3 & 10 \\ 0 & -3 & -6 & -29 \\ 0 & -6 & -12 & -58 \end{array} \right] \frac{1}{3}R_2$$

$$\left[ \begin{array}{ccc|c} 1 & 2 & 3 & 10 \\ 0 & 1 & 2 & \frac{29}{3} \\ 0 & -6 & -12 & -58 \end{array} \right] R_3 + 6R_2 \quad \begin{array}{cccc} 0 & -6 & -12 & -58 \\ 0 & 6 & 12 & 58 \\ \hline 0 & 0 & 0 & 0 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 2 & 3 & 10 \\ 0 & 1 & 2 & \frac{29}{3} \\ 0 & 0 & 0 & 0 \end{array} \right]$$

let  $z$  be the variable

$$\text{From Row 1} \Rightarrow y + 2z = \frac{29}{3}$$

$$y = \frac{29}{3} - 2z$$

$$\text{From Row 1} \Rightarrow x + 2y + 3z = 10$$

$$x = 10 - 2y - 3z$$

$$x = 10 - 2\left(\frac{29}{3} - 2z\right) - 3z$$

$$x = 10 - \frac{58}{3} + 4z - 3z$$

$$x = z - \frac{28}{3}$$

$$\text{Solution: } \left( z - \frac{28}{3}, \frac{29}{3} - 2z, z \right)$$

### Exercise

Use the Gauss-Jordan method to solve the system 
$$\begin{cases} 2x + y + 2z = 4 \\ 2x + 2y = 5 \\ 2x - y + 6z = 2 \end{cases}$$

### Solution

$$\begin{aligned} & \left[ \begin{array}{ccc|c} 2 & 1 & 2 & 4 \\ 2 & 2 & 0 & 5 \\ 2 & -1 & 6 & 2 \end{array} \right] \begin{array}{l} \frac{1}{2}R_1 \\ \\ \end{array} \quad \begin{array}{cccc} & & 1 & \frac{1}{2} \\ & & & 1 \\ & & & 2 \end{array} \\ & \left[ \begin{array}{ccc|c} 1 & \frac{1}{2} & 1 & 2 \\ 2 & 2 & 0 & 5 \\ 2 & -1 & 6 & 2 \end{array} \right] \begin{array}{l} \\ R_2 - 2R_1 \\ R_3 - 2R_1 \end{array} \quad \begin{array}{cccc} 2 & 2 & 0 & 5 \\ -2 & -1 & -2 & -4 \\ 0 & 1 & -2 & 1 \end{array} \quad \begin{array}{cccc} 2 & -1 & 6 & 2 \\ -2 & -1 & -2 & -4 \\ 0 & -2 & 4 & -2 \end{array} \\ & \left[ \begin{array}{ccc|c} 1 & \frac{1}{2} & 1 & 2 \\ 0 & 1 & -2 & 1 \\ 0 & -2 & 4 & -2 \end{array} \right] \begin{array}{l} R_1 - \frac{1}{2}R_2 \\ \\ R_3 + 2R_2 \end{array} \quad \begin{array}{cccc} 1 & \frac{1}{2} & 1 & 2 \\ 0 & -\frac{1}{2} & 1 & -\frac{1}{2} \\ 1 & 0 & 2 & \frac{3}{2} \end{array} \quad \begin{array}{cccc} 0 & -2 & 4 & -2 \\ 0 & 2 & -4 & 2 \\ 0 & 0 & 0 & 0 \end{array} \\ & \left[ \begin{array}{ccc|c} 1 & 0 & 2 & \frac{3}{2} \\ 0 & 1 & -2 & 1 \\ 0 & 0 & 0 & 0 \end{array} \right] \end{aligned}$$

From Row 3:  $0 = 0$  is a true statement. Let  $z$  be the variable.

From Row 2:  $y - 2z = 1$

$$\underline{y = 1 + 2z}$$

From Row 1:  $x + 2z = \frac{3}{2}$

$$\underline{x = -2z + \frac{3}{2}}$$

$\therefore$  **Solution:**  $\underline{\left( -2z + \frac{3}{2}, 2z + 1, z \right)}$

## Exercise

Use the Gauss-Jordan method to solve the system

$$\begin{cases} x_1 + x_2 + 2x_3 = 8 \\ -x_1 - 2x_2 + 3x_3 = 1 \\ 3x_1 - 7x_2 + 4x_3 = 10 \end{cases}$$

## Solution

$$\left[ \begin{array}{ccc|c} 1 & 1 & 2 & 8 \\ -1 & -2 & 3 & 1 \\ 3 & -7 & 4 & 10 \end{array} \right] \begin{array}{l} \\ R_2 + R_1 \\ R_3 - 3R_1 \end{array}$$

$$\begin{array}{cccc} -1 & -2 & 3 & 1 \\ 1 & 1 & 2 & 8 \\ \hline 0 & -1 & 5 & 9 \end{array}$$

$$\begin{array}{cccc} 3 & -7 & 4 & 10 \\ -3 & -3 & -6 & -24 \\ \hline 0 & -10 & -2 & -14 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 1 & 2 & 8 \\ 0 & -1 & 5 & 9 \\ 0 & -10 & -2 & -14 \end{array} \right] -R_2$$

$$\left[ \begin{array}{ccc|c} 1 & 1 & 2 & 8 \\ 0 & 1 & -5 & -9 \\ 0 & -10 & -2 & -14 \end{array} \right] \begin{array}{l} R_1 - R_2 \\ \\ R_3 + 10R_2 \end{array}$$

$$\begin{array}{cccc} 1 & 1 & 2 & 8 \\ 0 & -1 & 5 & 9 \\ \hline 1 & 0 & 7 & 17 \end{array}$$

$$\begin{array}{cccc} 0 & -10 & -2 & -14 \\ 0 & 10 & -50 & -90 \\ \hline 0 & 0 & -52 & -104 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 0 & 7 & 17 \\ 0 & 1 & -5 & -9 \\ 0 & 0 & -52 & -104 \end{array} \right] -\frac{1}{52}R_3$$

$$\left[ \begin{array}{ccc|c} 1 & 0 & 7 & 17 \\ 0 & 1 & -5 & -9 \\ 0 & 0 & 1 & 2 \end{array} \right] \begin{array}{l} R_1 - 7R_3 \\ R_2 + 5R_3 \\ \end{array}$$

$$\begin{array}{cccc} 1 & 0 & 7 & 17 \\ 0 & 0 & -7 & -14 \\ \hline 1 & 0 & 0 & 3 \end{array}$$

$$\begin{array}{cccc} 0 & 1 & -5 & -9 \\ 0 & 0 & 5 & 10 \\ \hline 0 & 1 & 0 & 1 \end{array}$$

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

$\therefore$  **Solution:** (3, 1, 2)

### Exercise

Use augmented elimination to solve linear system

$$2x - 5y + 3z = 1$$

$$x - 2y - 2z = 8$$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & -2 & -2 & 8 \\ 2 & -5 & 3 & 1 \end{array} \right] R_2 - 2R_1$$

$$\begin{array}{cccc} 2 & -5 & 3 & 1 \\ -2 & 4 & 4 & -16 \\ \hline 0 & -1 & 7 & -15 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & -2 & -2 & 8 \\ 0 & -1 & 7 & -15 \end{array} \right] -R_2$$

$$\left[ \begin{array}{ccc|c} 1 & -2 & -2 & 8 \\ 0 & 1 & -7 & 15 \end{array} \right] R_1 + 2R_2$$

$$\begin{array}{cccc} 1 & -2 & -2 & 8 \\ 0 & 2 & -14 & 30 \\ \hline 1 & 0 & -16 & 38 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 0 & -16 & 38 \\ 0 & 1 & -7 & 15 \end{array} \right] \rightarrow \begin{array}{l} x - 16z = 38 \\ y - 7z = 15 \end{array}$$

$$\begin{cases} x = 16z + 38 \\ y = 7z + 15 \end{cases}$$

$$\therefore \text{Solution: } \underline{(16z + 38, 7z + 15, z)}$$

### Exercise

Use augmented elimination to solve linear system

$$\begin{cases} x + y + z = 2 \\ 2x + y - z = 5 \\ x - y + z = -2 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & 1 & 1 & 2 \\ 2 & 1 & -1 & 5 \\ 1 & -1 & 1 & -2 \end{array} \right] \begin{array}{l} R_2 - 2R_1 \\ R_3 - R_1 \end{array}$$

$$\begin{array}{cccc} 2 & 1 & -1 & 5 \\ -2 & -2 & -2 & -4 \\ \hline 0 & -1 & -3 & 1 \end{array}$$

$$\begin{array}{cccc} 1 & -1 & 1 & -2 \\ -1 & -1 & -1 & -2 \\ \hline 0 & -2 & 0 & -4 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 1 & 1 & 2 \\ 0 & -1 & -3 & 1 \\ 0 & -2 & 0 & -4 \end{array} \right] \begin{array}{l} (2) \\ (1) \\ -2y = -4 \end{array}$$

$$\underline{y = 2}$$

$$(1) \rightarrow -y - 3z = 1$$

$$3z = -1 - 2$$

$$\underline{z = -1}$$

$$(2) \rightarrow x + y + z = 2$$

$$x = 2 - 2 + 1$$

$$\underline{\underline{=1}}$$

$$\therefore \text{Solution: } \underline{(1, 2, -1)}$$

### Exercise

Use augmented elimination to solve linear system 
$$\begin{cases} 2x + y + z = 9 \\ -x - y + z = 1 \\ 3x - y + z = 9 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} 2 & 1 & 1 & 9 \\ -1 & -1 & 1 & 1 \\ 3 & -1 & 1 & 9 \end{array} \right] \begin{array}{l} \\ 2R_2 + R_1 \\ 2R_3 - 3R_1 \end{array} \quad \begin{array}{cccc} -2 & -2 & 2 & 2 \\ 2 & 1 & 1 & 9 \\ \hline 0 & -1 & 3 & 11 \end{array} \quad \begin{array}{cccc} 6 & -2 & 2 & 18 \\ -6 & -3 & -3 & -27 \\ \hline 0 & -5 & -1 & -9 \end{array}$$

$$\left[ \begin{array}{ccc|c} 2 & 1 & 1 & 9 \\ 0 & -1 & 3 & 11 \\ 0 & -5 & -1 & -9 \end{array} \right] \begin{array}{l} \\ \\ R_3 - 5R_2 \end{array} \quad \begin{array}{cccc} 0 & -5 & -1 & -9 \\ 0 & 5 & -15 & -55 \\ \hline 0 & 0 & -16 & -64 \end{array}$$

$$\left[ \begin{array}{ccc|c} 2 & 1 & 1 & 9 \\ 0 & -1 & 3 & 11 \\ 0 & 0 & -16 & -64 \end{array} \right] \begin{array}{l} (2) \\ (1) \\ -16z = -64 \end{array}$$

$$\underline{\underline{z = 4}}$$

$$(1) \rightarrow -y + 3z = 11$$

$$y = 12 - 11$$

$$\underline{\underline{=1}}$$

$$(2) \rightarrow 2x + y + z = 9$$

$$2x = 9 - 1 - 4$$

$$\underline{\underline{x = 2}}$$

$$\therefore \text{Solution: } \underline{(2, 1, 4)}$$

### Exercise

Use augmented elimination to solve linear system 
$$\begin{cases} 3y - z = -1 \\ x + 5y - z = -4 \\ -3x + 6y + 2z = 11 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & 5 & -1 & -4 \\ 0 & 3 & -1 & -1 \\ -3 & 6 & 2 & 11 \end{array} \right] \quad R_3 + 3R_1 \quad \begin{array}{cccc} -3 & 6 & 2 & 11 \\ 3 & 15 & -3 & -12 \\ \hline 0 & 21 & -1 & -1 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 5 & -1 & -4 \\ 0 & 3 & -1 & -1 \\ 0 & 21 & -1 & -1 \end{array} \right] \quad R_3 - 7R_2 \quad \begin{array}{cccc} 0 & 21 & -1 & -1 \\ 0 & -21 & 7 & 7 \\ \hline 0 & 0 & 6 & 6 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 5 & -1 & -4 \\ 0 & 3 & -1 & -1 \\ 0 & 0 & 6 & 6 \end{array} \right] \rightarrow \begin{array}{l} x + 5y - z = -4 \quad (2) \\ 3y - z = -1 \quad (1) \\ 6z = 6 \end{array}$$

$$\underline{z = 1}$$

$$(1) \rightarrow 3y = -1 + 1$$

$$\underline{y = 0}$$

$$(2) \rightarrow x = -4 + 1$$

$$\underline{x = -3}$$

$$\therefore \text{Solution: } \underline{(-3, 0, 1)}$$

### Exercise

Use augmented elimination to solve linear system  $\begin{cases} x + 3y + 4z = 14 \\ 2x - 3y + 2z = 10 \\ 3x - y + z = 9 \end{cases}$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & 3 & 4 & 14 \\ 2 & -3 & 2 & 10 \\ 3 & -1 & 1 & 9 \end{array} \right] \quad \begin{array}{l} R_2 - 2R_1 \\ R_3 - 3R_1 \end{array} \quad \begin{array}{cccc} 2 & -3 & 2 & 10 \\ -2 & -6 & -8 & -28 \\ \hline 0 & -9 & -6 & -18 \end{array} \quad \begin{array}{cccc} 3 & -1 & 1 & 9 \\ -3 & -9 & -12 & -42 \\ \hline 0 & -10 & -11 & -33 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 3 & 4 & 14 \\ 0 & -9 & -6 & -18 \\ 0 & -10 & -11 & -33 \end{array} \right] \quad 9R_3 - 10R_2 \quad \begin{array}{cccc} 0 & -90 & -99 & -297 \\ 0 & 90 & 60 & 180 \\ \hline 0 & 0 & -39 & -117 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 3 & 4 & 14 \\ 0 & -9 & -6 & -18 \\ 0 & 0 & -39 & -117 \end{array} \right] \quad \begin{array}{l} x + 3y + 4z = 14 \quad (3) \\ -9y - 6z = -18 \quad (2) \\ -39z = -117 \quad (1) \end{array}$$

$$(1) \rightarrow z = \frac{117}{39} \\ \underline{= 3}$$

$$(2) \rightarrow 9y = 18 - 6(3)$$

$$9y = 0$$

$$\underline{y = 0}$$

$$(3) \rightarrow x = 14 - 12$$

$$\underline{x = 2}$$

$$\therefore \text{Solution: } \underline{(2, 0, 3)}$$

### Exercise

Use augmented elimination to solve linear system 
$$\begin{cases} x + 4y - z = 20 \\ 3x + 2y + z = 8 \\ 2x - 3y + 2z = -16 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & 4 & -1 & 20 \\ 3 & 2 & 1 & 8 \\ 2 & -3 & 2 & -16 \end{array} \right] \begin{array}{l} \\ R_2 - 3R_1 \\ R_3 - 2R_1 \end{array} \quad \begin{array}{cccc} 3 & 2 & 1 & 8 \\ -3 & -12 & 3 & -60 \\ 0 & -10 & 4 & -52 \end{array} \quad \begin{array}{cccc} 2 & -3 & 2 & -16 \\ -2 & -8 & 2 & -40 \\ 0 & -11 & 4 & -56 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 4 & -1 & 20 \\ 0 & -10 & 4 & -52 \\ 0 & -11 & 4 & -56 \end{array} \right] \begin{array}{l} \\ \\ 10R_3 - 11R_2 \end{array} \quad \begin{array}{cccc} 0 & -110 & 40 & -560 \\ 0 & 110 & -44 & 572 \\ 0 & 0 & -4 & 12 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 4 & -1 & 20 \\ 0 & -10 & 4 & -52 \\ 0 & 0 & -4 & 12 \end{array} \right] \begin{array}{l} x + 4y - z = 20 \quad (3) \\ -10y + 4z = -52 \quad (2) \\ -4z = 12 \quad (1) \end{array}$$

$$(1) \rightarrow \underline{z = -3}$$

$$(2) \rightarrow -10y = -52 + 12$$

$$-10y = -40$$

$$\underline{y = 4}$$

$$(3) \rightarrow x = 20 - 16 - 3$$

$$\underline{x = 1}$$

$$\therefore \text{Solution: } \underline{(1, 4, -3)}$$

### Exercise

Use augmented elimination to solve linear system 
$$\begin{cases} 2y - z = 7 \\ x + 2y + z = 17 \\ 2x - 3y + 2z = -1 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & 2 & 1 & 17 \\ 0 & 2 & -1 & 7 \\ 2 & -3 & 2 & -1 \end{array} \right] R_3 - 2R_1 \quad \begin{array}{cccc} 2 & -3 & 2 & -1 \\ -2 & -4 & -2 & -34 \\ \hline 0 & -7 & 0 & -35 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 2 & 1 & 17 \\ 0 & 2 & -1 & 7 \\ 0 & -7 & 0 & -35 \end{array} \right] \begin{array}{l} x + 2y + z = 17 \quad (3) \\ 2y - z = 7 \quad (2) \\ -7y = -35 \quad (1) \end{array}$$

$$(1) \rightarrow \underline{y = 5}$$

$$(2) \rightarrow \underline{z = 10 - 7} \\ = 3$$

$$(3) \rightarrow \underline{x = 17 - 10 - 3} \\ = 4$$

$$\therefore \text{Solution: } \underline{(4, 5, 3)}$$

### Exercise

Use augmented elimination to solve linear system 
$$\begin{cases} -2x + 6y + 7z = 3 \\ -4x + 5y + 3z = 7 \\ -6x + 3y + 5z = -4 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} -2 & 6 & 7 & 3 \\ -4 & 5 & 3 & 7 \\ -6 & 3 & 5 & -4 \end{array} \right] \begin{array}{l} R_2 - 2R_1 \\ R_3 - 3R_1 \end{array} \quad \begin{array}{cccc} -4 & 5 & 3 & 7 \\ 4 & -12 & -14 & -6 \\ \hline 0 & -7 & -11 & 1 \end{array} \quad \begin{array}{cccc} -6 & 3 & 5 & -4 \\ 6 & -18 & -21 & -9 \\ \hline 0 & -15 & -16 & -13 \end{array}$$

$$\left[ \begin{array}{ccc|c} -2 & 6 & 7 & 3 \\ 0 & -7 & -11 & 1 \\ 0 & -15 & -16 & -13 \end{array} \right] 7R_3 - 15R_1 \quad \begin{array}{cccc} 0 & -105 & -112 & -91 \\ 0 & 105 & 165 & -15 \\ \hline 0 & 0 & 53 & -106 \end{array}$$

$$\left[ \begin{array}{ccc|c} -2 & 6 & 7 & 3 \\ 0 & -7 & -11 & 1 \\ 0 & 0 & 53 & -106 \end{array} \right] \begin{array}{l} -2x + 6y + 7z = 3 \quad (3) \\ -7y - 11z = 1 \quad (2) \\ 53z = -106 \quad (1) \end{array}$$

$$(1) \rightarrow \underline{z = -2}$$



$$(2) \rightarrow -7y = 1 - 22$$

$$-7y = -21$$

$$\underline{y = 3}$$

$$(3) \rightarrow -2x = 3 - 18 + 14$$

$$-2x = -1$$

$$\underline{x = \frac{1}{2}}$$

$$\therefore \text{Solution: } \underline{\left( \frac{1}{2}, 3, -2 \right)}$$

### Exercise

Use augmented elimination to solve linear system  $\begin{cases} 2x - y + z = 1 \\ 3x - 3y + 4z = 5 \\ 4x - 2y + 3z = 4 \end{cases}$

### Solution

$$\begin{array}{ccc|c} 2 & -1 & 1 & 1 \\ 3 & -3 & 4 & 5 \\ 4 & -2 & 3 & 4 \end{array} \quad \begin{array}{l} 2R_2 - 3R_1 \\ R_3 - 2R_1 \end{array} \quad \begin{array}{cccc} 6 & -6 & 8 & 10 \\ -6 & 3 & -3 & -3 \\ \hline 0 & -3 & 5 & 7 \end{array} \quad \begin{array}{cccc} 4 & -2 & 3 & 4 \\ -4 & 2 & -2 & -2 \\ \hline 0 & 0 & 1 & 2 \end{array}$$

$$\begin{array}{ccc|c} 2 & -1 & 1 & 1 \\ 0 & -3 & 5 & 7 \\ 0 & 0 & 1 & 2 \end{array} \quad \begin{array}{l} 2x - y + z = 1 \quad (2) \\ -3y + 5z = 7 \quad (1) \\ \underline{z = 2} \end{array}$$

$$(1) \rightarrow -3y = 7 - 10$$

$$-3y = -3$$

$$\underline{y = 1}$$

$$(3) \rightarrow 2x = 1 + 1 - 2$$

$$\underline{x = 0}$$

$$\therefore \text{Solution: } \underline{(0, 1, 2)}$$

### Exercise

Use augmented elimination to solve linear system 
$$\begin{cases} 3x - 4y + 4z = 7 \\ x - y - 2z = 2 \\ 2x - 3y + 6z = 5 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & -1 & -2 & 2 \\ 3 & -4 & 4 & 7 \\ 2 & -3 & 6 & 5 \end{array} \right] \begin{array}{l} \\ R_2 - 3R_1 \\ R_3 - 2R_1 \end{array} \quad \begin{array}{cccc} 3 & -4 & 4 & 7 \\ -3 & 3 & 6 & -6 \\ \hline 0 & -1 & 10 & 1 \end{array} \quad \begin{array}{cccc} 2 & -3 & 6 & 5 \\ -2 & 2 & 4 & -4 \\ \hline 0 & -1 & 10 & 1 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & -1 & -2 & 2 \\ 0 & -1 & 10 & 1 \\ 0 & -1 & 10 & 1 \end{array} \right] \begin{array}{l} \\ \\ R_3 = R_2 \end{array} \quad \begin{array}{l} \rightarrow x - y - 2z = 2 \quad (2) \\ \rightarrow -y + 10z = 1 \quad (1) \end{array}$$

$$(1) \rightarrow \underline{y = 10z - 1}$$

$$(2) \rightarrow \underline{x = 2 + 10z - 1 + 2z} \\ \underline{= 12z + 1}$$

$$\therefore \text{Solution: } \underline{(12z + 1, 10z - 1, z)}$$

### Exercise

Use augmented elimination to solve linear system 
$$\begin{cases} x - 2y - z = 2 \\ 2x - y + z = 4 \\ -x + y + z = 4 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & -2 & -1 & 2 \\ 2 & -1 & 1 & 4 \\ -1 & 1 & 1 & 4 \end{array} \right] \begin{array}{l} \\ R_2 - 2R_1 \\ R_3 + R_1 \end{array} \quad \begin{array}{cccc} 2 & -1 & 1 & 4 \\ -2 & 4 & 2 & -4 \\ \hline 0 & 3 & 3 & 0 \end{array} \quad \begin{array}{cccc} -1 & 1 & 1 & 4 \\ 1 & -2 & -1 & 2 \\ \hline 0 & -1 & 0 & 6 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & -2 & -1 & 2 \\ 0 & 3 & 3 & 0 \\ 0 & -1 & 0 & 6 \end{array} \right] \begin{array}{l} x - 2y - z = 2 \quad (3) \\ 3y + 3z = 0 \quad (2) \\ -y = 6 \quad (1) \end{array}$$

$$(1) \rightarrow \underline{y = -6}$$

$$(2) \rightarrow \underline{z = -y} \\ \underline{= 6}$$

$$(3) \rightarrow \underline{x = 2 - 12 + 6} \\ \underline{= -4}$$

$$\therefore \text{Solution: } \underline{(-4, -6, 6)}$$

### Exercise

Use augmented elimination to solve linear system 
$$\begin{cases} x + y + z = 3 \\ -y + 2z = 1 \\ -x + z = 0 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & 1 & 1 & 3 \\ 0 & -1 & 2 & 1 \\ -1 & 0 & 1 & 0 \end{array} \right] \quad R_3 + R_1 \quad \begin{array}{cccc} -1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 3 \\ \hline 0 & 1 & 2 & 3 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 1 & 1 & 3 \\ 0 & -1 & 2 & 1 \\ 0 & 1 & 2 & 3 \end{array} \right] \quad R_3 + R_2 \quad \begin{array}{cccc} 0 & 1 & 2 & 3 \\ 0 & -1 & 2 & 1 \\ \hline 0 & 0 & 4 & 4 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 1 & 1 & 3 \\ 0 & -1 & 2 & 1 \\ 0 & 0 & 4 & 4 \end{array} \right] \quad \begin{array}{ll} x + y + z = 3 & (3) \\ -y + 2z = 1 & (2) \\ 4z = 4 & (1) \end{array}$$

$$(1) \rightarrow \underline{z=1}$$

$$(2) \rightarrow -y = 1 - 2$$

$$\underline{y=1}$$

$$(3) \rightarrow x = 3 - 1 - 1$$

$$\underline{\underline{=1}}$$

$$\therefore \text{Solution: } \underline{(1, 1, 1)}$$

### Exercise

Use augmented elimination to solve linear system 
$$\begin{cases} 3x + y + 3z = 14 \\ 7x + 5y + 8z = 37 \\ x + 3y + 2z = 9 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & 3 & 2 & 9 \\ 3 & 1 & 3 & 14 \\ 7 & 5 & 8 & 37 \end{array} \right] \quad \begin{array}{l} R_2 - 3R_1 \\ R_3 - 7R_1 \end{array} \quad \begin{array}{cccc} 3 & 1 & 3 & 14 \\ -3 & -9 & -6 & -27 \\ \hline 0 & -8 & -3 & -13 \end{array} \quad \begin{array}{cccc} 7 & 5 & 8 & 37 \\ -7 & -21 & -14 & -63 \\ \hline 0 & -16 & -6 & -26 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 3 & 2 & 9 \\ 0 & -8 & -3 & -13 \\ 0 & -16 & -6 & -26 \end{array} \right] \quad R_3 - 2R_2 \quad \begin{array}{cccc} 0 & -16 & -6 & -26 \\ 0 & 16 & 6 & 26 \\ \hline 0 & 0 & 0 & 0 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 3 & 2 & 9 \\ 0 & -8 & -3 & -13 \\ 0 & 0 & 0 & 0 \end{array} \right] \quad \begin{array}{l} x + 3y + 2z = 9 \quad (2) \\ -8y - 3z = -13 \quad (1) \end{array}$$

$$(1) \rightarrow -8y = 3z - 13$$

$$\underline{y = -\frac{3}{8}z + \frac{13}{8}}$$

$$(3) \rightarrow x = 9 - 3\left(\frac{13}{8} - \frac{3}{8}z\right) - 2z$$

$$= 9 - \frac{39}{8} + \frac{9}{8}z - 2z$$

$$\underline{= \frac{33}{8} - \frac{7}{8}z}$$

$$\therefore \text{Solution: } \underline{\left( \frac{33}{8} - \frac{7}{8}z, \frac{13}{8} - \frac{3}{8}z, z \right)}$$

### Exercise

Use augmented elimination to solve linear system  $\begin{cases} 4x - 2y + z = 7 \\ x + y + z = -2 \\ 4x + 2y + z = 3 \end{cases}$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & 1 & 1 & -2 \\ 4 & -2 & 1 & 7 \\ 4 & 2 & 1 & 3 \end{array} \right] \quad \begin{array}{l} R_2 - 4R_1 \\ R_3 - 4R_1 \end{array} \quad \begin{array}{ccc|c} 4 & -2 & 1 & 7 \\ -4 & -4 & -4 & 8 \\ \hline 0 & -6 & -3 & 15 \end{array} \quad \begin{array}{ccc|c} 4 & 2 & 1 & 3 \\ -4 & -4 & -4 & 8 \\ \hline 0 & -2 & -3 & 11 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 1 & 1 & -2 \\ 0 & -6 & -3 & 15 \\ 0 & -2 & -3 & 11 \end{array} \right] \quad -3R_3 + R_2 \quad \begin{array}{ccc|c} 0 & 6 & 9 & -33 \\ 0 & -6 & -3 & 15 \\ \hline 0 & 0 & 6 & -18 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 1 & 1 & -2 \\ 0 & -6 & -3 & 15 \\ 0 & 0 & 6 & -18 \end{array} \right] \quad \begin{array}{l} x + y + z = -2 \quad (3) \\ -6y - 3z = 15 \quad (2) \\ 6z = -18 \quad (1) \end{array}$$

$$(1) \rightarrow \underline{z = -3}$$

$$(2) \rightarrow -6y = 15 - 9$$

$$\underline{y = -1}$$

$$(3) \rightarrow x = -2 + 1 + 3$$

$$\underline{= 2}$$

$$\therefore \text{Solution: } \underline{(2, -1, -3)}$$

### Exercise

Use augmented elimination to solve linear system 
$$\begin{cases} 2x - 2y + z = -4 \\ 6x + 4y - 3z = -24 \\ x - 2y + 2z = 1 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & -2 & 2 & 1 \\ 2 & -2 & 1 & -4 \\ 6 & 4 & -3 & -24 \end{array} \right] \begin{array}{l} \\ R_2 - 2R_1 \\ R_3 - 6R_1 \end{array} \quad \begin{array}{cccc} 2 & -2 & 1 & -4 \\ -2 & 4 & -4 & -2 \\ \hline 0 & 2 & -3 & -6 \end{array} \quad \begin{array}{cccc} 6 & 4 & -3 & -24 \\ -6 & 12 & -12 & -6 \\ \hline 0 & 16 & -15 & -30 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & -2 & 2 & 1 \\ 0 & 2 & -3 & -6 \\ 0 & 16 & -15 & -30 \end{array} \right] \begin{array}{l} \\ \\ R_3 - 8R_2 \end{array} \quad \begin{array}{cccc} 0 & 16 & -15 & -30 \\ 0 & -16 & 24 & 48 \\ \hline 0 & 0 & 9 & 18 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & -2 & 2 & 1 \\ 0 & 2 & -3 & -6 \\ 0 & 0 & 9 & 18 \end{array} \right] \begin{array}{l} x - 2y + 2z = 1 \quad (3) \\ 2y - 3z = -6 \quad (2) \\ 9z = 18 \quad (1) \end{array}$$

$$(1) \rightarrow \underline{z = 2}$$

$$(2) \rightarrow 2y = -6 + 6$$

$$\underline{y = 0}$$

$$(3) \rightarrow x = 1 - 4$$

$$\underline{\underline{-3}}$$

$$\therefore \text{Solution: } \underline{(-3, 0, 2)}$$

### Exercise

Use augmented elimination to solve linear system 
$$\begin{cases} 9x + 3y + z = 4 \\ 16x + 4y + z = 2 \\ 25x + 5y + z = 2 \end{cases}$$

### Solution

$$\begin{cases} z + 9x + 3y = 4 \\ z + 16x + 4y = 2 \\ z + 25x + 5y = 2 \end{cases}$$

$$\left[ \begin{array}{ccc|c} 1 & 9 & 3 & 4 \\ 1 & 16 & 4 & 2 \\ 1 & 25 & 5 & 2 \end{array} \right] \begin{array}{l} \\ R_2 - R_1 \\ R_3 - R_1 \end{array} \quad \begin{array}{cccc} 1 & 16 & 4 & 2 \\ -1 & -9 & -3 & -4 \\ \hline 0 & 7 & 1 & -2 \end{array} \quad \begin{array}{cccc} 1 & 25 & 5 & 2 \\ -1 & -9 & -3 & -4 \\ \hline 0 & 16 & 2 & -2 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 9 & 3 & 4 \\ 0 & 7 & 1 & -2 \\ 0 & 16 & 2 & -2 \end{array} \right] \quad 7R_3 - 16R_2$$

$$\begin{array}{cccc} 0 & 112 & 14 & -14 \\ 0 & -112 & -16 & 32 \\ \hline 0 & 0 & -2 & 18 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 9 & 3 & 4 \\ 0 & 7 & 1 & -2 \\ 0 & 0 & -2 & 18 \end{array} \right] \quad \begin{array}{l} z + 9x + 3y = 4 \quad (3) \\ 7x + y = -2 \quad (2) \\ -2y = 18 \quad (1) \end{array}$$

$$(1) \rightarrow \underline{y = -9}$$

$$(2) \rightarrow 7x = -2 + 9$$

$$\underline{= 1}$$

$$(3) \rightarrow z = 4 - 9 + 27$$

$$\underline{= 22}$$

$$\therefore \text{Solution: } \underline{(1, -9, 22)}$$

### Exercise

Use augmented elimination to solve linear system  $\begin{cases} 2x - y + 2z = -8 \\ x + 2y - 3z = 9 \\ 3x - y - 4z = 3 \end{cases}$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & 2 & -3 & 9 \\ 2 & -1 & 2 & -8 \\ 3 & -1 & -4 & 3 \end{array} \right] \quad \begin{array}{l} R_2 - 2R_1 \\ R_3 - 3R_1 \end{array}$$

$$\begin{array}{cccc} 2 & -1 & 2 & -8 \\ -2 & -4 & 6 & -18 \\ \hline 0 & -5 & 8 & -26 \end{array} \quad \begin{array}{cccc} 3 & -1 & -4 & 3 \\ -3 & -6 & 9 & -27 \\ \hline 0 & -7 & 5 & -24 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 2 & -3 & 9 \\ 0 & -5 & 8 & -26 \\ 0 & -7 & 5 & -24 \end{array} \right] \quad 5R_3 - 7R_2$$

$$\begin{array}{cccc} 0 & -35 & 25 & -120 \\ 0 & 35 & -56 & 182 \\ \hline 0 & 0 & -31 & 62 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 2 & -3 & 9 \\ 0 & -5 & 8 & -26 \\ 0 & 0 & -31 & 62 \end{array} \right] \quad \begin{array}{l} x + 2y - 3z = 9 \quad (3) \\ -5y + 8z = -26 \quad (2) \\ -31z = 62 \quad (1) \end{array}$$

$$(1) \rightarrow \underline{z = -2}$$

$$(2) \rightarrow -5y = -26 + 16$$

$$-5y = 10$$

$$\underline{y = 2}$$

$$(3) \rightarrow x = 9 - 4 - 6$$

$$\underline{\underline{= -1}}$$

$$\therefore \text{Solution: } \underline{(-1, 2, -2)}$$

### Exercise

Use augmented elimination to solve linear system 
$$\begin{cases} x - 3z = -5 \\ 2x - y + 2z = 16 \\ 7x - 3y - 5z = 19 \end{cases}$$

### Solution

$$\begin{array}{ccc|ccc} 1 & 0 & -3 & -5 & & & \\ 2 & -1 & 2 & 16 & & & \\ 7 & -3 & -5 & 19 & & & \end{array} \quad \begin{array}{l} R_2 - 2R_1 \\ R_3 - 7R_1 \end{array} \quad \begin{array}{ccc|ccc} 2 & -1 & 2 & 16 & & & \\ -2 & 0 & 6 & 10 & & & \\ \hline 0 & -1 & 8 & 26 & & & \end{array} \quad \begin{array}{ccc|ccc} 7 & -3 & -5 & 19 & & & \\ -7 & 0 & 21 & 35 & & & \\ \hline 0 & -3 & 16 & 54 & & & \end{array}$$

$$\begin{array}{ccc|ccc} 1 & 0 & -3 & -5 & & & \\ 0 & -1 & 8 & 26 & & & \\ 0 & -3 & 16 & 54 & & & \end{array} \quad \begin{array}{l} R_3 - 3R_2 \end{array} \quad \begin{array}{ccc|ccc} 0 & -3 & 16 & 54 & & & \\ 0 & 3 & -24 & -78 & & & \\ \hline 0 & 0 & -8 & -24 & & & \end{array}$$

$$\begin{array}{ccc|ccc} 1 & 0 & -3 & -5 & & & \\ 0 & -1 & 8 & 26 & & & \\ 0 & 0 & -8 & -24 & & & \end{array} \quad \begin{array}{l} x - 3z = -5 \quad (3) \\ -y + 8z = 26 \quad (2) \\ -8z = -24 \quad (1) \end{array}$$

$$(1) \rightarrow \underline{z = 3}$$

$$(2) \rightarrow -y = 26 - 24$$

$$\underline{y = -2}$$

$$(3) \rightarrow x = -5 + 9$$

$$\underline{\underline{= 4}}$$

$$\therefore \text{Solution: } \underline{(4, -2, 3)}$$

### Exercise

Use augmented elimination to solve linear system 
$$\begin{cases} x + 2y - z = 5 \\ 2x - y + 3z = 0 \\ 2y + z = 1 \end{cases}$$

### Solution

$$\begin{array}{ccc|ccc} 1 & 2 & -1 & 5 & & & \\ 2 & -1 & 3 & 0 & & & \\ 0 & 2 & 1 & 1 & & & \end{array} \quad \begin{array}{l} R_2 - 2R_1 \end{array} \quad \begin{array}{ccc|ccc} 2 & -1 & 3 & 0 & & & \\ -2 & -4 & 2 & -10 & & & \\ \hline 0 & -5 & 5 & -10 & & & \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 2 & -1 & 5 \\ 0 & -5 & 5 & -10 \\ 0 & 2 & 1 & 1 \end{array} \right] \quad 5R_3 + 2R_2 \quad \begin{array}{cccc} 0 & 10 & 5 & 5 \\ 0 & -10 & 10 & -20 \\ \hline 0 & 0 & 15 & -15 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 2 & -1 & 5 \\ 0 & -5 & 5 & -10 \\ 0 & 0 & 15 & -15 \end{array} \right] \quad \begin{array}{l} x + 2y - z = 5 \quad (3) \\ -5y + 5z = -10 \quad (2) \\ 15z = -15 \quad (1) \end{array}$$

$$(1) \rightarrow \underline{z = -1}$$

$$(2) \rightarrow -5y = -10 + 5$$

$$\underline{y = 1}$$

$$(3) \rightarrow x = 5 - 2 - 1$$

$$\underline{= 2}$$

$$\therefore \text{Solution: } \underline{(2, 1, -1)}$$

### Exercise

Use augmented elimination to solve linear system  $\begin{cases} x + y + z = 6 \\ 3x + 4y - 7z = 1 \\ 2x - y + 3z = 5 \end{cases}$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & 1 & 1 & 6 \\ 3 & 4 & -7 & 1 \\ 2 & -1 & 3 & 5 \end{array} \right] \quad \begin{array}{l} R_2 - 3R_1 \\ R_3 - 2R_1 \end{array} \quad \begin{array}{cccc} 3 & 4 & -7 & 1 \\ -3 & -3 & -3 & -18 \\ \hline 0 & 1 & -10 & -17 \end{array} \quad \begin{array}{cccc} 2 & -1 & 3 & 5 \\ -2 & -2 & -2 & -12 \\ \hline 0 & -3 & 1 & -7 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 1 & 1 & 6 \\ 0 & 1 & -10 & -17 \\ 0 & -3 & 1 & -7 \end{array} \right] \quad R_3 + 3R_2 \quad \begin{array}{cccc} 0 & -3 & 1 & -7 \\ 0 & 3 & -30 & -51 \\ \hline 0 & 0 & -29 & -58 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 1 & 1 & 6 \\ 0 & 1 & -10 & -17 \\ 0 & 0 & -29 & -58 \end{array} \right] \quad \begin{array}{l} x + y + z = 6 \quad (3) \\ y - 10z = -17 \quad (2) \\ -29z = -58 \quad (1) \end{array}$$

$$(1) \rightarrow \underline{z = 2}$$

$$(2) \rightarrow y = -17 + 20$$

$$\underline{= 3}$$

$$(3) \rightarrow x = 6 - 3 - 2$$



$$\underline{=1}$$

$$\therefore \text{Solution: } \underline{(1, 3, 2)}$$

### Exercise

Use augmented elimination to solve linear system 
$$\begin{cases} 3x + 2y + 3z = 3 \\ 4x - 5y + 7z = 1 \\ 2x + 3y - 2z = 6 \end{cases}$$

### Solution

$$\begin{bmatrix} 3 & 2 & 3 & | & 3 \\ 4 & -5 & 7 & | & 1 \\ 2 & 3 & -2 & | & 6 \end{bmatrix} \begin{array}{l} \\ 3R_2 - 4R_1 \\ 3R_3 - 2R_1 \end{array} \quad \begin{array}{cccc} 12 & -15 & 21 & 3 \\ -12 & -8 & -12 & -12 \\ \hline 0 & -23 & 9 & -9 \end{array} \quad \begin{array}{cccc} 6 & 9 & -6 & 18 \\ -6 & -4 & -6 & -6 \\ \hline 0 & 5 & -12 & 12 \end{array}$$

$$\begin{bmatrix} 3 & 2 & 3 & | & 3 \\ 0 & -23 & 9 & | & -9 \\ 0 & 5 & -12 & | & 12 \end{bmatrix} \begin{array}{l} \\ \\ 23R_3 + 5R_2 \end{array} \quad \begin{array}{cccc} 0 & 115 & -276 & 276 \\ 0 & -115 & 45 & -45 \\ \hline 0 & 0 & -231 & 231 \end{array}$$

$$\begin{bmatrix} 3 & 2 & 3 & | & 3 \\ 0 & -23 & 9 & | & -9 \\ 0 & 0 & -231 & | & 231 \end{bmatrix} \begin{array}{l} 3x + 2y + 3z = 3 \quad (3) \\ -23y + 9z = -9 \quad (2) \\ -231z = 231 \quad (1) \end{array}$$

$$(1) \rightarrow \underline{z = -1}$$

$$(2) \rightarrow -23y = -9 + 9$$

$$\underline{y = 0}$$

$$(3) \rightarrow 3x = 3 + 3$$

$$\underline{x = 2}$$

$$\therefore \text{Solution: } \underline{(2, 0, -1)}$$

### Exercise

Use augmented elimination to solve linear system 
$$\begin{cases} x - 3y + z = 2 \\ 4x - 12y + 4z = 8 \\ -2x + 6y - 2z = -4 \end{cases}$$

### Solution

$$\begin{cases} x - 3y + z = 2 \\ \frac{1}{4} \times 4x - 12y + 4z = 8 \\ -\frac{1}{2} \times -2x + 6y - 2z = -4 \end{cases}$$

$$\begin{cases} x - 3y + z = 2 \\ x - 3y + z = 2 \\ x - 3y + z = 2 \end{cases}$$

Since all three equations are the same.

$\therefore$  **Solution:** is the plane  $\underline{x - 3y + z = 2}$

### Exercise

Use augmented elimination to solve linear system 
$$\begin{cases} 2x - 2y + z = -1 \\ x + 2y - z = 2 \\ 6x + 4y + 3z = 5 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & 2 & -1 & 2 \\ 2 & -2 & 1 & -1 \\ 6 & 4 & 3 & 5 \end{array} \right] \begin{array}{l} \\ R_2 - 2R_1 \\ R_3 - 6R_1 \end{array} \quad \begin{array}{cccc} 2 & -2 & 1 & -1 \\ -2 & -4 & 2 & -4 \\ \hline 0 & -6 & 3 & -5 \end{array} \quad \begin{array}{cccc} 6 & 4 & 3 & 5 \\ -6 & -12 & 6 & -12 \\ \hline 0 & -8 & 9 & -7 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 2 & -1 & 2 \\ 0 & -6 & 3 & -5 \\ 0 & -8 & 9 & -7 \end{array} \right] \begin{array}{l} \\ \\ 3R_3 - 4R_2 \end{array} \quad \begin{array}{cccc} 0 & -24 & 27 & -21 \\ 0 & 24 & -12 & 20 \\ \hline 0 & 0 & 15 & -1 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 2 & -1 & 2 \\ 0 & -6 & 3 & -5 \\ 0 & 0 & 15 & -1 \end{array} \right] \begin{array}{l} x + 2y - z = 2 \quad (3) \\ -6y + 3z = -5 \quad (2) \\ 15z = -1 \quad (1) \end{array}$$

$$(1) \rightarrow \underline{z = -\frac{1}{15}}$$

$$(2) \rightarrow -6y = -5 + \frac{1}{5} \\ -6y = -\frac{24}{5}$$

$$\underline{y = \frac{4}{5}}$$

$$(3) \rightarrow x = 2 - \frac{8}{5} - \frac{1}{15}$$

$$\underline{= \frac{1}{3}}$$

$$\therefore \text{Solution: } \underline{\left( \frac{1}{3}, \frac{4}{5}, -\frac{1}{15} \right)}$$

### Exercise

Use augmented elimination to solve linear system

$$\begin{cases} x_1 - 5x_2 + 2x_3 - 2x_4 = 4 \\ x_2 - 3x_3 - x_4 = 0 \\ 3x_1 + 2x_3 - x_4 = 6 \\ -4x_1 + x_2 + 4x_3 + 2x_4 = -3 \end{cases}$$

### Solution

$$\left[ \begin{array}{cccc|c} 1 & -5 & 2 & -2 & 4 \\ 0 & 1 & -3 & -1 & 0 \\ 3 & 0 & 2 & -1 & 6 \\ -4 & 1 & 4 & 2 & -3 \end{array} \right] \begin{array}{l} \\ R_3 - 3R_1 \\ R_4 + 4R_1 \end{array}$$

$$\begin{array}{ccccc} 3 & 0 & 2 & -1 & 6 \\ -3 & 15 & -6 & 6 & -12 \\ \hline 0 & 15 & -4 & 5 & -6 \end{array} \quad \begin{array}{ccccc} -4 & 1 & 4 & 2 & -3 \\ 4 & -20 & 8 & -8 & 16 \\ \hline 0 & -19 & 12 & -6 & 13 \end{array}$$

$$\left[ \begin{array}{cccc|c} 1 & -5 & 2 & -2 & 4 \\ 0 & 1 & -3 & -1 & 0 \\ 0 & 15 & -4 & 5 & -6 \\ 0 & -19 & 12 & -6 & 13 \end{array} \right] \begin{array}{l} \\ R_3 - 15R_2 \\ R_4 + 19R_2 \end{array}$$

$$\begin{array}{ccccc} 0 & 15 & -4 & 5 & -6 \\ 0 & -15 & 45 & 15 & 0 \\ \hline 0 & 0 & 41 & 20 & -6 \end{array} \quad \begin{array}{ccccc} 0 & -19 & 12 & -6 & 13 \\ 0 & 19 & -57 & -19 & 0 \\ \hline 0 & 0 & -45 & -25 & 13 \end{array}$$

$$\left[ \begin{array}{cccc|c} 1 & -5 & 2 & -2 & 4 \\ 0 & 1 & -3 & -1 & 0 \\ 0 & 0 & 41 & 20 & -6 \\ 0 & 0 & -45 & -25 & 13 \end{array} \right] 41R_4 + 45R_2$$

$$\begin{array}{ccccc} 0 & 0 & -1845 & -1025 & 533 \\ 0 & 0 & 1845 & 900 & -270 \\ \hline 0 & 0 & 0 & -125 & 263 \end{array}$$

$$\left[ \begin{array}{cccc|c} 1 & -5 & 2 & -2 & 4 \\ 0 & 1 & -3 & -1 & 0 \\ 0 & 0 & 41 & 20 & -6 \\ 0 & 0 & 0 & -125 & 263 \end{array} \right] \begin{array}{l} x_1 - 5x_2 + 2x_3 - 2x_4 = 4 \quad (4) \\ x_2 - 3x_3 - x_4 = 0 \quad (3) \\ 41x_3 + 20x_4 = -6 \quad (2) \\ -125x_4 = 263 \quad (1) \end{array}$$

$$(1) \rightarrow \underline{x_4 = -\frac{263}{125}}$$

$$(2) \rightarrow 41x_3 = -6 + \frac{1,052}{25}$$

$$= \frac{902}{25}$$

$$x_3 = \frac{22}{25}$$

$$(3) \rightarrow x_2 = \frac{66}{25} - \frac{263}{125}$$

$$= \frac{67}{125}$$

$$(4) \rightarrow x_1 = 4 + \frac{67}{25} - \frac{44}{25} - \frac{526}{125}$$

$$= 4 + \frac{23}{25} - \frac{526}{125}$$

$$= \frac{500 + 115 - 526}{125}$$

$$= \frac{89}{125}$$

$$\therefore \text{Solution: } \left( \frac{89}{125}, \frac{67}{125}, \frac{22}{25}, -\frac{263}{125} \right)$$

### Exercise

Use augmented elimination to solve linear system

$$\begin{cases} x_1 + x_2 + x_3 + x_4 = 5 \\ x_1 + 2x_2 - x_3 - 2x_4 = -1 \\ x_1 - 3x_2 - 3x_3 - x_4 = -1 \\ 2x_1 - x_2 + 2x_3 - x_4 = -2 \end{cases}$$

### Solution

$$\left[ \begin{array}{cccc|c} 1 & 1 & 1 & 1 & 5 \\ 1 & 2 & -1 & -2 & -1 \\ 1 & -3 & -3 & -1 & -1 \\ 2 & -1 & 2 & -1 & -2 \end{array} \right] \begin{array}{l} \\ R_2 - R_1 \\ R_3 - R_1 \\ R_4 - 2R_1 \end{array}$$

$$\begin{array}{ccccc} 1 & 2 & -1 & -2 & -1 \\ -1 & -1 & -1 & -1 & -5 \\ \hline 0 & 1 & -2 & -3 & -6 \end{array}$$

$$\begin{array}{ccccc} 1 & -3 & -3 & -1 & -1 \\ -1 & -1 & -1 & -1 & -5 \\ \hline 0 & -4 & -4 & -2 & -6 \end{array}$$

$$\begin{array}{ccccc} 2 & -1 & 2 & -1 & -2 \\ -2 & -2 & -2 & -2 & -10 \\ \hline 0 & -3 & 0 & -3 & -12 \end{array}$$

$$\left[ \begin{array}{cccc|c} 1 & 1 & 1 & 1 & 5 \\ 0 & 1 & -2 & -3 & -6 \\ 0 & -4 & -4 & -2 & -6 \\ 0 & -3 & 0 & -3 & -12 \end{array} \right] \begin{array}{l} R_3 + 4R_2 \\ R_4 + 3R_2 \end{array}$$

$$\begin{array}{ccccc} 0 & -4 & -4 & -2 & -6 \\ 0 & 4 & -8 & -12 & -24 \\ \hline 0 & 0 & -12 & -14 & -30 \end{array}$$

$$\begin{array}{ccccc} 0 & -3 & 0 & -3 & -12 \\ 0 & 3 & -6 & -9 & -18 \\ \hline 0 & 0 & -6 & -12 & -30 \end{array}$$

$$\left[ \begin{array}{cccc|c} 1 & 1 & 1 & 1 & 5 \\ 0 & 1 & -2 & -3 & -6 \\ 0 & 0 & -12 & -14 & -30 \\ 0 & 0 & -6 & -12 & -30 \end{array} \right] -2R_4 + R_3$$

$$\begin{array}{ccccc} 0 & 0 & 12 & 24 & 60 \\ 0 & 0 & -12 & -14 & -30 \\ \hline 0 & 0 & 0 & 10 & 30 \end{array}$$

$$\left[ \begin{array}{cccc|c} 1 & 1 & 1 & 1 & 5 \\ 0 & 1 & -2 & -3 & -6 \\ 0 & 0 & -12 & -14 & -30 \\ 0 & 0 & 0 & 10 & 30 \end{array} \right] \begin{array}{l} x_1 + x_2 + x_3 + x_4 = 5 \quad (4) \\ x_2 - 2x_3 - 3x_4 = -6 \quad (3) \\ -12x_3 - 14x_4 = -30 \quad (2) \\ 10x_4 = 30 \quad (1) \end{array}$$

$$(1) \rightarrow \underline{x_4 = 3}$$

$$(2) \rightarrow -12x_3 = -30 + 42 \\ = 12$$

$$\underline{x_3 = -1}$$

$$(3) \rightarrow x_2 = -6 - 2 + 9 \\ = 1$$

$$(4) \rightarrow x_1 = 5 - 1 + 1 - 3 \\ = 2$$

$$\therefore \text{Solution: } \underline{(2, 1, -1, 3)}$$

### Exercise

Use augmented elimination to solve linear system

$$\begin{cases} 2x + 8y - z + w = 0 \\ 4x + 16y - 3z - w = -10 \\ -2x + 4y - z + 3w = -6 \\ -6x + 2y + 5z + w = 3 \end{cases}$$

### Solution

$$\left[ \begin{array}{cccc|c} 2 & 8 & -1 & 1 & 0 \\ 4 & 16 & -3 & -1 & -10 \\ -2 & 4 & -1 & 3 & -6 \\ -6 & 2 & 5 & 1 & 3 \end{array} \right] \begin{array}{l} \\ R_2 - 2R_1 \\ R_3 + R_1 \\ R_4 + 3R_1 \end{array}$$

$$\left[ \begin{array}{cccc|c} 2 & 8 & -1 & 1 & 0 \\ 0 & 12 & -2 & 4 & -6 \\ 0 & 0 & -1 & -3 & -10 \\ 0 & 26 & 2 & 4 & 3 \end{array} \right] R_4 - \frac{13}{6}R_2$$

$$\left[ \begin{array}{cccc|c} 2 & 8 & -1 & 1 & 0 \\ 0 & 0 & -1 & -3 & -10 \\ 0 & 12 & -2 & 4 & -6 \\ 0 & 26 & 2 & 4 & 3 \end{array} \right] \text{Interchange } R_2 \text{ and } R_3$$

$$\left[ \begin{array}{cccc|c} 2 & 8 & -1 & 1 & 0 \\ 0 & 12 & -2 & 4 & -6 \\ 0 & 0 & -1 & -3 & -10 \\ 0 & 0 & \frac{19}{3} & -\frac{14}{3} & 16 \end{array} \right] R_4 + \frac{19}{3}R_3$$

$$\left[ \begin{array}{cccc|c} 2 & 8 & -1 & 1 & 0 \\ 0 & 12 & -2 & 4 & -6 \\ 0 & 0 & -1 & -3 & -10 \\ 0 & 0 & 0 & -\frac{71}{3} & -\frac{142}{3} \end{array} \right] \begin{array}{l} 2x + 8y - z + w = 0 \quad (3) \\ 12y - 2z + 4w = -6 \quad (2) \\ -z - 3w = -10 \quad (1) \\ -\frac{71}{3}w = -\frac{142}{3} \rightarrow \underline{w = 2} \end{array}$$

$$(1) \rightarrow z = 10 - 3w = \underline{4}$$

$$(2) \rightarrow 12y = 2z - 4w - 6$$

$$\underline{y = -\frac{1}{2}}$$

$$(3) \rightarrow 2x = -8y + z - w$$

$$2x = 4 + 4 - 2$$

$$\underline{x = 3}$$

$$\therefore \text{Solution: } \underline{\left( 3, -\frac{1}{2}, 4, 2 \right)}$$

### Exercise

Use augmented elimination to solve linear system

$$\begin{cases} 2x_1 + x_2 + 3x_3 = 0 \\ x_1 + 2x_2 = 0 \\ x_2 + x_3 = 0 \end{cases}$$

### Solution

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

$$2x_1 + x_2 + 3x_3 = 0$$

$$-4x_2 + x_2 - 3x_2 = 0 \rightarrow \underline{x_2 = 0}$$

$$\therefore \text{Solution: } \underline{(0, 0, 0)}$$

### Exercise

Use augmented elimination to solve linear system

$$\begin{cases} 2x + 2y + 4z = 0 \\ -y - 3z + w = 0 \\ 3x + y + z + 2w = 0 \\ x + 3y - 2z - 2w = 0 \end{cases}$$

### Solution

$$\left[ \begin{array}{cccc|c} 2 & 2 & 4 & 0 & 0 \\ 0 & -1 & -3 & 1 & 0 \\ 3 & 1 & 1 & 2 & 0 \\ 1 & 3 & -2 & -2 & 0 \end{array} \right] \begin{array}{l} \\ -R_2 \\ 2R_3 - 3R_1 \\ 2R_4 - R_1 \end{array}$$

$$\left[ \begin{array}{cccc|c} 2 & 2 & 4 & 0 & 0 \\ 0 & 1 & 3 & -1 & 0 \\ 0 & -4 & -10 & 4 & 0 \\ 0 & 4 & -8 & -4 & 0 \end{array} \right] \begin{array}{l} \\ R_3 + 4R_2 \\ R_4 - 4R_2 \end{array}$$

$$\left[ \begin{array}{cccc|c} 2 & 2 & 4 & 0 & 0 \\ 0 & 1 & 3 & -1 & 0 \\ 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & -20 & 0 & 0 \end{array} \right] \begin{array}{l} 2x + 2y - 4z = 0 \quad (1) \\ y + 3z - w = 0 \quad (2) \\ \rightarrow \underline{z = 0} \end{array}$$

$$(2) \rightarrow \underline{y = w}$$

$$(1) \rightarrow 2x = -2y \quad \underline{x = -w}$$

$$\therefore \text{Solution: } \underline{(-w, w, 0, w)}$$

### Exercise

Use augmented elimination to solve linear system

$$\begin{cases} 2x & + z + w = 5 \\ & y & - w = -1 \\ 3x & & - z - w = 0 \\ 4x + y + 2z + w = 9 \end{cases}$$

### Solution

$$\left[ \begin{array}{cccc|c} 2 & 0 & 1 & 1 & 5 \\ 0 & 1 & 0 & -1 & -1 \\ 3 & 0 & -1 & -1 & 0 \\ 4 & 1 & 2 & 1 & 9 \end{array} \right] \begin{array}{l} \\ 2R_3 - 3R_1 \\ 2R_4 - 4R_1 \end{array}$$
$$\left[ \begin{array}{cccc|c} 2 & 0 & 1 & 1 & 5 \\ 0 & 1 & 0 & -1 & -1 \\ 0 & 0 & -5 & -5 & -15 \\ 0 & 2 & 0 & -2 & -2 \end{array} \right] R_4 - 2R_2$$
$$\left[ \begin{array}{cccc|c} 2 & 0 & 1 & 1 & 5 \\ 0 & 1 & 0 & -1 & -1 \\ 0 & 0 & -5 & -5 & -15 \\ 0 & 0 & 0 & 0 & 0 \end{array} \right] \begin{array}{l} 2x + z + w = 5 \quad (1) \\ y - w = -1 \quad (2) \\ -5z - 5w = -15 \quad (3) \end{array}$$

$$(2) \rightarrow \underline{y = 1 + w}$$

$$(3) \rightarrow \underline{z = 3 - w}$$

$$(1) \rightarrow 2x = 5 - (3 - w) - w \Rightarrow \underline{x = 1}$$

$$\therefore \text{Solution: } \underline{(1, 1 + w, 3 - w, w)}$$

### Exercise

Use augmented elimination to solve linear system

$$\begin{cases} & 4y + z = 20 \\ 2x - 2y + z = 0 \\ & x & + z = 5 \\ & x + y - z = 10 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & 1 & -1 & 10 \\ 2 & -2 & 1 & 0 \\ 1 & 0 & 1 & 5 \\ 0 & 4 & 1 & 20 \end{array} \right] \begin{array}{l} \\ R_2 - 2R_1 \\ R_3 - R_1 \end{array}$$



$$\begin{array}{l}
 \left[ \begin{array}{ccc|c} 1 & 1 & -1 & 10 \\ 0 & -4 & 3 & -20 \\ 0 & -1 & 2 & -5 \\ 0 & 4 & 1 & 20 \end{array} \right] \begin{array}{l} \\ 4R_3 - R_2 \\ R_4 + R_2 \\ \end{array} \\
 \left[ \begin{array}{ccc|c} 1 & 1 & -1 & 10 \\ 0 & -4 & 3 & -20 \\ 0 & 0 & 5 & 0 \\ 0 & 0 & 4 & 0 \end{array} \right] \begin{array}{l} x + y = 10 \\ \rightarrow -4y = -20 \\ \rightarrow z = 0 \\ \end{array}
 \end{array}$$

**$\therefore$  Solution:** (5, 5, 0)

### Exercise

Solve the linear system by Gauss-Jordan elimination.

$$\begin{cases} x - y + 2z - w = -1 \\ 2x + y - 2z - 2w = -2 \\ -x + 2y - 4z + w = 1 \\ 3x \quad \quad - 3w = -3 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} 1 & 2 & 1 & 8 \\ -1 & 3 & -2 & 1 \\ 3 & 4 & -7 & 10 \end{array} \right] \begin{array}{l} \\ R_2 + R_1 \\ R_3 - 3R_1 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 2 & 1 & 8 \\ 0 & 5 & -1 & 9 \\ 0 & -2 & -10 & -14 \end{array} \right] 5R_3 + 2R_2$$

$$\left[ \begin{array}{ccc|c} 1 & 2 & 1 & 8 \\ 0 & 5 & -1 & 9 \\ 0 & 0 & -52 & -52 \end{array} \right] \begin{array}{l} x + 2y + z = 8 \quad (3) \\ 5y - z = 9 \quad (2) \\ -52z = -52 \quad (1) \end{array}$$

$$(1) \Rightarrow z = 1$$

$$(2) \Rightarrow 5y = 9 + 1 = 10 \rightarrow y = 2$$

$$(3) \Rightarrow x = 8 - 4 - 1 = 3$$

**$\therefore$  Solution:** (3, 2, 1)

### Exercise

Solve the linear system by Gauss-Jordan elimination.

$$\begin{cases} 2u - 3v + w - x + y = 0 \\ 4u - 6v + 2w - 3x - y = -5 \\ -2u + 3v - 2w + 2x - y = 3 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccccc|c} 2 & -3 & 1 & -1 & 1 & 0 \\ 4 & -6 & 2 & -3 & -1 & -5 \\ -2 & 3 & -2 & 2 & -1 & 3 \end{array} \right] \begin{array}{l} \\ R_2 - 2R_1 \\ R_3 + R_1 \end{array}$$

$$\left[ \begin{array}{ccccc|c} 2 & -3 & 1 & -1 & 1 & 0 \\ 0 & 0 & 0 & -1 & -3 & -5 \\ 0 & 0 & -1 & 1 & 0 & 3 \end{array} \right] \begin{array}{l} 2u - 3v + w - x + y = 0 \quad (3) \\ -x - 3y = -5 \quad (2) \\ -w + x = 3 \quad (1) \end{array}$$

$$(2) \Rightarrow x = 5 - 3y$$

$$(1) \Rightarrow w = x - 3 = 2 - 3y$$

$$(3) \Rightarrow 2u = 3v - 2 + 3y + 5 - 3y - y = 3v - y + 3$$

$$u = \frac{3}{2}v - \frac{1}{2}y + \frac{3}{2}$$

$$\therefore \text{Solution: } \left( \frac{3}{2}v - \frac{1}{2}y + \frac{3}{2}, v, 2 - 3y, 5 - 3y, y \right)$$

### Exercise

Use augmented elimination to solve linear system

$$\begin{cases} 6x_3 + 2x_4 - 4x_5 - 8x_6 = 8 \\ 3x_3 + x_4 - 2x_5 - 4x_6 = 4 \\ 2x_1 - 3x_2 + x_3 + 4x_4 - 7x_5 + x_6 = 2 \\ 6x_1 - 9x_2 + 11x_4 - 19x_5 + 3x_6 = 1 \end{cases}$$

### Solution

$$\left[ \begin{array}{cccccc|c} 2 & -3 & 1 & 4 & -7 & 1 & 2 \\ 0 & 0 & 3 & 1 & -2 & -4 & 4 \\ 0 & 0 & 6 & 2 & -4 & -8 & 8 \\ 6 & -9 & 0 & 11 & -19 & 3 & 1 \end{array} \right] R_4 - 3R_1$$

$$\left[ \begin{array}{cccccc|c} 2 & -3 & 1 & 4 & -7 & 1 & 2 \\ 0 & 0 & 3 & 1 & -2 & -4 & 4 \\ 0 & 0 & 6 & 2 & -4 & -8 & 8 \\ 0 & 0 & -3 & -1 & 2 & 0 & -5 \end{array} \right] \begin{array}{l} \\ R_3 - 2R_2 \\ R_4 + R_2 \end{array}$$

$$\left[ \begin{array}{cccccc|c} 2 & -3 & 1 & 4 & -7 & 1 & 2 \\ 0 & 0 & 3 & 1 & -2 & -4 & 4 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -4 & -1 \end{array} \right] \quad \begin{array}{l} 2x_1 - 3x_2 + x_3 + 4x_4 - 7x_5 = 2 - x_6 \\ 3x_3 + x_4 - 2x_5 = 4 + 4x_6 \end{array}$$

$$\rightarrow \underline{x_6 = \frac{1}{4}}$$

$$\begin{cases} 3x_3 = 5 - x_4 + 2x_5 \\ 2x_1 = \frac{7}{4} + 3x_2 - \frac{1}{3}(5 - x_4 + 2x_5) - 4x_4 + 7x_5 \end{cases}$$

$$\begin{cases} \underline{x_3 = \frac{5}{3} - \frac{1}{3}x_4 + \frac{2}{3}x_5} \\ 2x_1 = \frac{1}{12} + 3x_2 - \frac{11}{3}x_4 + \frac{19}{3}x_5 \end{cases}$$

$$\therefore \text{Solution: } \underline{\left( \frac{1}{24} + \frac{3}{2}x_2 - \frac{11}{6}x_4 + \frac{19}{6}x_5, x_2, \frac{5}{3} - \frac{1}{3}x_4 + \frac{2}{3}x_5, x_4, x_5, \frac{1}{4} \right)}$$

### Exercise

Use augmented elimination to solve linear system

$$\begin{cases} 3x_1 + 2x_2 - x_3 = -15 \\ 5x_1 + 3x_2 + 2x_3 = 0 \\ 3x_1 + x_2 + 3x_3 = 11 \\ -6x_1 - 4x_2 + 2x_3 = 30 \end{cases}$$

### Solution

$$\left[ \begin{array}{ccc|c} 3 & 2 & -1 & -15 \\ 5 & 3 & 2 & 0 \\ 3 & 1 & 3 & 11 \\ -6 & -4 & 2 & 30 \end{array} \right] \quad \begin{array}{l} 3R_2 - 5R_1 \\ R_3 - R_1 \\ R_4 + 2R_1 \end{array}$$

$$\left[ \begin{array}{ccc|c} 3 & 2 & -1 & -15 \\ 0 & -1 & 11 & 75 \\ 0 & -1 & 4 & 26 \\ 0 & 0 & 0 & 0 \end{array} \right] \quad R_3 - R_2$$

$$\left[ \begin{array}{ccc|c} 3 & 2 & -1 & -15 \\ 0 & -1 & 11 & 75 \\ 0 & 0 & -7 & -49 \\ 0 & 0 & 0 & 0 \end{array} \right] \quad \begin{array}{l} 3x_1 + 2x_2 - x_3 = -15 \quad (3) \\ -x_2 + 11x_3 = 75 \quad (2) \\ -7x_3 = -49 \quad (1) \end{array}$$

$$(1) \rightarrow x_3 = 7$$

$$(2) \rightarrow x_2 = 77 - 75 = 2$$

$$(1) \rightarrow 3x_1 = -15 - 4 + 7 = 12 \Rightarrow x_1 = -4$$

**∴ Solution:**  $(-4, 2, 7)$

### Exercise

Use augmented elimination to solve linear system

$$\begin{cases} x_1 + 3x_2 - 2x_3 + 2x_5 = 0 \\ 2x_1 + 6x_2 - 5x_3 - 2x_4 + 4x_5 - 3x_6 = -1 \\ 5x_3 + 10x_4 + 15x_6 = 5 \\ 2x_1 + 6x_2 + 8x_4 + 4x_5 + 18x_6 = 6 \end{cases}$$

### Solution

$$\left[ \begin{array}{cccccc|c} 1 & 3 & -2 & 0 & 2 & 0 & 0 \\ 2 & 6 & -5 & -2 & 4 & -3 & -1 \\ 0 & 0 & 5 & 10 & 0 & 15 & 5 \\ 2 & 6 & 0 & 8 & 4 & 18 & 6 \end{array} \right] \begin{array}{l} \\ R_2 - 2R_1 \\ \\ R_4 - 2R_1 \end{array}$$

$$\left[ \begin{array}{cccccc|c} 1 & 3 & -2 & 0 & 2 & 0 & 0 \\ 0 & 0 & -1 & -2 & 0 & -3 & -1 \\ 0 & 0 & 5 & 10 & 0 & 15 & 5 \\ 0 & 0 & 4 & 8 & 0 & 18 & 6 \end{array} \right] -R_2$$

$$\left[ \begin{array}{cccccc|c} 1 & 3 & -2 & 0 & 2 & 0 & 0 \\ 0 & 0 & 1 & 2 & 0 & 3 & 1 \\ 0 & 0 & 5 & 10 & 0 & 15 & 5 \\ 0 & 0 & 4 & 8 & 0 & 18 & 6 \end{array} \right] \begin{array}{l} \\ R_3 - 5R_2 \\ R_4 - 4R_2 \end{array}$$

$$\left[ \begin{array}{cccccc|c} 1 & 3 & -2 & 0 & 2 & 0 & 0 \\ 0 & 0 & 1 & 2 & 0 & 3 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 6 & 2 \end{array} \right] \frac{1}{6}R_4 \text{ then interchanging row3 and row4}$$

$$\left[ \begin{array}{cccccc|c} 1 & 3 & -2 & 0 & 2 & 0 & 0 \\ 0 & 0 & 1 & 2 & 0 & 3 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & \frac{1}{3} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array} \right] R_2 - 3R_3$$

$$\left[ \begin{array}{cccccc|c} 1 & 3 & -2 & 0 & 2 & 0 & 0 \\ 0 & 0 & 1 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & \frac{1}{3} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array} \right] \rightarrow \begin{cases} x_1 + 3x_2 + 4x_4 + 2x_5 = 0 \\ x_3 + 2x_4 = 0 \\ + x_6 = \frac{1}{3} \end{cases}$$

The general solution of the system:  $x_6 = \frac{1}{3}, \quad x_3 = -2x_4, \quad x_1 = -3x_2 - 4x_4 - 2x_5$

**∴ Solution:**  $\left( -3x_2 - 4x_4 - 2x_5, x_2, -2x_4, x_4, x_5, \frac{1}{3} \right)$

### Exercise

Add 3 times the second row to the first of

$$\begin{bmatrix} 5 & -1 & 5 \\ 7 & 3 & -2 \\ 8 & 1 & 2 \\ 6 & 0 & -1 \end{bmatrix}$$

### Solution

$$E = \begin{bmatrix} 1 & 3 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$EA = \begin{bmatrix} 1 & 3 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 5 & -1 & 5 \\ 7 & 3 & -2 \\ 8 & 1 & 2 \\ 6 & 0 & -1 \end{bmatrix}$$

$$= \begin{bmatrix} 27 & 8 & -1 \\ 7 & 3 & -2 \\ 8 & 1 & 2 \\ 6 & 0 & -1 \end{bmatrix}$$

$$\begin{bmatrix} 5 & -1 & 5 \\ 7 & 3 & -2 \\ 8 & 1 & 2 \\ 6 & 0 & -1 \end{bmatrix} \xrightarrow{R_1 + 3R_2} \begin{bmatrix} 27 & 8 & -1 \\ 7 & 3 & -2 \\ 8 & 1 & 2 \\ 6 & 0 & -1 \end{bmatrix}$$

### Exercise

For what value(s) of  $k$ , if any, does the system 
$$\begin{cases} x + y - z = 1 \\ 2x + 3y + kz = 3 \\ x + ky + 3z = 2 \end{cases}$$
 have

- a) A unique solution?
- b) Infinitely many solutions?
- c) No solution?

### Solution

$$\left[ \begin{array}{ccc|c} 1 & 1 & -1 & 1 \\ 2 & 3 & k & 3 \\ 1 & k & 3 & 2 \end{array} \right] \begin{array}{l} \\ R_2 - 2R_1 \\ R_3 - R_1 \end{array}$$

$$\left[ \begin{array}{ccc|c} 1 & 1 & -1 & 1 \\ 0 & 1 & k+2 & 1 \\ 0 & k-1 & 4 & 1 \end{array} \right] R_3 - (k-1)R_2$$

$$\left[ \begin{array}{ccc|c} 1 & 1 & -1 & 1 \\ 0 & 1 & k+2 & 1 \\ 0 & 0 & 4-(k-1)(k+2) & 2-k \end{array} \right] \begin{array}{l} x = 1 - y + z \\ y = 1 - (k+2)z \\ \rightarrow (6 - k^2 - k)z = -(k-2) \end{array}$$

$$\begin{cases} z = -\frac{k-2}{-(k-2)(k+3)} = \frac{1}{k+3} \quad (k \neq 2, -3) \\ y = 1 - \frac{k+2}{k+3} = \frac{1}{k+3} \\ x = \frac{k+2}{k+3} + \frac{1}{k+3} = 1 \end{cases}$$

- a) Unique solution if  $k \neq 2, -3$
- b) Infinitely solution if  $k = 2$
- c) No solution if  $k = -3$

### Exercise

Choose a coefficient  $b$  that makes the system singular.

$$\begin{cases} 3x + 4y = 16 \\ 4x + by = g \end{cases}$$

Then choose a right-hand side  $g$  that makes it solvable.  
Find 2 solutions in that singular case.

### Solution

$$\left( \begin{array}{cc|c} 3 & 4 & 16 \\ 4 & b & g \end{array} \right) \xrightarrow{3R_2 - 4R_1} \left( \begin{array}{cc|c} 3 & 4 & 16 \\ 0 & 3b-16 & 3g-64 \end{array} \right)$$

So, the system is singular if

$$3b - 16 = 0 \Rightarrow b = \frac{16}{3}$$

$$\& 3g - 64 = 0 \Rightarrow g = \frac{64}{3}$$

$$\begin{cases} 3x + 4y = 16 \\ 4x + \frac{16}{3}y = \frac{64}{3} \end{cases} \rightarrow \underline{3x + 4y = 16}$$

$$\text{If } \begin{cases} x = 0 \rightarrow y = 4 \\ x = 4 \rightarrow y = 1 \end{cases}$$

### ***Exercise***

This system is not linear, in some sense,

$$\begin{cases} 2\sin\alpha - \cos\beta + 3\tan\theta = 3 \\ 4\sin\alpha + 2\cos\beta - 2\tan\theta = 10 \\ 6\sin\alpha - 3\cos\beta + \tan\theta = 9 \end{cases}$$

Does the system have a solution?

### ***Solution***

$$\left[ \begin{array}{ccc|c} 2 & -1 & 3 & 3 \\ 4 & 2 & -2 & 10 \\ 6 & -3 & 1 & 9 \end{array} \right] \begin{array}{l} \\ R_2 - 2R_1 \\ R_3 - 3R_1 \end{array}$$

$$\left[ \begin{array}{ccc|c} 2 & -1 & 3 & 3 \\ 0 & 4 & -8 & 4 \\ 0 & 0 & -8 & 0 \end{array} \right] \begin{array}{l} 2\sin\alpha = 3 + \cos\beta \\ 4\cos\beta = 4 \\ \tan\theta = 0 \end{array}$$

$$\begin{cases} \sin\alpha = \frac{3}{2} + \frac{1}{2} = 2 \\ \cos\beta = 1 \\ \tan\theta = 0 \end{cases}$$

The system has *no solution* since  $\sin\alpha$  cannot be equal 2. ( $-1 \leq \sin\alpha \leq 1$ )

## ***Solution***      **Section 1.3 – Matrices and Matrix operations**

### ***Exercise***

For the matrices:  $A = \begin{bmatrix} p & 0 \\ q & r \end{bmatrix}$  and  $B = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$ , when does  $AB = BA$

### **Solution**

$$\begin{aligned} AB &= \begin{pmatrix} p & 0 \\ q & r \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \\ &= \begin{pmatrix} p & p \\ q & q+r \end{pmatrix} \end{aligned}$$

$$\begin{aligned} BA &= \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} p & 0 \\ q & r \end{pmatrix} \\ &= \begin{pmatrix} p+q & r \\ q & r \end{pmatrix} \end{aligned}$$

$$AB = BA$$

$$\begin{pmatrix} p & p \\ q & q+r \end{pmatrix} = \begin{pmatrix} p+q & r \\ q & r \end{pmatrix}$$

$$\begin{cases} p = p+q \\ p = r \\ q+r = r \end{cases} \Rightarrow \begin{cases} q = 0 \\ q = 0 \end{cases}$$

### ***Exercise***

Find values for the variables so that the matrices are equal.  $\begin{bmatrix} w & x \\ 8 & -12 \end{bmatrix} = \begin{bmatrix} 9 & 17 \\ y & z \end{bmatrix}$

### **Solution**

$$\begin{bmatrix} w & x \\ 8 & -12 \end{bmatrix} = \begin{bmatrix} 9 & 17 \\ y & z \end{bmatrix}$$

$$\Rightarrow \begin{cases} w = 9 & x = 17 \\ y = 8 & z = -12 \end{cases}$$



### Exercise

Find values for the variables so that the matrices are equal.  $\begin{bmatrix} x & y+3 \\ 2z & 8 \end{bmatrix} = \begin{bmatrix} 12 & 5 \\ 6 & 8 \end{bmatrix}$

### Solution

$$\begin{cases} \underline{x = 12} \\ y + 3 = 5 \rightarrow \underline{y = 2} \\ 2z = 6 \rightarrow \underline{z = 3} \end{cases}$$

### Exercise

Find values for the variables so that the matrices are equal.  $\begin{bmatrix} 5 & x-4 & 9 \\ 2 & -3 & 8 \\ 6 & 0 & 5 \end{bmatrix} = \begin{bmatrix} y+3 & 2 & 9 \\ z+4 & -3 & 8 \\ 6 & 0 & w \end{bmatrix}$

### Solution

$$\begin{bmatrix} 5 = y + 3 & x - 4 = 2 & 9 = 9 \\ 2 = z + 4 & -3 = -3 & 8 = 8 \\ 6 = 6 & 0 = 0 & 5 = w \end{bmatrix}$$

$$\rightarrow \begin{cases} y = 2 & z = -2 \\ x = 6 & w = 5 \end{cases}$$

### Exercise

Find values for the variables so that the matrices are equal.

$$\begin{bmatrix} a+2 & 3b & 4c \\ d & 7f & 8 \end{bmatrix} + \begin{bmatrix} -7 & 2b & 6 \\ -3d & -6 & -2 \end{bmatrix} = \begin{bmatrix} 15 & 25 & 6 \\ -8 & 1 & 6 \end{bmatrix}$$

### Solution

$$\begin{bmatrix} a-5 & 5b & 4c+6 \\ -2d & 7f-6 & 6 \end{bmatrix} = \begin{bmatrix} 15 & 25 & 6 \\ -8 & 1 & 6 \end{bmatrix}$$

$$\begin{cases} a - 5 = 15 \rightarrow a = 20 \\ 5b = 25 \rightarrow b = 5 \\ 4c + 6 = 6 \rightarrow 4c = 0 \rightarrow c = 0 \\ -2d = -8 \rightarrow d = 4 \\ 7f - 6 = 1 \rightarrow 7f = 7 \rightarrow f = 1 \end{cases}$$

### Exercise

Find values for the variables so that the matrices are equal.

$$\begin{bmatrix} a+11 & 12z+1 & 5m \\ 11k & 3 & 1 \end{bmatrix} + \begin{bmatrix} 9a & 9z & 4m \\ 12k & 5 & 3 \end{bmatrix} = \begin{bmatrix} 41 & -62 & 72 \\ 92 & 8 & 4 \end{bmatrix}$$

### Solution

$$\begin{bmatrix} a+11+9a & 12z+1+9z & 5m+4m \\ 11k+12k & 3+5 & 1+3 \end{bmatrix} = \begin{bmatrix} 41 & -62 & 72 \\ 92 & 8 & 4 \end{bmatrix}$$

$$\begin{bmatrix} 10a+11 & 21z+1 & 9m \\ 23k & 8 & 4 \end{bmatrix} = \begin{bmatrix} 41 & -62 & 72 \\ 92 & 8 & 4 \end{bmatrix}$$

$$10a+11=41 \rightarrow 10a=30$$

$$\underline{a=3}$$

$$21z+1=-62 \rightarrow 21z=-63$$

$$\underline{z=-3}$$

$$9m=72 \rightarrow \underline{m=8}$$

$$23k=92 \rightarrow \underline{k=\frac{92}{23}=\underline{4}}$$

### Exercise

Find values for the variables so that the matrices are equal.

$$\begin{bmatrix} x+2 & 3y+1 & 5z \\ 8w & 2 & 3 \end{bmatrix} + \begin{bmatrix} 3x & 2y & 5z \\ 2w & 5 & -5 \end{bmatrix} = \begin{bmatrix} 10 & -14 & 80 \\ 10 & 7 & -2 \end{bmatrix}$$

### Solution

$$\begin{bmatrix} 4x+2 & 5y+1 & 10z \\ 10w & 7 & -2 \end{bmatrix} = \begin{bmatrix} 10 & -14 & 80 \\ 10 & 7 & -2 \end{bmatrix}$$

$$\begin{cases} 4x+2=10 & \rightarrow \underline{x=2} \\ 5y+1=-14 & \rightarrow \underline{y=-3} \\ 10z=80 & \rightarrow \underline{z=8} \\ 10w=10 & \rightarrow \underline{w=1} \end{cases}$$

### Exercise

Find values for the variables so that the matrices are equal.

$$\begin{bmatrix} 2x-3 & y-2 & 2z+1 \\ 5 & 2w & 7 \end{bmatrix} + \begin{bmatrix} 3x-3 & y+2 & z-1 \\ -5 & 5w+1 & 3 \end{bmatrix} = \begin{bmatrix} 20 & 8 & 9 \\ 0 & 8 & 10 \end{bmatrix}$$

### Solution

$$\begin{bmatrix} 5x-6 & 2y & 3z \\ 0 & 7w+1 & 10 \end{bmatrix} = \begin{bmatrix} 20 & 8 & 9 \\ 0 & 8 & 10 \end{bmatrix}$$

$$\begin{cases} 5x-6=20 & \rightarrow x=\frac{26}{5} \\ 2y=8 & \rightarrow y=4 \\ 3z=9 & \rightarrow z=3 \\ 7w+1=8 & \rightarrow w=1 \end{cases}$$

### Exercise

Find a combination  $x_1 w_1 + x_2 w_2 + x_3 w_3$  that gives the zero vector:

$$w_1 = \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}; \quad w_2 = \begin{bmatrix} 4 \\ 5 \\ 6 \end{bmatrix}; \quad w_3 = \begin{bmatrix} 7 \\ 8 \\ 9 \end{bmatrix}.$$

Those vectors are independent or dependent?

The vectors lie in a \_\_\_\_\_.

The matrix W with those columns is not invertible.

### Solution

$$w_1 - 2w_2 + w_3 = 0; \text{ Therefore those vectors are dependent}$$

The vectors lie in a plane.

### Exercise

The very last words say that the 5 by 5 centered difference matrix is not invertible, Write down the 5 equations  $Cx = b$ . Find a combination of left sides that gives zero. What combination of

$b_1, b_2, b_3, b_4, b_5$  must be zero?

### Solution

The 5 by 5 centered difference matrix is

$$C = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & -1 & 0 & 1 \\ 0 & 0 & 0 & -1 & 0 \end{pmatrix}$$

The five equations  $Cx = b$  are:

$$x_2 = b_1, \quad -x_1 + x_3 = b_2, \quad -x_2 + x_4 = b_3, \quad -x_3 + x_5 = b_4, \quad -x_4 = b_5.$$

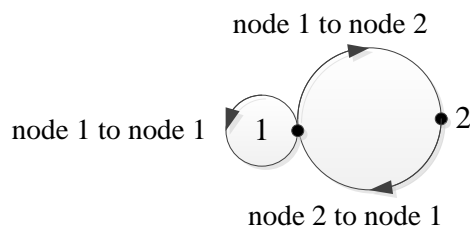
Observe that the sum of the first

$$x_2 - x_2 + x_4 - x_4 = b_1 + b_2 + b_5$$

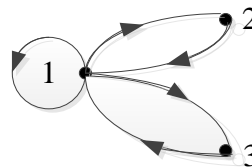
$$0 = b_1 + b_2 + b_5$$

### Exercise

A directed graph starts with  $n$  nodes. There are  $n^2$  possible edges, each edge leaves one of the  $n$  nodes and enters one of the  $n$  nodes (possibly itself). The  $n$  by  $n$  adjacency matrix has  $a_{ij} = 1$  when edge leaves node  $i$  and enter node  $j$ ; if no edge then  $a_{ij} = 0$ . Here are directed graphs and their adjacency matrices:



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



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

The  $i, j$  entry of  $A^2$  is  $a_{i1}a_{1j} + \dots + a_{in}a_{nj}$ .

Why does that sum count the two-step paths from  $i$  to any node to  $j$ ?

The  $i, j$  entry of  $A^k$  counts  $k$ -steps paths:

$$\begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}^2 = \begin{bmatrix} 2 & 1 \\ 1 & 1 \end{bmatrix} \quad \begin{array}{l} \text{counts the paths} \\ \text{with two edges} \end{array} \quad \begin{bmatrix} 1 \text{ to } 2 \text{ to } 1, 1 \text{ to } 1 \text{ to } 1 & 1 \text{ to } 1 \text{ to } 2 \\ 2 \text{ to } 1 \text{ to } 1 & 2 \text{ to } 1 \text{ to } 2 \end{bmatrix}$$

List all 3-step paths between each pair of nodes and compare with  $A^3$ . When  $A^k$  has **no zeros**, that number  $k$  is the diameter of the graph – the number of edges needed to connect the most pair of nodes.

What is the diameter of the second graph?

### Solution

The number  $a_{ik} a_{kj}$  will be “1” if there is an edge from node  $i$  to  $k$  and an edge from  $k$  to  $j$ .

This is a 2-step path. The number  $a_{ik} a_{kj}$  will be “0” if either of those edge (from node  $i$  to  $k$  and from  $k$  to  $j$ ) is missing.

The sum of  $a_{ik} a_{kj}$  is the number of 2-step paths leaving  $i$  and entering  $j$ .

Matrix multiplication is right for this count.

The 3-step paths are counted by  $A^3$ ; we look at paths to node 2:

$$\begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}^3 = \begin{bmatrix} 3 & 2 \\ 2 & 1 \end{bmatrix} \quad \begin{array}{l} \text{counts the paths} \\ \text{with three steps} \end{array} \quad \begin{bmatrix} \dots & 1 \text{ to } 1 \text{ to } 1 \text{ to } 2, 1 \text{ to } 2 \text{ to } 1 \text{ to } 2 \\ \dots & 2 \text{ to } 1 \text{ to } 1 \text{ to } 2 \end{bmatrix}$$

The  $A^k$  contain Fibonacci numbers 0, 1, 1, 2, 3, 5, 8, 13, ....

Fibonacci's rule  $F_{k+2} = F_{k+1} + F_k$  show up in  $(A)(A^k) = A^{k+1}$

$$\begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} F_{k+1} & F_k \\ F_k & F_{k-1} \end{pmatrix} = \begin{pmatrix} F_{k+2} & F_{k+1} \\ F_{k+1} & F_k \end{pmatrix} = A^{k+1}$$

There are **13 six-step** paths from node one to node 1.

## Exercise

$A$  is 3 by 5,  $B$  is 5 by 3,  $C$  is 5 by 1, and  $D$  is 3 by 1. All entries are 1. Which of these matrix operations are allowed, and what are the results?

a)  $AB$

c)  $ABD$

e)  $ABC$

g)  $A(B+C)$

b)  $BA$

d)  $DBA$

f)  $ABCD$

## Solution

$$A = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \end{pmatrix} \quad B = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \quad C = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} \quad D = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

a)  $AB: (3 \times 5)(5 \times 3) = (3 \times 3)$

$$\begin{pmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} = \begin{pmatrix} 5 & 5 & 5 \\ 5 & 5 & 5 \\ 5 & 5 & 5 \end{pmatrix}$$

b)  $BA: (5 \times 3)(3 \times 5) = (5 \times 5)$

$$\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \end{pmatrix} = \begin{pmatrix} 3 & 3 & 3 & 3 & 3 \\ 3 & 3 & 3 & 3 & 3 \\ 3 & 3 & 3 & 3 & 3 \\ 3 & 3 & 3 & 3 & 3 \\ 3 & 3 & 3 & 3 & 3 \end{pmatrix}$$

c)  $ABD : (3 \times 5)(5 \times 3)(3 \times 1) = (3 \times 1)$

$$\begin{pmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 5 & 5 & 5 \\ 5 & 5 & 5 \\ 5 & 5 & 5 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

$$= \begin{pmatrix} 15 \\ 15 \\ 15 \end{pmatrix}$$

d)  $DBA : (3 \times 1)(5 \times 3)(3 \times 5) = NA$

e)  $ABC : (3 \times 5)(5 \times 3)(5 \times 1) = NA$

f)  $ABCD : (3 \times 5)(5 \times 3)(5 \times 1)(3 \times 1) = NA$

g)  $A(B + C) : (3 \times 5)((5 \times 3) + (5 \times 1)) = NA$

Matrices  $B$  and  $C$  are not the same size.

### ***Exercise***

What rows or columns or matrices do you multiply to find.

- The third column of  $AB$ ?
- The second column of  $AB$ ?
- The first row of  $AB$ ?
- The second row of  $AB$ ?
- The entry in row 3, column 4 of  $AB$ ?
- The entry in row 2, column 3 of  $AB$ ?

### **Solution**

- $A$  (column 3 of  $B$ )
- $A$  (column 2 of  $B$ )
- (Row 1 of  $A$ )  $B$
- (Row 2 of  $A$ )  $B$
- (Row 3 of  $A$ ) (Column 4 of  $B$ )
- (Row 2 of  $A$ ) (Column 3 of  $B$ )

### Exercise

Add  $AB$  to  $AC$  and compare with  $A(B + C)$ :

$$A = \begin{bmatrix} 1 & 5 \\ 2 & 3 \end{bmatrix} \quad \text{and} \quad B = \begin{bmatrix} 0 & 2 \\ 0 & 1 \end{bmatrix} \quad \text{and} \quad C = \begin{bmatrix} 3 & 1 \\ 0 & 0 \end{bmatrix}$$

### Solution

$$AB = \begin{bmatrix} 1 & 5 \\ 2 & 3 \end{bmatrix} \begin{bmatrix} 0 & 2 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 7 \\ 0 & 7 \end{bmatrix}$$

$$AC = \begin{bmatrix} 1 & 5 \\ 2 & 3 \end{bmatrix} \begin{bmatrix} 3 & 1 \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} 3 & 1 \\ 6 & 2 \end{bmatrix}$$

$$\begin{aligned} A(B + C) &= \begin{bmatrix} 1 & 5 \\ 2 & 3 \end{bmatrix} \left( \begin{bmatrix} 0 & 2 \\ 0 & 1 \end{bmatrix} + \begin{bmatrix} 3 & 1 \\ 0 & 0 \end{bmatrix} \right) \\ &= \begin{bmatrix} 1 & 5 \\ 2 & 3 \end{bmatrix} \begin{bmatrix} 3 & 3 \\ 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} 3 & 8 \\ 6 & 9 \end{bmatrix} \end{aligned}$$

$$\begin{aligned} AB + AC &= \begin{bmatrix} 0 & 7 \\ 0 & 7 \end{bmatrix} + \begin{bmatrix} 3 & 1 \\ 6 & 2 \end{bmatrix} \\ &= \begin{bmatrix} 3 & 8 \\ 6 & 9 \end{bmatrix} \end{aligned}$$

$$\underline{A(B + C) = AB + AC}$$

### Exercise

True or False

- a) If  $A^2$  is defined then  $A$  is necessarily square.
- b) If  $AB$  and  $BA$  are defined then  $A$  and  $B$  are square.
- c) If  $AB$  and  $BA$  are defined then  $AB$  and  $BA$  are square.
- d) If  $AB = B$ , then  $A = I$

### Solution

- a) True
- b) False, if  $A$  has an order  $m$  by  $n$  and  $B$   $n$  by  $m$ :  $AB : m \times m$      $BA : n \times n$
- c) True;  $AB : m \times m$      $BA : n \times n$
- d) False, if  $B$  is the matrix of all zeros.

### Exercise

a) Find a nonzero matrix  $A$  such that  $A^2 = 0$

b) Find a matrix that has  $A^2 \neq 0$  but  $A^3 = 0$

### Solution

a) A nonzero matrix  $A$  such that  $A^2 = 0$

$$A = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \Rightarrow A^2 = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}$$

b) A matrix that has  $A^2 \neq 0$  but  $A^3 = 0$

$$A = \begin{pmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$$

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

$$= \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$A^3 = A^2 A$$

$$= \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$$

$$= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

### Exercise

Suppose you solve  $Ax = b$  for three special right sides  $b$ :

$$Ax_1 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad Ax_2 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \quad Ax_3 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

If the three solutions  $x_1, x_2, x_3$  are the columns of a matrix  $X$ , what is  $A$  times  $X$ ?

### Solution



$$Ax = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = I$$

Therefore,  $Ax = I$

### ***Exercise***

Show that  $(A + B)^2$  is different from  $A^2 + 2AB + B^2$ , when

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

Write down the correct rule for  $(A + B)(A + B) = A^2 + \underline{\hspace{2cm}} + B^2$

### ***Solution***

$$\begin{aligned} A + B &= \begin{bmatrix} 1 & 2 \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 3 & 0 \end{bmatrix} \\ &= \begin{bmatrix} 2 & 2 \\ 3 & 0 \end{bmatrix} \end{aligned}$$

$$\begin{aligned} (A + B)^2 &= \begin{bmatrix} 2 & 2 \\ 3 & 0 \end{bmatrix} \begin{bmatrix} 2 & 2 \\ 3 & 0 \end{bmatrix} \\ &= \begin{bmatrix} 10 & 4 \\ 6 & 6 \end{bmatrix} \end{aligned}$$

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

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

$$AB = \begin{bmatrix} 1 & 2 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 3 & 0 \end{bmatrix} = \begin{bmatrix} 7 & 0 \\ 0 & 0 \end{bmatrix}$$

$$2AB = 2 \begin{bmatrix} 7 & 0 \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} 14 & 0 \\ 0 & 0 \end{bmatrix}$$

$$\begin{aligned} A^2 + 2AB + B^2 &= \begin{bmatrix} 1 & 2 \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} 14 & 0 \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 3 & 0 \end{bmatrix} \\ &= \begin{bmatrix} 16 & 2 \\ 3 & 0 \end{bmatrix} \end{aligned}$$

$$\begin{bmatrix} 10 & 4 \\ 6 & 6 \end{bmatrix} \neq \begin{bmatrix} 16 & 2 \\ 3 & 0 \end{bmatrix}$$

$$\boxed{(A+B)^2 \neq A^2 + 2AB + B^2}$$

$$\begin{aligned} BA &= \begin{bmatrix} 1 & 0 \\ 3 & 0 \end{bmatrix} \begin{bmatrix} 1 & 2 \\ 0 & 0 \end{bmatrix} \\ &= \begin{bmatrix} 1 & 2 \\ 3 & 6 \end{bmatrix} \end{aligned}$$

$$\begin{aligned} A^2 + AB + BA + B^2 &= \begin{bmatrix} 1 & 2 \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} 7 & 0 \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} 1 & 2 \\ 3 & 6 \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 3 & 0 \end{bmatrix} \\ &= \begin{bmatrix} 10 & 4 \\ 5 & 6 \end{bmatrix} \end{aligned}$$

$$\boxed{(A+B)(A+B) = A^2 + \textcolor{teal}{-}AB + \textcolor{red}{BA}\textcolor{teal}{-} + B^2}$$

### ***Exercise***

Find the product of the 2 matrices by rows or by columns:  $\begin{bmatrix} 2 & 3 \\ 5 & 1 \end{bmatrix} \begin{bmatrix} 4 \\ 2 \end{bmatrix}$

### ***Solution***

$$\begin{aligned} \text{By rows: } \begin{bmatrix} 2 & 3 \\ 5 & 1 \end{bmatrix} \begin{bmatrix} 4 \\ 2 \end{bmatrix} &= \begin{pmatrix} (2 \quad 3) \begin{pmatrix} 4 \\ 2 \end{pmatrix} \\ (5 \quad 1) \begin{pmatrix} 4 \\ 2 \end{pmatrix} \end{pmatrix} \\ &= \begin{pmatrix} \textcolor{blue}{14} \\ \textcolor{blue}{22} \end{pmatrix} \end{aligned}$$

$$\begin{aligned} \text{By columns: } \begin{pmatrix} 2 & 3 \\ 5 & 1 \end{pmatrix} \begin{pmatrix} 4 \\ 2 \end{pmatrix} &= 4 \begin{pmatrix} 2 \\ 5 \end{pmatrix} + 2 \begin{pmatrix} 3 \\ 1 \end{pmatrix} \\ &= \begin{pmatrix} \textcolor{blue}{14} \\ \textcolor{blue}{22} \end{pmatrix} \end{aligned}$$

### ***Exercise***

Find the product of the 2 matrices by rows or by columns:  $\begin{bmatrix} 3 & 6 \\ 6 & 12 \end{bmatrix} \begin{bmatrix} 2 \\ -1 \end{bmatrix}$

### **Solution**

$$\begin{aligned} \text{By rows: } \begin{pmatrix} 3 & 6 \\ 6 & 12 \end{pmatrix} \begin{pmatrix} 2 \\ -1 \end{pmatrix} &= \begin{pmatrix} (3 \ 6)(2 \ -1) \\ (6 \ 12)(2 \ -1) \end{pmatrix} \\ &= \begin{pmatrix} 0 \\ 0 \end{pmatrix} \end{aligned}$$

$$\begin{aligned} \text{By columns: } \begin{pmatrix} 3 & 6 \\ 6 & 12 \end{pmatrix} \begin{pmatrix} 2 \\ -1 \end{pmatrix} &= 2 \begin{pmatrix} 3 \\ 6 \end{pmatrix} - 1 \begin{pmatrix} 6 \\ 12 \end{pmatrix} \\ &= \begin{pmatrix} 0 \\ 0 \end{pmatrix} \end{aligned}$$

### ***Exercise***

Find the product of the 2 matrices by rows or by columns:  $\begin{bmatrix} 1 & 2 & 4 \\ 2 & 0 & 1 \end{bmatrix} \begin{bmatrix} 3 \\ 1 \\ 1 \end{bmatrix}$

### **Solution**

$$\begin{aligned} \text{By rows: } \begin{pmatrix} 1 & 2 & 4 \\ 2 & 0 & 1 \end{pmatrix} \begin{pmatrix} 3 \\ 1 \\ 1 \end{pmatrix} &= \begin{pmatrix} (1 \ 2 \ 4)(3 \ 1 \ 1) \\ (2 \ 0 \ 1)(3 \ 1 \ 1) \end{pmatrix} \\ &= \begin{pmatrix} 1(3) + 2(1) + 4(1) \\ 2(3) + 0(1) + 1(1) \end{pmatrix} \\ &= \begin{pmatrix} 9 \\ 7 \end{pmatrix} \end{aligned}$$

$$\begin{aligned} \text{By columns: } \begin{pmatrix} 1 & 2 & 4 \\ 2 & 0 & 1 \end{pmatrix} \begin{pmatrix} 3 \\ 1 \\ 1 \end{pmatrix} &= 3 \begin{pmatrix} 1 \\ 2 \end{pmatrix} + 1 \begin{pmatrix} 2 \\ 0 \end{pmatrix} + 1 \begin{pmatrix} 4 \\ 1 \end{pmatrix} \\ &= \begin{pmatrix} 9 \\ 7 \end{pmatrix} \end{aligned}$$

### Exercise

Find the product of the 2 matrices by rows or by columns:  $\begin{bmatrix} 1 & 2 & 4 \\ -2 & 3 & 1 \\ -4 & 1 & 2 \end{bmatrix} \begin{bmatrix} 2 \\ 2 \\ 3 \end{bmatrix}$

### Solution

$$\begin{aligned} \text{By rows: } \begin{pmatrix} 1 & 2 & 4 \\ -2 & 3 & 1 \\ -4 & 1 & 2 \end{pmatrix} \begin{pmatrix} 2 \\ 2 \\ 3 \end{pmatrix} &= \begin{pmatrix} (1 \ 2 \ 4)(2 \ 2 \ 3) \\ (-2 \ 3 \ 1)(2 \ 2 \ 3) \\ (-4 \ 1 \ 2)(2 \ 2 \ 3) \end{pmatrix} \\ &= \begin{pmatrix} 18 \\ 5 \\ 0 \end{pmatrix} \end{aligned}$$

$$\begin{aligned} \text{By columns: } \begin{pmatrix} 1 & 2 & 4 \\ -2 & 3 & 1 \\ -4 & 1 & 2 \end{pmatrix} \begin{pmatrix} 2 \\ 2 \\ 3 \end{pmatrix} &= 2 \begin{pmatrix} 1 \\ -2 \\ -4 \end{pmatrix} + 2 \begin{pmatrix} 2 \\ 3 \\ 1 \end{pmatrix} + 3 \begin{pmatrix} 4 \\ 1 \\ 2 \end{pmatrix} \\ &= \begin{pmatrix} 18 \\ 5 \\ 0 \end{pmatrix} \end{aligned}$$

### Exercise

Given  $A = \begin{bmatrix} 4 & 1 & 3 \\ 3 & -1 & -2 \\ 0 & 0 & 4 \end{bmatrix}$        $B = \begin{bmatrix} -3 & -2 & -3 \\ -1 & 0 & 0 \\ 8 & -2 & -4 \end{bmatrix}$       Find  $A + B$ ,  $2A$ , and  $-B$

### Solution

$$\begin{aligned} A + B &= \begin{bmatrix} 4 & 1 & 3 \\ 3 & -1 & -2 \\ 0 & 0 & 4 \end{bmatrix} + \begin{bmatrix} -3 & -2 & -3 \\ -1 & 0 & 0 \\ 8 & -2 & -4 \end{bmatrix} \\ &= \begin{bmatrix} 1 & -1 & 0 \\ 2 & -1 & -2 \\ 8 & -2 & 0 \end{bmatrix} \end{aligned}$$

$$2A = 2 \begin{bmatrix} 4 & 1 & 3 \\ 3 & -1 & -2 \\ 0 & 0 & 4 \end{bmatrix}$$

$$= \begin{bmatrix} 8 & 2 & 6 \\ 6 & -2 & -4 \\ 0 & 0 & 8 \end{bmatrix}$$

$$\begin{aligned} -B &= - \begin{bmatrix} -3 & -2 & -3 \\ -1 & 0 & 0 \\ 8 & -2 & -4 \end{bmatrix} \\ &= \begin{bmatrix} 3 & 2 & 3 \\ 1 & 0 & 0 \\ -8 & 2 & 4 \end{bmatrix} \end{aligned}$$

### ***Exercise***

Given  $A = \begin{bmatrix} 1 & 3 \\ -2 & 5 \end{bmatrix}$  and  $B = \begin{bmatrix} -2 & 7 \\ 0 & 2 \end{bmatrix}$ . Find  $AB$  and  $BA$ .

### **Solution**

$$AB = \begin{bmatrix} 1 & 3 \\ -2 & 5 \end{bmatrix} \begin{bmatrix} -2 & 7 \\ 0 & 2 \end{bmatrix} = \begin{bmatrix} -2 & 13 \\ 4 & -4 \end{bmatrix}$$

$$BA = \begin{bmatrix} -2 & 7 \\ 0 & 2 \end{bmatrix} \begin{bmatrix} 1 & 3 \\ -2 & 5 \end{bmatrix} = \begin{bmatrix} -16 & 29 \\ -4 & 10 \end{bmatrix}$$

**Note:**  $AB \neq BA$

### ***Exercise***

Given  $A = \begin{pmatrix} 2 & -3 \\ 1 & 4 \end{pmatrix}$   $B = \begin{pmatrix} -2 & 4 \\ 2 & -3 \end{pmatrix}$ . Find  $AB$  and  $BA$ .

### **Solution**

$$\begin{aligned} AB &= \begin{pmatrix} 2 & -3 \\ 1 & 4 \end{pmatrix} \begin{pmatrix} -2 & 4 \\ 2 & -3 \end{pmatrix} \\ &= \begin{pmatrix} -6 & 17 \\ 6 & -8 \end{pmatrix} \end{aligned}$$

$$\begin{aligned} BA &= \begin{pmatrix} -2 & 4 \\ 2 & -3 \end{pmatrix} \begin{pmatrix} 2 & -3 \\ 1 & 4 \end{pmatrix} \\ &= \begin{pmatrix} 0 & 14 \\ 1 & -20 \end{pmatrix} \end{aligned}$$

### ***Exercise***

Given  $A = \begin{pmatrix} 3 & -2 \\ 4 & 1 \end{pmatrix}$   $B = \begin{pmatrix} -1 & -1 \\ 0 & 4 \end{pmatrix}$ . Find  $AB$  and  $BA$ .

### **Solution**

$$\begin{aligned} AB &= \begin{pmatrix} 3 & -2 \\ 4 & 1 \end{pmatrix} \begin{pmatrix} -1 & -1 \\ 0 & 4 \end{pmatrix} \\ &= \begin{pmatrix} -3 & -11 \\ 4 & 0 \end{pmatrix} \end{aligned}$$

$$\begin{aligned} BA &= \begin{pmatrix} -1 & -1 \\ 0 & 4 \end{pmatrix} \begin{pmatrix} 3 & -2 \\ 4 & 1 \end{pmatrix} \\ &= \begin{pmatrix} -7 & 1 \\ 16 & 4 \end{pmatrix} \end{aligned}$$

### ***Exercise***

Given  $A = \begin{pmatrix} 3 & -1 \\ 2 & 3 \end{pmatrix}$   $B = \begin{pmatrix} 4 & 1 \\ 2 & -3 \end{pmatrix}$ . Find  $AB$  and  $BA$ .

### **Solution**

$$\begin{aligned} AB &= \begin{pmatrix} 3 & -1 \\ 2 & 3 \end{pmatrix} \begin{pmatrix} 4 & 1 \\ 2 & -3 \end{pmatrix} \\ &= \begin{pmatrix} 10 & 6 \\ 14 & -7 \end{pmatrix} \end{aligned}$$

$$\begin{aligned} BA &= \begin{pmatrix} 4 & 1 \\ 2 & -3 \end{pmatrix} \begin{pmatrix} 3 & -1 \\ 2 & 3 \end{pmatrix} \\ &= \begin{pmatrix} 14 & -1 \\ 0 & -11 \end{pmatrix} \end{aligned}$$

### ***Exercise***

Given  $A = \begin{pmatrix} -3 & 2 \\ 2 & -2 \end{pmatrix}$   $B = \begin{pmatrix} 0 & 2 \\ -2 & 4 \end{pmatrix}$ . Find  $AB$  and  $BA$ .

### **Solution**

$$\begin{aligned} AB &= \begin{pmatrix} -3 & 2 \\ 2 & -2 \end{pmatrix} \begin{pmatrix} 0 & 2 \\ -2 & 4 \end{pmatrix} \\ &= \begin{pmatrix} -4 & 2 \\ 4 & -4 \end{pmatrix} \end{aligned}$$

$$\begin{aligned}
 BA &= \begin{pmatrix} 0 & 2 \\ -2 & 4 \end{pmatrix} \begin{pmatrix} -3 & 2 \\ 2 & -2 \end{pmatrix} \\
 &= \begin{pmatrix} 4 & -4 \\ 14 & -12 \end{pmatrix}
 \end{aligned}$$

### ***Exercise***

Given  $A = \begin{pmatrix} 2 & -1 \\ 0 & 3 \\ 1 & -2 \end{pmatrix}$   $B = \begin{pmatrix} 1 & -2 & 3 \\ 2 & 0 & 1 \end{pmatrix}$ . Find  $AB$  and  $BA$ .

### **Solution**

$$\begin{aligned}
 AB &= \begin{pmatrix} 2 & -1 \\ 0 & 3 \\ 1 & -2 \end{pmatrix} \begin{pmatrix} 1 & -2 & 3 \\ 2 & 0 & 1 \end{pmatrix} \\
 &= \begin{pmatrix} 0 & -4 & 5 \\ 6 & 0 & 3 \\ -3 & -2 & 1 \end{pmatrix}
 \end{aligned}$$

$$\begin{aligned}
 BA &= \begin{pmatrix} 1 & -2 & 3 \\ 2 & 0 & 1 \end{pmatrix} \begin{pmatrix} 2 & -1 \\ 0 & 3 \\ 1 & -2 \end{pmatrix} \\
 &= \begin{pmatrix} 5 & -13 \\ 3 & -4 \end{pmatrix}
 \end{aligned}$$

### ***Exercise***

Given  $A = \begin{pmatrix} -1 & 3 \\ 2 & 1 \\ -3 & 2 \end{pmatrix}$   $B = \begin{pmatrix} 1 & -2 & 3 \\ 0 & 1 & 2 \end{pmatrix}$ . Find  $AB$  and  $BA$ .

### **Solution**

$$\begin{aligned}
 AB &= \begin{pmatrix} -1 & 3 \\ 2 & 1 \\ -3 & 2 \end{pmatrix} \begin{pmatrix} 1 & -2 & 3 \\ 0 & 1 & 2 \end{pmatrix} \\
 &= \begin{pmatrix} -1 & 5 & 4 \\ 2 & -3 & 8 \\ -3 & 8 & -5 \end{pmatrix}
 \end{aligned}$$

$$\begin{aligned}
 BA &= \begin{pmatrix} 1 & -2 & 3 \\ 0 & 1 & 2 \end{pmatrix} \begin{pmatrix} -1 & 3 \\ 2 & 1 \\ -3 & 2 \end{pmatrix} \\
 &= \begin{pmatrix} -14 & 7 \\ -4 & 5 \end{pmatrix}
 \end{aligned}$$

### ***Exercise***

Given  $A = \begin{pmatrix} 2 & 4 \\ 0 & -1 \\ -3 & 2 \end{pmatrix}$   $B = \begin{pmatrix} 3 & 0 & -2 \\ -2 & 6 & 2 \end{pmatrix}$ . Find  $AB$  and  $BA$ .

### **Solution**

$$\begin{aligned}
 AB &= \begin{pmatrix} 2 & 4 \\ 0 & -1 \\ -3 & 2 \end{pmatrix} \begin{pmatrix} 3 & 0 & -2 \\ -2 & 6 & 2 \end{pmatrix} \\
 &= \begin{pmatrix} -2 & 24 & 4 \\ 2 & -6 & -2 \\ -13 & 12 & 10 \end{pmatrix}
 \end{aligned}$$

$$\begin{aligned}
 BA &= \begin{pmatrix} 3 & 0 & -2 \\ -2 & 6 & 2 \end{pmatrix} \begin{pmatrix} 2 & 4 \\ 0 & -1 \\ -3 & 2 \end{pmatrix} \\
 &= \begin{pmatrix} 12 & 8 \\ -10 & 10 \end{pmatrix}
 \end{aligned}$$

### ***Exercise***

Given  $A = \begin{bmatrix} 3 & 2 & -3 \\ 0 & 1 & 0 \end{bmatrix}$   $B = \begin{bmatrix} 3 & -4 \\ 0 & 1 \\ 1 & 0 \end{bmatrix}$  Find  $AB$  and  $BA$  if possible

### **Solution**

$$\begin{aligned}
 AB &= \begin{bmatrix} 3 & 2 & -3 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 3 & -4 \\ 0 & 1 \\ 1 & 0 \end{bmatrix} \\
 &= \begin{bmatrix} 3(3) + 2(0) - 3(1) & 3(-4) + 2(1) - 3(0) \\ 0(3) + 1(0) + 0(1) & 0(-4) + 1(1) + 0(0) \end{bmatrix}
 \end{aligned}$$



$$\begin{aligned}
&= \begin{bmatrix} 6 & -10 \\ 0 & 1 \end{bmatrix} \\
BA &= \begin{bmatrix} 3 & -4 \\ 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 3 & 2 & -3 \\ 0 & 1 & 0 \end{bmatrix} \\
&= \begin{bmatrix} 3(3) - 4(0) & 3(2) - 4(1) & 3(-3) - 4(0) \\ 0(3) + 1(0) & 0(2) + 1(1) & 0(-3) + 1(0) \\ 1(3) + 0(0) & 1(2) + 0(1) & 1(-3) + 0(0) \end{bmatrix} \\
&= \begin{bmatrix} 9 & 2 & -9 \\ 0 & 1 & 0 \\ 3 & 2 & -3 \end{bmatrix}
\end{aligned}$$

### ***Exercise***

Given  $A = \begin{bmatrix} 5 & 3 \\ -1 & 0 \end{bmatrix}$   $B = \begin{bmatrix} 4 & -2 \\ -2 & 0 \\ 9 & 1 \end{bmatrix}$  Find  $AB$  and  $BA$  if possible

### **Solution**

$AB = \text{Undefined}$

$$\begin{aligned}
BA &= \begin{bmatrix} 4 & -2 \\ -2 & 0 \\ 9 & 1 \end{bmatrix} \begin{bmatrix} 5 & 3 \\ -1 & 0 \end{bmatrix} \\
&= \begin{bmatrix} 22 & 12 \\ -10 & -6 \\ 44 & 27 \end{bmatrix}
\end{aligned}$$

### ***Exercise***

Given  $A = \begin{bmatrix} 3 & 0 \\ -1 & 2 \\ 1 & 1 \end{bmatrix}$   $B = \begin{bmatrix} 4 & -1 \\ 0 & 2 \end{bmatrix}$  Find  $AB$  and  $BA$  if possible

### **Solution**

$$AB = \begin{bmatrix} 3 & 0 \\ -1 & 2 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} 4 & -1 \\ 0 & 2 \end{bmatrix}$$

$$= \begin{bmatrix} 12 & -3 \\ -4 & 5 \\ 4 & 1 \end{bmatrix}$$

$$BA = \text{Undefined}$$

### ***Exercise***

Given  $A = \begin{pmatrix} 2 & -1 & 3 \\ 0 & 2 & -1 \\ 0 & 1 & 2 \end{pmatrix}$   $B = \begin{pmatrix} 3 & 0 & 0 \\ 1 & -1 & 0 \\ 2 & -1 & -2 \end{pmatrix}$ . Find  $AB$  and  $BA$ .

### **Solution**

$$\begin{aligned} AB &= \begin{pmatrix} 2 & -1 & 3 \\ 0 & 2 & -1 \\ 0 & 1 & 2 \end{pmatrix} \begin{pmatrix} 3 & 0 & 0 \\ 1 & -1 & 0 \\ 2 & -1 & -2 \end{pmatrix} \\ &= \begin{pmatrix} 11 & -2 & -6 \\ 0 & -1 & 2 \\ 5 & -3 & -4 \end{pmatrix} \end{aligned}$$

$$\begin{aligned} BA &= \begin{pmatrix} 3 & 0 & 0 \\ 1 & -1 & 0 \\ 2 & -1 & -2 \end{pmatrix} \begin{pmatrix} 2 & -1 & 3 \\ 0 & 2 & -1 \\ 0 & 1 & 2 \end{pmatrix} \\ &= \begin{pmatrix} 6 & -3 & 9 \\ 2 & -3 & 4 \\ 4 & -6 & 3 \end{pmatrix} \end{aligned}$$

### ***Exercise***

Given  $A = \begin{pmatrix} -1 & 2 & 0 \\ 2 & -1 & 1 \\ -2 & 2 & -1 \end{pmatrix}$   $B = \begin{pmatrix} 2 & -1 & 0 \\ 1 & 5 & -1 \\ 0 & -1 & 3 \end{pmatrix}$ . Find  $AB$  and  $BA$ .

### **Solution**

$$\begin{aligned} AB &= \begin{pmatrix} -1 & 2 & 0 \\ 2 & -1 & 1 \\ -2 & 2 & -1 \end{pmatrix} \begin{pmatrix} 2 & -1 & 0 \\ 1 & 5 & -1 \\ 0 & -1 & 3 \end{pmatrix} \\ &= \begin{pmatrix} 0 & 8 & -2 \\ 3 & -8 & 4 \\ -2 & 13 & -5 \end{pmatrix} \end{aligned}$$

$$\begin{aligned}
 BA &= \begin{pmatrix} 2 & -1 & 0 \\ 1 & 5 & -1 \\ 0 & -1 & 3 \end{pmatrix} \begin{pmatrix} -1 & 2 & 0 \\ 2 & -1 & 1 \\ -2 & 2 & -1 \end{pmatrix} \\
 &= \begin{pmatrix} -4 & 5 & -1 \\ 11 & -5 & 6 \\ -8 & 7 & -4 \end{pmatrix}
 \end{aligned}$$

### Exercise

Given  $A = \begin{pmatrix} 1 & -2 & 0 \\ 2 & 0 & 1 \\ 2 & -2 & -1 \end{pmatrix}$   $B = \begin{pmatrix} -3 & 1 & 0 \\ 1 & 4 & -1 \\ 0 & 0 & 2 \end{pmatrix}$ . Find  $AB$  and  $BA$ .

### Solution

$$\begin{aligned}
 AB &= \begin{pmatrix} 1 & -2 & 0 \\ 2 & 0 & 1 \\ 2 & -2 & -1 \end{pmatrix} \begin{pmatrix} -3 & 1 & 0 \\ 1 & 4 & -1 \\ 0 & 0 & 2 \end{pmatrix} \\
 &= \begin{pmatrix} -5 & -7 & 2 \\ -6 & 2 & 2 \\ -8 & -6 & 0 \end{pmatrix}
 \end{aligned}$$

$$\begin{aligned}
 BA &= \begin{pmatrix} -3 & 1 & 0 \\ 1 & 4 & -1 \\ 0 & 0 & 2 \end{pmatrix} \begin{pmatrix} 1 & -2 & 0 \\ 2 & 0 & 1 \\ 2 & -2 & -1 \end{pmatrix} \\
 &= \begin{pmatrix} -1 & 6 & 1 \\ 7 & 0 & 5 \\ 4 & -4 & -2 \end{pmatrix}
 \end{aligned}$$

### Exercise

Consider the matrices

$$A = \begin{bmatrix} 3 & 0 \\ -1 & 2 \\ 1 & 1 \end{bmatrix} \quad B = \begin{bmatrix} 4 & -1 \\ 0 & 2 \end{bmatrix} \quad C = \begin{bmatrix} 1 & 4 & 2 \\ 3 & 1 & 5 \end{bmatrix} \quad D = \begin{bmatrix} 1 & 5 & 2 \\ -1 & 0 & 1 \\ 3 & 2 & 4 \end{bmatrix} \quad E = \begin{bmatrix} 6 & 1 & 3 \\ -1 & 1 & 2 \\ 4 & 1 & 3 \end{bmatrix}$$

Compute the following (where possible):

$$\text{a) } D + E \quad \text{b) } D - E \quad \text{c) } 5A \quad \text{d) } -7C \quad \text{e) } 2B - C \quad \text{f) } -3(D + 2E)$$

### Solution

$$\begin{aligned}
 a) \quad D + E &= \begin{bmatrix} 1 & 5 & 2 \\ -1 & 0 & 1 \\ 3 & 2 & 4 \end{bmatrix} + \begin{bmatrix} 6 & 1 & 3 \\ -1 & 1 & 2 \\ 4 & 1 & 3 \end{bmatrix} \\
 &= \begin{bmatrix} 7 & 6 & 5 \\ -2 & 1 & 3 \\ 7 & 3 & 7 \end{bmatrix}
 \end{aligned}$$

$$\begin{aligned}
 b) \quad D - E &= \begin{bmatrix} 1 & 5 & 2 \\ -1 & 0 & 1 \\ 3 & 2 & 4 \end{bmatrix} - \begin{bmatrix} 6 & 1 & 3 \\ -1 & 1 & 2 \\ 4 & 1 & 3 \end{bmatrix} \\
 &= \begin{bmatrix} -5 & 4 & -1 \\ 0 & -1 & -1 \\ -1 & 1 & 1 \end{bmatrix}
 \end{aligned}$$

$$\begin{aligned}
 c) \quad 5A &= 5 \begin{bmatrix} 3 & 0 \\ -1 & 2 \\ 1 & 1 \end{bmatrix} \\
 &= \begin{bmatrix} 15 & 0 \\ -5 & 10 \\ 5 & 5 \end{bmatrix}
 \end{aligned}$$

$$\begin{aligned}
 d) \quad -7C &= -7 \begin{bmatrix} 1 & 4 & 2 \\ 3 & 1 & 5 \end{bmatrix} \\
 &= \begin{bmatrix} -7 & -28 & -14 \\ -21 & -7 & -35 \end{bmatrix}
 \end{aligned}$$

e) Since  $B$  and  $C$  are not the same size

$2B - C$ : *can't be calculated*

$$\begin{aligned}
 f) \quad -3(D + 2E) &= -3 \left( \begin{bmatrix} 1 & 5 & 2 \\ -1 & 0 & 1 \\ 3 & 2 & 4 \end{bmatrix} + \begin{bmatrix} 12 & 2 & 6 \\ -2 & 2 & 4 \\ 8 & 2 & 6 \end{bmatrix} \right) \\
 &= -3 \begin{bmatrix} 13 & 7 & 8 \\ -3 & 2 & 5 \\ 11 & 4 & 10 \end{bmatrix} \\
 &= \begin{bmatrix} -39 & -21 & -24 \\ 9 & -6 & -15 \\ -33 & -12 & -30 \end{bmatrix}
 \end{aligned}$$

## Exercise

Consider the matrices

$$A = \begin{bmatrix} 3 & 0 \\ -1 & 2 \\ 1 & 1 \end{bmatrix} \quad B = \begin{bmatrix} 1 & 5 & 2 \\ -1 & 1 & 0 \\ -4 & 1 & 3 \end{bmatrix} \quad C = \begin{bmatrix} -3 & -1 \\ 2 & 1 \\ 4 & 3 \end{bmatrix} \quad D = \begin{bmatrix} 4 & -1 \\ 2 & 0 \end{bmatrix}$$

Compute the following (where possible):

- a)  $A + B$       b)  $A + C$       c)  $AB$       d)  $BA$       e)  $CD$       f)  $DC$   
g)  $BD$       h)  $DB$       i)  $A^2$       j)  $B^2$       k)  $D^2$

## Solution

- a) Since  $A$  and  $B$  are not the same size, then

$$A + B = \text{can't be calculated}$$

$$\begin{aligned} \text{b) } A + C &= \begin{bmatrix} 3 & 0 \\ -1 & 2 \\ 1 & 1 \end{bmatrix} + \begin{bmatrix} -3 & -1 \\ 2 & 1 \\ 4 & 3 \end{bmatrix} \\ &= \begin{bmatrix} 0 & -1 \\ 1 & 3 \\ 5 & 4 \end{bmatrix} \end{aligned}$$

- c)  $A: 3 \times 2$      $B: 3 \times 3$

$AB$  *can't be calculated*, since the inner are not equal.

- d)  $B: 3 \times 3$      $A: 3 \times 2$

$$\begin{aligned} BA &= \begin{bmatrix} 1 & 5 & 2 \\ -1 & 1 & 0 \\ -4 & 1 & 3 \end{bmatrix} \begin{bmatrix} 3 & 0 \\ -1 & 2 \\ 1 & 1 \end{bmatrix} \\ &= \begin{bmatrix} 0 & 12 \\ -1 & 2 \\ -10 & 5 \end{bmatrix} \end{aligned}$$

- e)  $C: 3 \times 2$      $D: 2 \times 2$

$$\begin{aligned} CD &= \begin{bmatrix} -3 & -1 \\ 2 & 1 \\ 4 & 3 \end{bmatrix} \begin{bmatrix} 4 & -1 \\ 2 & 0 \end{bmatrix} \\ &= \begin{bmatrix} -14 & 3 \\ 10 & -2 \\ 22 & -4 \end{bmatrix} \end{aligned}$$

- f)  $D: 2 \times 2$   $C: 3 \times 2$   
 $DC$  *can't be calculated*, since the inner are not equal.
- g)  $B: 3 \times 3$   $D: 2 \times 2$   
 $BD$  *can't be calculated*, since the inner are not equal.
- h)  $D: 2 \times 2$   $B: 3 \times 3$   
 $DB$  *can't be calculated*, since the inner are not equal.
- i)  $A^2$  *can't be calculated*, since  $A$  is not square matrix.

$$j) \quad B^2 = \begin{bmatrix} 1 & 5 & 2 \\ -1 & 1 & 0 \\ -4 & 1 & 3 \end{bmatrix} \begin{bmatrix} 1 & 5 & 2 \\ -1 & 1 & 0 \\ -4 & 1 & 3 \end{bmatrix}$$

$$= \begin{bmatrix} -12 & 12 & 8 \\ -2 & -4 & -2 \\ -17 & -16 & 1 \end{bmatrix}$$

$$k) \quad D^2 = \begin{bmatrix} 4 & -1 \\ 2 & 0 \end{bmatrix} \begin{bmatrix} 4 & -1 \\ 2 & 0 \end{bmatrix}$$

$$= \begin{bmatrix} 14 & -4 \\ 8 & -2 \end{bmatrix}$$

### Exercise

Let  $B = \begin{pmatrix} a & 0 \\ 1 & b \end{pmatrix}$ , show that  $B^4 = \begin{pmatrix} a^4 & 0 \\ a^3 + a^2b + ab^2 + b^3 & b^4 \end{pmatrix}$

### Solution

$$B^2 = \begin{pmatrix} a & 0 \\ 1 & b \end{pmatrix} \begin{pmatrix} a & 0 \\ 1 & b \end{pmatrix}$$

$$= \begin{pmatrix} a^2 & 0 \\ a+b & b^2 \end{pmatrix}$$

$$B^4 = B^2 B^2 = \begin{pmatrix} a^2 & 0 \\ a+b & b^2 \end{pmatrix} \begin{pmatrix} a^2 & 0 \\ a+b & b^2 \end{pmatrix}$$

$$= \begin{pmatrix} a^4 & 0 \\ a^3 + a^2b + ab^2 + b^3 & b^4 \end{pmatrix} \quad \checkmark$$

### Exercise

Let  $B = \begin{pmatrix} a & 0 \\ 1 & b \end{pmatrix}$ , show that  $B^n = \begin{pmatrix} a^n & 0 \\ \sum_{k=0}^{n-1} a^{n-1-k} b^k & b^n \end{pmatrix}$

### Solution

$$\begin{aligned} n=2 \rightarrow B^2 &= \begin{pmatrix} a & 0 \\ 1 & b \end{pmatrix} \begin{pmatrix} a & 0 \\ 1 & b \end{pmatrix} \\ &= \begin{pmatrix} a^2 & 0 \\ a+b & b^2 \end{pmatrix} \quad \checkmark \end{aligned}$$

Let assume  $B^n = \begin{pmatrix} a^n & 0 \\ \sum_{k=0}^{n-1} a^{n-1-k} b^k & b^n \end{pmatrix}$  is true

We need to also prove that it is true for  $B^{n+1} = \begin{pmatrix} a^{n+1} & 0 \\ \sum_{k=0}^n a^{n-k} b^k & b^{n+1} \end{pmatrix}$

$$\begin{aligned} B^{n+1} &= B^n B = \begin{pmatrix} a^n & 0 \\ \sum_{k=0}^{n-1} a^{n-1-k} b^k & b^n \end{pmatrix} \begin{pmatrix} a & 0 \\ 1 & b \end{pmatrix} \\ &= \begin{pmatrix} a^{n+1} & 0 \\ b^n + a \sum_{k=0}^{n-1} a^{n-1-k} b^k & b^{n+1} \end{pmatrix} \\ &= \begin{pmatrix} a^{n+1} & 0 \\ b^n + \sum_{k=0}^n a^{n-k} b^k & b^{n+1} \end{pmatrix} \\ &= \begin{pmatrix} a^{n+1} & 0 \\ \sum_{k=0}^n a^{n-k} b^k & b^{n+1} \end{pmatrix} \quad \checkmark \end{aligned}$$

### Exercise

Let  $A = \begin{bmatrix} 7 & 4 \\ -9 & -5 \end{bmatrix}$ . Prove that  $A^n = \begin{bmatrix} 1+6n & 4n \\ -9n & 1-6n \end{bmatrix}$  if  $n \geq 1$

### Solution

Using the principle of mathematical induction.

For  $n=1 \rightarrow A = \begin{bmatrix} 1+6 & 4 \\ -9 & 1-6 \end{bmatrix} = \begin{bmatrix} 7 & 4 \\ -9 & -5 \end{bmatrix}$  ✓  $P_1$  is true

Assume that  $P_n$  is true,  $A^n = \begin{bmatrix} 1+6n & 4n \\ -9n & 1-6n \end{bmatrix}$

We need to prove that  $P_{n+1}$ :

$$\begin{aligned} A^{n+1} &= \begin{bmatrix} 1+6(n+1) & 4(n+1) \\ -9(n+1) & 1-6(n+1) \end{bmatrix} \\ &= \begin{bmatrix} 7+6n & 4n+4 \\ -9n-9 & -6n-5 \end{bmatrix} \quad \text{is also true.} \end{aligned}$$

$$\begin{aligned} A^{n+1} &= AA^n \\ &= \begin{bmatrix} 7 & 4 \\ -9 & -5 \end{bmatrix} \begin{bmatrix} 1+6n & 4n \\ -9n & 1-6n \end{bmatrix} \\ &= \begin{bmatrix} 7+42n-36n & 28n+4-24n \\ -9-54n+45n & -36n-5+30n \end{bmatrix} \\ &= \begin{bmatrix} 7+6n & 4n+4 \\ -9n-9 & -6n-5 \end{bmatrix} \quad \text{✓ } P_{n+1} \text{ is also true} \end{aligned}$$

$\therefore$  By mathematical induction, the proof of  $A^n = \begin{bmatrix} 1+6n & 4n \\ -9n & 1-6n \end{bmatrix}$  is completed.

### Exercise

Let  $A = \begin{bmatrix} 2a & -a^2 \\ 1 & 0 \end{bmatrix}$ . Prove that  $A^n = \begin{bmatrix} (n+1)a^n & -na^{n+1} \\ na^{n-1} & (1-n)a^n \end{bmatrix}$  if  $n \geq 1$

### Solution

Using the principle of mathematical induction.

For  $n=1 \rightarrow A^1 = \begin{bmatrix} (1+1)a & -a^2 \\ 1a^0 & (1-1)a \end{bmatrix} = \begin{bmatrix} 2a & -a^2 \\ 1 & 0 \end{bmatrix}$  ✓  $P_1$  is true



Assume that  $P_n$  is true,  $A^n = \begin{bmatrix} (n+1)a^n & -na^{n+1} \\ na^{n-1} & (1-n)a^n \end{bmatrix}$

We need to prove that  $P_{n+1}$  :

$$A^{n+1} = \begin{bmatrix} (n+2)a^{n+1} & -(n+1)a^{n+2} \\ (n+1)a^n & -na^{n+1} \end{bmatrix} \text{ is also } \textcolor{red}{true}.$$

$$\begin{aligned} A^{n+1} &= AA^n \\ &= \begin{bmatrix} 2a & -a^2 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} (n+1)a^n & -na^{n+1} \\ na^{n-1} & (1-n)a^n \end{bmatrix} \\ &= \begin{bmatrix} 2(n+1)a^{n+1} - na^{n+1} & -2na^{n+2} - (1-n)a^{n+2} \\ (n+1)a^n & -na^{n+1} \end{bmatrix} \\ &= \begin{bmatrix} (2n+2-n)a^{n+1} & -(2n+1-n)a^{n+2} \\ (n+1)a^n & -na^{n+1} \end{bmatrix} \\ &= \begin{bmatrix} (n+2)a^{n+1} & -(n+1)a^{n+2} \\ (n+1)a^n & -na^{n+1} \end{bmatrix} \checkmark P_{n+1} \text{ is also true} \end{aligned}$$

$\therefore$  By mathematical induction, the proof of  $A^n = \begin{bmatrix} (n+1)a^n & -na^{n+1} \\ na^{n-1} & (1-n)a^n \end{bmatrix}$  is completed.

### ***Exercise***

The following system of recurrence relations holds for all  $n \geq 0$

$$\begin{cases} x_{n+1} = 7x_n + 4y_n \\ y_{n+1} = -9x_n - 5y_n \end{cases}$$

Solve the system for  $x_n$  and  $y_n$  in terms of  $x_0$  and  $y_0$

### **Solution**

$$\begin{cases} x_{n+1} = 7x_n + 4y_n \\ y_{n+1} = -9x_n - 5y_n \end{cases}$$

$$\begin{pmatrix} x_{n+1} \\ y_{n+1} \end{pmatrix} = \begin{pmatrix} 7 & 4 \\ -9 & -5 \end{pmatrix} \begin{pmatrix} x_n \\ y_n \end{pmatrix}$$

$$X_{n+1} = AX_n$$

$$A = \begin{pmatrix} 7 & 4 \\ -9 & -5 \end{pmatrix} \quad X_n = \begin{pmatrix} x_n \\ y_n \end{pmatrix}$$

$$X_1 = AX_0$$

$$X_2 = AX_1 = A(AX_0) = A^2X_0$$

$$X_3 = AX_2 = A(A^2X_0) = A^3X_0$$

$$\vdots \quad \vdots$$

$$X_n = A^nX_0$$

$$\begin{pmatrix} x_n \\ y_n \end{pmatrix} = \begin{pmatrix} 7 & 4 \\ -9 & -5 \end{pmatrix}^n \begin{pmatrix} x_0 \\ y_0 \end{pmatrix}$$

Since, when  $\begin{pmatrix} 7 & 4 \\ -9 & -5 \end{pmatrix}$  that implies  $A^n = \begin{pmatrix} 1+6n & 4n \\ -9n & 1-6n \end{pmatrix}$  (from previous prove).

$$\begin{aligned} \begin{pmatrix} x_n \\ y_n \end{pmatrix} &= \begin{pmatrix} 1+6n & 4n \\ -9n & 1-6n \end{pmatrix} \begin{pmatrix} x_0 \\ y_0 \end{pmatrix} \\ &= \begin{pmatrix} (1+6n)x_0 + 4ny_0 \\ -9nx_0 + (1-6n)y_0 \end{pmatrix} \end{aligned}$$

$$\therefore \begin{cases} x_n = (1+6n)x_0 + 4ny_0 \\ y_n = -9nx_0 + (1-6n)y_0 \end{cases}$$

### **Exercise**

If  $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ , prove that  $A^2 - (a+d)A + (ad-bc)I_{2 \times 2} = 0$

### **Solution**

$$\begin{aligned} A^2 &= \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} a & b \\ c & d \end{pmatrix} \\ &= \begin{pmatrix} a^2 + bc & ab + bd \\ ac + cd & bc + d^2 \end{pmatrix} \end{aligned}$$

$$A^2 - (a+d)A + (ad-bc)I = \begin{pmatrix} a^2 + bc & ab + bd \\ ac + cd & bc + d^2 \end{pmatrix} - (a+d) \begin{pmatrix} a & b \\ c & d \end{pmatrix} + (ad-bc) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$\begin{aligned}
&= \begin{pmatrix} a^2 + bc & ab + bd \\ ac + cd & bc + d^2 \end{pmatrix} - \begin{pmatrix} a^2 + ad & ab + bd \\ ac + cd & ad + d^2 \end{pmatrix} + \begin{pmatrix} ad - bc & 0 \\ 0 & ad - bc \end{pmatrix} \\
&= \begin{pmatrix} a^2 + bc - a^2 - ad + ad - bc & ab + bd - ab - bd \\ ac + cd - ac - cd & bc + d^2 - ad - d^2 + ad - bc \end{pmatrix} \\
&= \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \\
&= \underline{0} \quad \checkmark
\end{aligned}$$

### Exercise

If  $A = \begin{pmatrix} 4 & -3 \\ 1 & 0 \end{pmatrix}$ , use the fact  $A^2 = 4A - 3I$  and mathematical induction, to prove that

$$A^n = \frac{3^n - 1}{2}A + \frac{3 - 3^n}{2}I \quad \text{if } n \geq 1$$

### Solution

$$\begin{aligned}
A^2 &= \begin{pmatrix} 4 & -3 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 4 & -3 \\ 1 & 0 \end{pmatrix} \\
&= \begin{pmatrix} 13 & -12 \\ 4 & -3 \end{pmatrix}
\end{aligned}$$

$$\begin{aligned}
4A - 3I &= 4 \begin{pmatrix} 4 & -3 \\ 1 & 0 \end{pmatrix} - 3 \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\
&= \begin{pmatrix} 16 & -12 \\ 4 & 0 \end{pmatrix} - \begin{pmatrix} 3 & 0 \\ 0 & 3 \end{pmatrix} \\
&= \begin{pmatrix} 13 & -12 \\ 4 & -3 \end{pmatrix} \\
&= \underline{A^2}
\end{aligned}$$

Using mathematical induction model

$$\text{For } n=1 \rightarrow A^1 = \frac{3^1 - 1}{2}A + \frac{3 - 3^1}{2}I$$

$$A = A + 0 = A \quad \checkmark \quad \text{is true for } P_1$$

$$\text{Assume is true for } P_k \rightarrow A^k = \frac{3^k - 1}{2}A + \frac{3 - 3^k}{2}I$$

$$\text{We need to prove that is also true for } P_{k+1} \rightarrow A^{k+1} = \frac{3^{k+1} - 1}{2}A + \frac{3 - 3^{k+1}}{2}I$$

$$A^{k+1} = AA^k$$

$$\begin{aligned}
&= A \left( \frac{3^k - 1}{2} A + \frac{3 - 3^k}{2} I \right) \\
&= \frac{3^k - 1}{2} A^2 + \frac{3 - 3^k}{2} (AI) \quad A^2 = 4A - 3I \\
&= \frac{3^k - 1}{2} (4A - 3I) + \frac{3 - 3^k}{2} A \\
&= 2(3^k - 1)A - \frac{3(3^k - 1)}{2} I + \frac{3 - 3^k}{2} A \\
&= \left( 2 \cdot 3^k - 2 + \frac{3 - 3^k}{2} \right) A - \frac{3^{k+1} - 3}{2} I \\
&= \left( \frac{4 \cdot 3^k - 4 + 3 - 3^k}{2} \right) A - \frac{3^{k+1} - 3}{2} I \\
&= \left( \frac{3 \cdot 3^k - 1}{2} \right) A - \frac{3^{k+1} - 3}{2} I \\
&= \frac{3^{k+1} - 1}{2} A + \frac{3 - 3^{k+1}}{2} I \quad \checkmark \text{ is also true for } P_{k+1}
\end{aligned}$$

By mathematical induction, the proof that  $A^n = \frac{3^n - 1}{2} A + \frac{3 - 3^n}{2} I$  if  $n \geq 1$  is completed.

### Exercise

A sequence of numbers  $x_1, x_2, \dots, x_n, \dots$  satisfies the recurrence relation  $x_{n+1} = ax_n + bx_{n-1}$  for  $n \geq 1$ , where  $a$  and  $b$  are constants. Prove that

$$\begin{bmatrix} x_{n+1} \\ x_n \end{bmatrix} = A \begin{bmatrix} x_n \\ x_{n-1} \end{bmatrix}$$

Where  $A = \begin{bmatrix} a & b \\ 1 & 0 \end{bmatrix}$  and hence express  $\begin{bmatrix} x_{n+1} \\ x_n \end{bmatrix}$  in terms of  $\begin{bmatrix} x_1 \\ x_0 \end{bmatrix}$ .

If  $a = 4$  and  $b = -3$ , use the previous question to find a formula for  $x_n$  in terms  $x_1$  and  $x_0$

### Solution

$$\begin{aligned}
x_{n+1} &= ax_n + bx_{n-1} \\
&= \begin{bmatrix} a & b \end{bmatrix} \begin{bmatrix} x_n \\ x_{n-1} \end{bmatrix}
\end{aligned}$$

$$x_n = x_n$$

$$= \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_n \\ x_{n-1} \end{bmatrix}$$

$$\begin{bmatrix} x_{n+1} \\ x_n \end{bmatrix} = \begin{bmatrix} a & b \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x_n \\ x_{n-1} \end{bmatrix}$$

$$= A \begin{bmatrix} x_n \\ x_{n-1} \end{bmatrix}$$

$$x_{n+1} = ax_n + bx_{n-1}$$

$$= 4x_n - 3x_{n-1} \quad |$$

$$n=1 \rightarrow x_2 = 4x_1 - 3x_0$$

$$n=2 \rightarrow x_3 = 4x_2 - 3x_1$$

$$= 4(4x_1 - 3x_0) - 3x_1 = (4^2 - 3)x_1 - 3x_0$$

$$= 13x_1 - 12x_0$$

$$n=3 \rightarrow x_4 = 4x_3 - 3x_2$$

$$= 4(13x_1 - 12x_0) - 3(4x_1 - 3x_0)$$

$$= 40x_1 - 39x_0$$

$$n=4 \rightarrow x_5 = 4x_4 - 3x_3$$

$$= 4(40x_1 - 39x_0) - 3(13x_1 - 12x_0)$$

$$= 121x_1 - 120x_0$$

	$x_1$	$x_0$
$n=2 \rightarrow$	4	-3
$n=3 \rightarrow$	13	-12
$n=4 \rightarrow$	40	-39
$n=5 \rightarrow$	121	-120

$$x_n = \frac{3^n - 1}{2} x_1 + \frac{3 - 3^n}{2} x_0 \quad |$$

## Solution

### Section 1.4 – Inverse Matrices - Finding $A^{-1}$

#### *Exercise*

Apply Gauss-Jordan method to find the inverse of this triangular “Pascal matrix”

$$\text{Triangular Pascal matrix} \quad A = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 2 & 1 & 0 \\ 1 & 3 & 3 & 1 \end{bmatrix}$$

#### Solution

$$\left[ \begin{array}{cccc|cccc} 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 2 & 1 & 0 & 0 & 0 & 1 & 0 \\ 1 & 3 & 3 & 1 & 0 & 0 & 0 & 1 \end{array} \right] \begin{array}{l} \\ R_2 - R_1 \\ R_3 - R_1 \\ R_4 - R_1 \end{array}$$

$$\left[ \begin{array}{cccc|cccc} 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 2 & 1 & 0 & -1 & 0 & 1 & 0 \\ 0 & 3 & 3 & 1 & -1 & 0 & 0 & 1 \end{array} \right] \begin{array}{l} \\ \\ R_3 - 2R_2 \\ R_4 - 3R_2 \end{array}$$

$$\left[ \begin{array}{cccc|cccc} 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 3 & 1 & 2 & -3 & 0 & 1 \end{array} \right] \begin{array}{l} \\ \\ \\ R_4 - 3R_3 \end{array}$$

$$\left[ \begin{array}{cccc|cccc} 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 0 & 1 & -1 & 3 & -3 & 1 \end{array} \right]$$

$$A^{-1} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 1 & -2 & 1 & 0 \\ -1 & 3 & -3 & 1 \end{pmatrix}$$

✚ The inverse matrix  $A^{-1}$  looks like  $A$ , except odd-numbered diagonals are multiplied by -1.

### Exercise

If  $A$  is invertible and  $AB = AC$ , prove that  $B = C$

### Solution

$$AB = AC$$

*Multiply by  $A^{-1}$  both sides.*

$$A^{-1}(AB) = A^{-1}(AC)$$

*Multiplication is associative*

$$(A^{-1}A)B = (A^{-1}A)C$$

$$A^{-1}A = I$$

$$IB = IC$$

$$\boxed{B = C}$$

### Exercise

If  $A = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$ , find two matrices  $B \neq C$  such that  $AB = AC$

### Solution

$$\text{Let } B = \begin{bmatrix} 0 & 1 \\ 2 & 1 \end{bmatrix} \quad \text{and} \quad C = \begin{bmatrix} 1 & 0 \\ 1 & 2 \end{bmatrix}$$

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

$$= \begin{bmatrix} 2 & 2 \\ 2 & 2 \end{bmatrix}$$

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

$$= \begin{bmatrix} 2 & 2 \\ 2 & 2 \end{bmatrix}$$

$$\boxed{B \neq C \Rightarrow AB = AC}$$

### Exercise

If  $A$  has  $\text{row } 1 + \text{row } 2 = \text{row } 3$ , show that  $A$  is not invertible

- a) Explain why  $Ax = (1, 0, 0)$  can't have a solution.
- b) Which right sides  $(b_1, b_2, b_3)$  might allow a solution to  $Ax = b$
- c) What happens to  $\text{row } 3$  in elimination?

### Solution

- a) Let  $A_1, A_2, A_3$  be the row vectors of  $A$  and  $x$  is a solution to  $Ax = (1, 0, 0)$ .

Then  $A_1 \cdot x = 1, A_2 \cdot x = 0, A_3 \cdot x = 0$ .

Since  $A_1 + A_2 = A_3$

Means  $A_1 \cdot x + A_2 \cdot x = A_3 \cdot x$

Implies  $1 + 0 = 0$  a contradiction

- b) If  $Ax = (b_1, b_2, b_3) \Rightarrow A_1 \cdot x = b_1, A_2 \cdot x = b_2, A_3 \cdot x = b_3$

Since  $A_1 + A_2 = A_3$

$A_1 \cdot x + A_2 \cdot x = A_3 \cdot x$

$\Rightarrow b_1 + b_2 = b_3$

- c) In the elimination matrix, the third row will be zero.

### Exercise

True or false (with a counterexample if false and a reason if true):

- a) A 4 by 4 matrix with a row of zeros is not invertible.
- b) A matrix with 1's down the main diagonal is invertible.
- c) If  $A$  is invertible then  $A^{-1}$  is invertible.
- d) If  $A$  is invertible then  $A^2$  is invertible.

### Solution

- a) True, because it can have at most 3 pivots.

- b) False, if the matrix:  $A = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$  and only has 2 pivots, thus is not invertible.

- c) True, If  $A$  is invertible then necessarily  $A^{-1}$  is invertible.

- d) True,  $A^2 x = 0$  where  $x$  is nonzero matrix.



$$A^{-1}A^2x = (A^{-1}A)Ax = IAx = Ax = 0$$

Since  $A$  is invertible, this can only be true if  $x$  was zero to begin with. Thus  $A^2$  must also be invertible.

### ***Exercise***

Do there exist 2 by 2 matrices  $A$  and  $B$  with real entries such that  $AB - BA = I$ , where  $I$  is the identity matrix?

### **Solution**

$$\text{Let } A = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} e & f \\ g & h \end{pmatrix}$$

$$\begin{aligned} AB &= \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} e & f \\ g & h \end{pmatrix} \\ &= \begin{pmatrix} ae + bg & af + bh \\ ce + dg & cf + dh \end{pmatrix} \end{aligned}$$

$$\begin{aligned} BA &= \begin{pmatrix} e & f \\ g & h \end{pmatrix} \begin{pmatrix} a & b \\ c & d \end{pmatrix} \\ &= \begin{pmatrix} ae + cf & be + df \\ ag + ch & bg + dh \end{pmatrix} \end{aligned}$$

$$\begin{aligned} AB - BA &= \begin{pmatrix} ae + bg & af + bh \\ ce + dg & cf + dh \end{pmatrix} - \begin{pmatrix} ae + cf & be + df \\ ag + ch & bg + dh \end{pmatrix} \\ &= \begin{pmatrix} bg - cf & af + bh - be - df \\ ce + dg - ag - ch & cf - bg \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \end{aligned}$$

$$\begin{cases} bg - cf = 1 \\ af + bh - be - df = 0 \\ ce + dg - ag - ch = 0 \\ cf - bg = 1 \end{cases}$$

$$\rightarrow \begin{cases} bg - cf = 1 \\ cf - bg = 1 \\ \hline 0 = 2 \end{cases}$$

Therefore,  $AB - BA \neq I$  for any 2 by 2 matrices.

### Exercise

If  $B$  is the inverse of  $A^2$ , show that  $AB$  is the inverse of  $A$ .

### Solution

Since  $B$  is the inverse of  $A^2$  that implies:  $\underline{B = (A^2)^{-1} = (AA)^{-1} = A^{-1}A^{-1}}$

Show that  $AB$  is the inverse of  $A$

$$\begin{aligned}(AB)A &= \left( A \left( A^{-1}A^{-1} \right) \right) A \\ &= \left( (AA^{-1})A^{-1} \right) A \\ &= (IA^{-1})A \\ &= A^{-1}A \\ &= \underline{I}\end{aligned}$$

Therefore,  $AB$  is the inverse of  $A$ .

### Exercise

Find and check the inverses (assuming they exist) of these block matrices.

$$\begin{bmatrix} I & 0 \\ C & I \end{bmatrix} \quad \begin{bmatrix} A & 0 \\ C & D \end{bmatrix} \quad \begin{bmatrix} 0 & I \\ I & D \end{bmatrix}$$

### Solution

$$\begin{bmatrix} I & 0 \\ C & I \end{bmatrix} \begin{bmatrix} I & 0 \\ A & I \end{bmatrix} = \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix}$$

$$\begin{bmatrix} I & 0 \\ C+A & I \end{bmatrix} = \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix} \Rightarrow C+A=0 \rightarrow \mathbf{A = -C}$$

$$\begin{pmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{C} & \mathbf{I} \end{pmatrix}^{-1} = \begin{pmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{-C} & \mathbf{I} \end{pmatrix}$$

$$\begin{bmatrix} A & 0 \\ C & D \end{bmatrix} \begin{bmatrix} E & 0 \\ F & G \end{bmatrix} = \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix}$$

$$\begin{bmatrix} AE & 0 \\ CE+DF & DG \end{bmatrix} = \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix}$$

$$\Rightarrow \begin{cases} AE = I \\ CE + DF = 0 \\ DG = I \end{cases} \rightarrow \begin{cases} E = A^{-1} \\ G = D^{-1} \end{cases}$$

$$\begin{aligned} CE + DF = 0 &\rightarrow CA^{-1} + DF = 0 \\ DF &= -CA^{-1} \\ D^{-1}DF &= -D^{-1}CA^{-1} \\ IF &= -D^{-1}CA^{-1} \\ F &= -D^{-1}CA^{-1} \end{aligned}$$

$$\begin{pmatrix} A & 0 \\ C & D \end{pmatrix}^{-1} = \begin{pmatrix} A^{-1} & 0 \\ -D^{-1}CA^{-1} & D^{-1} \end{pmatrix}$$

$$\begin{aligned} \begin{bmatrix} 0 & I \\ I & D \end{bmatrix} \begin{bmatrix} A & I \\ I & B \end{bmatrix} &= \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix} \\ \begin{bmatrix} I & B \\ A+D & I+DB \end{bmatrix} &= \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix} \\ \rightarrow \begin{cases} B=0 \\ A+D=0 \\ I+DB=I \end{cases} &\Rightarrow \begin{cases} A=-D \\ DB=0 \end{cases} \end{aligned}$$

$$\begin{pmatrix} 0 & I \\ I & D \end{pmatrix}^{-1} = \begin{pmatrix} -D & I \\ I & 0 \end{pmatrix}$$

### ***Exercise***

For which three numbers  $c$  is this matrix not invertible, and why not?

$$A = \begin{bmatrix} 2 & c & c \\ c & c & c \\ 8 & 7 & c \end{bmatrix}$$

### **Solution**

$$c=0, A = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 0 & 0 \\ 8 & 7 & 0 \end{bmatrix} \text{ (zero column 2 / row 2)}$$

$$c=2, A = \begin{bmatrix} 2 & 2 & 2 \\ 2 & 2 & 2 \\ 8 & 7 & 2 \end{bmatrix} \text{ (equal rows)}$$

$$c=7, A = \begin{bmatrix} 2 & 7 & 7 \\ 7 & 7 & 7 \\ 8 & 7 & 7 \end{bmatrix} \text{ (equal columns)}$$

### ***Exercise***

Find  $A^{-1}$  and  $B^{-1}$  (if they exist) by elimination.

$$A = \begin{bmatrix} 2 & 1 & 1 \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{bmatrix} \quad B = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$$

### **Solution**

$$\left( \begin{array}{ccc|ccc} 2 & 1 & 1 & 1 & 0 & 0 \\ 1 & 2 & 1 & 0 & 1 & 0 \\ 1 & 1 & 2 & 0 & 0 & 1 \end{array} \right) \frac{1}{2}R_1$$

$$\left( \begin{array}{ccc|ccc} 1 & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ 1 & 2 & 1 & 0 & 1 & 0 \\ 1 & 1 & 2 & 0 & 0 & 1 \end{array} \right) \begin{array}{l} R_2 - R_1 \\ R_3 - R_1 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ 0 & \frac{3}{2} & \frac{1}{2} & -\frac{1}{2} & 1 & 0 \\ 0 & \frac{1}{2} & \frac{3}{2} & -\frac{1}{2} & 0 & 1 \end{array} \right) \frac{2}{3}R_2$$

$$\left( \begin{array}{ccc|ccc} 1 & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ 0 & 1 & \frac{1}{3} & -\frac{1}{3} & \frac{2}{3} & 0 \\ 0 & \frac{1}{2} & \frac{3}{2} & -\frac{1}{2} & 0 & 1 \end{array} \right) \begin{array}{l} R_1 - \frac{1}{2}R_2 \\ R_3 - \frac{1}{2}R_2 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & \frac{1}{3} & \frac{2}{3} & -\frac{1}{3} & 0 \\ 0 & 1 & \frac{1}{3} & -\frac{1}{3} & \frac{2}{3} & 0 \\ 0 & 0 & \frac{4}{3} & -\frac{1}{3} & -\frac{1}{3} & 1 \end{array} \right) \frac{3}{4}R_3$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & \frac{1}{3} & \frac{2}{3} & -\frac{1}{3} & 0 \\ 0 & 1 & \frac{1}{3} & -\frac{1}{3} & \frac{2}{3} & 0 \\ 0 & 0 & 1 & -\frac{1}{4} & -\frac{1}{4} & \frac{3}{4} \end{array} \right) \begin{array}{l} R_1 - \frac{1}{3}R_3 \\ R_2 - \frac{1}{3}R_3 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & 0 & \frac{3}{4} & -\frac{1}{4} & -\frac{1}{4} \\ 0 & 1 & 0 & -\frac{1}{4} & \frac{3}{4} & -\frac{1}{4} \\ 0 & 0 & 1 & -\frac{1}{4} & -\frac{1}{4} & \frac{3}{4} \end{array} \right)$$

$$A^{-1} = \begin{pmatrix} \frac{3}{4} & -\frac{1}{4} & -\frac{1}{4} \\ -\frac{1}{4} & \frac{3}{4} & -\frac{1}{4} \\ -\frac{1}{4} & -\frac{1}{4} & \frac{3}{4} \end{pmatrix}$$

$$\left( \begin{array}{ccc|ccc} 2 & -1 & -1 & 1 & 0 & 0 \\ -1 & 2 & -1 & 0 & 1 & 0 \\ -1 & -1 & 2 & 0 & 0 & 1 \end{array} \right) \frac{1}{2}R_1$$

$$\left( \begin{array}{ccc|ccc} 1 & -\frac{1}{2} & -\frac{1}{2} & \frac{1}{2} & 0 & 0 \\ -1 & 2 & -1 & 0 & 1 & 0 \\ -1 & -1 & 2 & 0 & 0 & 1 \end{array} \right) \begin{array}{l} R_2 + R_1 \\ R_3 + R_1 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ 0 & \frac{3}{2} & -\frac{3}{2} & \frac{1}{2} & 1 & 0 \\ 0 & -\frac{3}{2} & \frac{3}{2} & -\frac{1}{2} & 0 & 1 \end{array} \right) R_3 + R_2$$

$$\left( \begin{array}{ccc|ccc} 1 & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ 0 & \frac{3}{2} & -\frac{3}{2} & \frac{1}{2} & 1 & 0 \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & 0 & 1 & 1 \end{array} \right)$$

$B^{-1}$  **doesn't** exist, and if we add the columns in  $B$ , the result is zero.

### ***Exercise***

Find  $A^{-1}$  using the Gauss-Jordan method, which has a remarkable inverse.

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

### **Solution**

$$\left( \begin{array}{cccc|cccc} 1 & -1 & 1 & -1 & 1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{array} \right) R_1 + R_2$$

$$\left( \begin{array}{cccc|cccc} 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & -1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{array} \right) R_2 + R_3$$

$$\left( \begin{array}{cccc|cccc} 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{array} \right) R_3 + R_4$$

$$\left( \begin{array}{cccc|cccc} 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{array} \right)$$

$$A^{-1} = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

***Exercise***

Find the inverse, if exists of  $\begin{bmatrix} 6 & -4 \\ -3 & 2 \end{bmatrix}$

**Solution**

$$\begin{aligned} \begin{bmatrix} 6 & -4 \\ -3 & 2 \end{bmatrix}^{-1} &= \frac{1}{12+12} \begin{bmatrix} 2 & 4 \\ 3 & 6 \end{bmatrix} \\ &= \begin{bmatrix} \frac{1}{12} & \frac{1}{6} \\ \frac{1}{8} & \frac{1}{4} \end{bmatrix} \end{aligned}$$

***Exercise***

Find the inverse, if exists of  $\begin{bmatrix} 1 & 4 \\ 2 & 7 \end{bmatrix}$

**Solution**

$$\begin{aligned} \begin{bmatrix} 1 & 4 \\ 2 & 7 \end{bmatrix}^{-1} &= \frac{1}{7-8} \begin{bmatrix} 7 & -4 \\ -2 & 1 \end{bmatrix} \\ &= - \begin{bmatrix} 7 & -4 \\ -2 & 1 \end{bmatrix} \\ &= \begin{bmatrix} -7 & 4 \\ 2 & -1 \end{bmatrix} \end{aligned}$$

***Exercise***

Find the inverse, if exists of  $\begin{bmatrix} -3 & 6 \\ 4 & 5 \end{bmatrix}$

**Solution**

$$\begin{aligned} \begin{bmatrix} -3 & 6 \\ 4 & 5 \end{bmatrix}^{-1} &= \frac{1}{-15-24} \begin{bmatrix} 5 & -6 \\ -4 & -3 \end{bmatrix} \\ &= -\frac{1}{39} \begin{bmatrix} 5 & -6 \\ -4 & -3 \end{bmatrix} \\ &= \begin{bmatrix} -\frac{5}{39} & \frac{2}{13} \\ \frac{4}{39} & \frac{1}{13} \end{bmatrix} \end{aligned}$$

### Exercise

Find the inverse, if exists, of  $A = \begin{bmatrix} 2 & -6 \\ 1 & -2 \end{bmatrix}$

### Solution

$$\begin{aligned} A^{-1} &= \frac{1}{-4+6} \begin{bmatrix} -2 & 6 \\ -1 & 2 \end{bmatrix} \\ &= \frac{1}{2} \begin{bmatrix} -2 & 6 \\ -1 & 2 \end{bmatrix} \\ &= \begin{bmatrix} -1 & 3 \\ -\frac{1}{2} & 1 \end{bmatrix} \end{aligned}$$

### Exercise

Find the inverse, if exists, of  $A = \begin{bmatrix} 10 & -2 \\ -5 & 1 \end{bmatrix}$

### Solution

$$\begin{aligned} A^{-1} &= \frac{1}{10-10} \begin{bmatrix} 10 & -2 \\ -5 & 1 \end{bmatrix} \\ &= \frac{1}{0} \begin{bmatrix} 10 & -2 \\ -5 & 1 \end{bmatrix} \end{aligned}$$

$\therefore$  Inverse *doesn't exist*

### Exercise

Find the inverse of  $A = \begin{bmatrix} -2 & 3 \\ -3 & 4 \end{bmatrix}$

### Solution

$$\begin{aligned} \left[ \begin{array}{cc|cc} -2 & 3 & 1 & 0 \\ -3 & 4 & 0 & 1 \end{array} \right] & \quad -\frac{1}{2}R_1 & \quad \begin{array}{cccc} 1 & -\frac{3}{2} & -\frac{1}{2} & 0 \\ -3 & 4 & 0 & 1 \end{array} \\ \\ \left[ \begin{array}{cc|cc} 1 & -\frac{3}{2} & -\frac{1}{2} & 0 \\ -3 & 4 & 0 & 1 \end{array} \right] & \quad R_2 + 3R_1 & \quad \begin{array}{cccc} -3 & 4 & 0 & 1 \\ 3 & -\frac{9}{2} & -\frac{3}{2} & 0 \\ \hline 0 & -\frac{1}{2} & -\frac{3}{2} & 1 \end{array} \\ \\ \left[ \begin{array}{cc|cc} 1 & -\frac{3}{2} & -\frac{1}{2} & 0 \\ 0 & -\frac{1}{2} & -\frac{3}{2} & 1 \end{array} \right] & \quad -2R_2 & \quad \begin{array}{cccc} 0 & 1 & 3 & -2 \end{array} \end{aligned}$$



$$\left[ \begin{array}{cc|cc} 1 & -\frac{3}{2} & -\frac{1}{2} & 0 \\ 0 & 1 & 3 & -2 \end{array} \right] R_1 + \frac{3}{2}R_2 \quad \begin{array}{cccc} 1 & -\frac{3}{2} & -\frac{1}{2} & 0 \\ 0 & \frac{3}{2} & \frac{9}{2} & -3 \\ \hline 1 & 0 & 4 & -3 \end{array}$$

$$\left[ \begin{array}{cc|cc} 1 & 0 & 4 & -3 \\ 0 & 1 & 3 & -2 \end{array} \right]$$

$$A^{-1} = \begin{bmatrix} 4 & -3 \\ 3 & -2 \end{bmatrix}$$

### ***Exercise***

Find the inverse of  $A = \begin{bmatrix} a & b \\ 3 & 3 \end{bmatrix}$

### **Solution**

$$\begin{aligned} A^{-1} &= \frac{1}{3a-3b} \begin{bmatrix} 3 & -b \\ -3 & a \end{bmatrix} \\ &= \begin{bmatrix} \frac{3}{3(a-b)} & \frac{-b}{3(a-b)} \\ \frac{-3}{3(a-b)} & \frac{a}{3(a-b)} \end{bmatrix} \\ &= \begin{bmatrix} \frac{1}{a-b} & \frac{-b}{3(a-b)} \\ \frac{-1}{a-b} & \frac{a}{3(a-b)} \end{bmatrix} \end{aligned}$$

### ***Exercise***

Find the inverse of  $A = \begin{bmatrix} -2 & a \\ 4 & a \end{bmatrix}$

### **Solution**

$$\begin{aligned} A^{-1} &= \frac{1}{-2a-4a} \begin{bmatrix} a & -a \\ -4 & -2 \end{bmatrix} \\ &= \begin{bmatrix} \frac{a}{-6a} & \frac{-a}{-6a} \\ \frac{-4}{-6a} & \frac{-2}{-6a} \end{bmatrix} \end{aligned}$$

$$= \begin{bmatrix} -\frac{1}{6} & \frac{1}{6} \\ \frac{2}{3a} & \frac{1}{3a} \end{bmatrix}$$

### ***Exercise***

Find the inverse of  $A = \begin{bmatrix} 4 & 4 \\ b & a \end{bmatrix}$

### **Solution**

$$\begin{aligned} A^{-1} &= \frac{1}{4a-4b} \begin{bmatrix} a & -4 \\ -b & 4 \end{bmatrix} \\ &= \begin{bmatrix} \frac{a}{4(a-b)} & \frac{-4}{4(a-b)} \\ \frac{-b}{4(a-b)} & \frac{4}{4(a-b)} \end{bmatrix} \\ &= \begin{bmatrix} \frac{a}{4(a-b)} & \frac{-1}{a-b} \\ \frac{-b}{4(a-b)} & \frac{1}{a-b} \end{bmatrix} \end{aligned}$$

### ***Exercise***

Find the inverse of  $A = \begin{pmatrix} -1 & 2 \\ -2 & 1 \end{pmatrix}$

### **Solution**

$$\begin{aligned} A^{-1} &= \frac{1}{-1+4} \begin{pmatrix} 1 & -2 \\ 2 & -1 \end{pmatrix} \\ &= \frac{1}{3} \begin{pmatrix} 1 & -2 \\ 2 & -1 \end{pmatrix} \\ &= \begin{pmatrix} \frac{1}{3} & -\frac{2}{3} \\ \frac{2}{3} & -\frac{1}{3} \end{pmatrix} \end{aligned}$$

***Exercise***

Find the inverse of  $A = \begin{pmatrix} 1 & -2 \\ 2 & -1 \end{pmatrix}$

**Solution**

$$\begin{aligned} A^{-1} &= \frac{1}{3} \begin{pmatrix} -1 & 2 \\ -2 & 1 \end{pmatrix} \\ &= \begin{pmatrix} -\frac{1}{3} & \frac{2}{3} \\ -\frac{2}{3} & \frac{1}{3} \end{pmatrix} \end{aligned}$$

***Exercise***

Find the inverse of  $A = \begin{pmatrix} 2 & 4 \\ 3 & -1 \end{pmatrix}$

**Solution**

$$\begin{aligned} A^{-1} &= -\frac{1}{14} \begin{pmatrix} -1 & -4 \\ -3 & 2 \end{pmatrix} \\ &= \begin{pmatrix} \frac{1}{14} & \frac{2}{7} \\ \frac{3}{14} & -\frac{1}{7} \end{pmatrix} \end{aligned}$$

***Exercise***

Find the inverse of  $A = \begin{pmatrix} -1 & 3 \\ 2 & -1 \end{pmatrix}$

**Solution**

$$\begin{aligned} A^{-1} &= -\frac{1}{5} \begin{pmatrix} -1 & -3 \\ -2 & -1 \end{pmatrix} \\ &= \begin{pmatrix} \frac{1}{5} & \frac{3}{5} \\ \frac{2}{5} & \frac{1}{5} \end{pmatrix} \end{aligned}$$

***Exercise***

Find the inverse of  $A = \begin{pmatrix} 1 & 3 \\ -2 & 5 \end{pmatrix}$

**Solution**

$$A^{-1} = \frac{1}{11} \begin{pmatrix} 5 & -3 \\ 2 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} \frac{5}{11} & -\frac{3}{11} \\ \frac{2}{11} & \frac{1}{11} \end{pmatrix}$$

### ***Exercise***

Find the inverse of  $A = \begin{pmatrix} 4 & 6 \\ 2 & 3 \end{pmatrix}$

### **Solution**

$$A^{-1} = \frac{1}{\textcolor{red}{0}} \begin{pmatrix} 4 & 6 \\ 2 & 3 \end{pmatrix}$$

$\therefore$  Inverse *doesn't exist*

### ***Exercise***

Find the inverse of  $A = \begin{pmatrix} -6 & 9 \\ 2 & -3 \end{pmatrix}$

### **Solution**

$$A^{-1} = \frac{1}{\textcolor{red}{18-18}} \begin{pmatrix} & \\ & \end{pmatrix}$$

$\therefore$  Inverse *doesn't exist*

### ***Exercise***

Find the inverse of  $A = \begin{pmatrix} -2 & 7 \\ 0 & 2 \end{pmatrix}$

### **Solution**

$$A^{-1} = \frac{1}{4} \begin{pmatrix} 2 & -7 \\ 0 & -2 \end{pmatrix}$$

$$= \begin{pmatrix} \frac{1}{2} & -\frac{7}{4} \\ 0 & -\frac{1}{2} \end{pmatrix}$$

### ***Exercise***

Find the inverse of  $A = \begin{pmatrix} 4 & -16 \\ 1 & -4 \end{pmatrix}$

### **Solution**

$$A = \frac{1}{-16+16} \begin{pmatrix} 4 & -16 \\ 1 & -4 \end{pmatrix}$$

$\therefore$  Inverse *doesn't exist*

### ***Exercise***

Find the inverse of  $A = \begin{pmatrix} 2 & 1 \\ 1 & 1 \end{pmatrix}$

### **Solution**

$$A^{-1} = \begin{pmatrix} 1 & -1 \\ -1 & 2 \end{pmatrix}$$

### ***Exercise***

Find the inverse of  $A = \begin{pmatrix} 2 & 1 \\ a & a \end{pmatrix}$

### **Solution**

$$\begin{aligned} A^{-1} &= \frac{1}{a} \begin{pmatrix} a & -1 \\ -a & 2 \end{pmatrix} \\ &= \begin{pmatrix} 1 & -\frac{1}{a} \\ -1 & \frac{2}{a} \end{pmatrix} \end{aligned}$$

### ***Exercise***

Find the inverse of  $A = \begin{pmatrix} b & 3 \\ b & 2 \end{pmatrix}$

### **Solution**

$$\begin{aligned} A^{-1} &= -\frac{1}{b} \begin{pmatrix} 2 & -3 \\ -b & b \end{pmatrix} \\ &= \begin{pmatrix} -\frac{2}{b} & \frac{3}{b} \\ 1 & -1 \end{pmatrix} \end{aligned}$$

### ***Exercise***

Find the inverse of  $A = \begin{pmatrix} 1 & a \\ 3 & a \end{pmatrix}$

### **Solution**

$$\begin{aligned} A^{-1} &= -\frac{1}{2a} \begin{pmatrix} a & -a \\ -3 & 1 \end{pmatrix} \\ &= \begin{pmatrix} -\frac{1}{2} & \frac{1}{2} \\ \frac{3}{2a} & -\frac{1}{2a} \end{pmatrix} \end{aligned}$$

### ***Exercise***

Find the inverse of  $A = \begin{pmatrix} a & 2 \\ 2 & a \end{pmatrix}$

### **Solution**

$$\begin{aligned} A^{-1} &= \frac{1}{a^2 - 4} \begin{pmatrix} a & -2 \\ -2 & a \end{pmatrix} \\ &= \begin{pmatrix} \frac{a}{a^2 - 4} & \frac{-2}{a^2 - 4} \\ \frac{-2}{a^2 - 4} & \frac{a}{a^2 - 4} \end{pmatrix} \end{aligned}$$

### ***Exercise***

Find the inverse of  $A = \begin{pmatrix} 4 & -2 \\ 2 & -1 \end{pmatrix}$

### **Solution**

$$A^{-1} = \frac{1}{\textcolor{red}{0}} \begin{pmatrix} & \\ & \end{pmatrix}$$

$\therefore$  Inverse *doesn't exist*

### ***Exercise***

Find the inverse of  $A = \begin{pmatrix} -3 & \frac{1}{2} \\ 6 & -1 \end{pmatrix}$

### **Solution**

$$A^{-1} = \frac{1}{\textcolor{red}{0}} \begin{pmatrix} & \\ & \end{pmatrix}$$

$\therefore$  Inverse *doesn't exist*

### Exercise

Find  $A^{-1}$  if  $A = \begin{bmatrix} 1 & 0 & 1 \\ 2 & -2 & -1 \\ 3 & 0 & 0 \end{bmatrix}$

### Solution

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 1 & 1 & 0 & 0 \\ 2 & -2 & -1 & 0 & 1 & 0 \\ 3 & 0 & 0 & 0 & 0 & 1 \end{array} \right] \begin{array}{l} \\ R_2 - 2R_1 \\ R_3 - 3R_1 \end{array} \quad \begin{array}{cccccc} 2 & -2 & -1 & 0 & 1 & 0 \\ -2 & 0 & -2 & -2 & 0 & 0 \\ 0 & -2 & -3 & -2 & 1 & 0 \end{array} \quad \begin{array}{cccccc} 3 & 0 & 0 & 0 & 0 & 1 \\ -3 & 0 & -3 & -3 & 0 & 0 \\ 0 & 0 & -3 & -3 & 0 & 1 \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & -2 & -3 & -2 & 1 & 0 \\ 0 & 0 & -3 & -3 & 0 & 1 \end{array} \right] -\frac{1}{2}R_2$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & \frac{3}{2} & 1 & -\frac{1}{2} & 0 \\ 0 & 0 & -3 & -3 & 0 & 1 \end{array} \right] -\frac{1}{3}R_3$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & \frac{3}{2} & 1 & -\frac{1}{2} & 0 \\ 0 & 0 & 1 & 1 & 0 & -\frac{1}{3} \end{array} \right] \begin{array}{l} R_1 - R_3 \\ R_2 - \frac{3}{2}R_3 \\ \end{array} \quad \begin{array}{cccccc} 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & -1 & -1 & 0 & \frac{1}{3} \\ 1 & 0 & 0 & 0 & 0 & \frac{1}{3} \end{array} \quad \begin{array}{cccccc} 0 & 1 & \frac{3}{2} & 1 & -\frac{1}{2} & 0 \\ 0 & 0 & -\frac{3}{2} & -\frac{3}{2} & 0 & \frac{1}{2} \\ 0 & 1 & 0 & -\frac{1}{2} & -\frac{1}{2} & \frac{1}{2} \end{array}$$

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

$$A^{-1} = \begin{bmatrix} 0 & 0 & \frac{1}{3} \\ -\frac{1}{2} & -\frac{1}{2} & \frac{1}{2} \\ 1 & 0 & -\frac{1}{3} \end{bmatrix}$$

### Exercise

Find  $A^{-1}$ , where  $A = \begin{bmatrix} 1 & 2 & -1 \\ 3 & 5 & 3 \\ 2 & 4 & 3 \end{bmatrix}$

### Solution

$$\left[ \begin{array}{ccc|ccc} 1 & 2 & -1 & 1 & 0 & 0 \\ 3 & 5 & 3 & 0 & 1 & 0 \\ 2 & 4 & 3 & 0 & 0 & 1 \end{array} \right] \begin{array}{l} \\ R_2 - 3R_1 \\ R_3 + 2R_1 \end{array}$$

$$\begin{array}{cccccc} 3 & 5 & 3 & 0 & 1 & 0 \\ -3 & -6 & 3 & -3 & 0 & 0 \\ 0 & -1 & 6 & -3 & 1 & 0 \end{array} \quad \begin{array}{cccccc} 2 & 4 & 3 & 0 & 0 & 1 \\ -2 & -4 & 2 & -2 & 0 & 0 \\ 0 & 0 & 5 & -2 & 0 & 1 \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & 2 & -1 & 1 & 0 & 0 \\ 0 & -1 & 6 & -3 & 1 & 0 \\ 0 & 0 & 5 & -2 & 0 & 1 \end{array} \right] -R_2$$

$$\left[ \begin{array}{ccc|ccc} 1 & 2 & -1 & 1 & 0 & 0 \\ 0 & 1 & -6 & 3 & -1 & 0 \\ 0 & 0 & 5 & -2 & 0 & 1 \end{array} \right] \begin{array}{l} \\ R_1 - 2R_2 \\ \end{array}$$

$$\begin{array}{cccccc} 1 & 2 & -1 & 1 & 0 & 0 \\ 0 & -2 & 12 & -6 & 2 & 0 \\ 1 & 0 & 11 & -5 & 2 & 0 \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 11 & -5 & 2 & 0 \\ 0 & 1 & -6 & 3 & -1 & 0 \\ 0 & 0 & 5 & -2 & 0 & 1 \end{array} \right] \frac{1}{5}R_3$$

$$\begin{array}{cccccc} 0 & 0 & 1 & -\frac{2}{5} & 0 & \frac{1}{5} \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 11 & -5 & 2 & 0 \\ 0 & 1 & -6 & 3 & -1 & 0 \\ 0 & 0 & 1 & -\frac{2}{5} & 0 & \frac{1}{5} \end{array} \right] \begin{array}{l} R_1 - 11R_3 \\ R_2 + 6R_3 \\ \end{array}$$

$$\begin{array}{cccccc} 0 & 1 & -6 & 3 & -1 & 0 \\ 0 & 0 & 6 & -\frac{12}{5} & 0 & \frac{6}{5} \\ 0 & 1 & 0 & \frac{3}{5} & -1 & \frac{6}{5} \end{array} \quad \begin{array}{cccccc} 1 & 0 & 11 & -5 & 2 & 0 \\ 0 & 0 & -11 & \frac{22}{5} & 0 & -\frac{11}{5} \\ 1 & 0 & 0 & -\frac{3}{5} & 2 & -\frac{11}{5} \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 0 & -\frac{3}{5} & 2 & -\frac{11}{5} \\ 0 & 1 & 0 & \frac{3}{5} & -1 & \frac{6}{5} \\ 0 & 0 & 1 & -\frac{2}{5} & 0 & \frac{1}{5} \end{array} \right]$$

$$A^{-1} = \begin{bmatrix} -\frac{3}{5} & 2 & -\frac{11}{5} \\ \frac{3}{5} & -1 & \frac{6}{5} \\ -\frac{2}{5} & 0 & \frac{1}{5} \end{bmatrix}$$



### Exercise

Find  $A^{-1}$ , where  $A = \begin{bmatrix} 1 & 2 & -1 \\ -2 & 0 & 1 \\ 1 & -1 & 0 \end{bmatrix}$

### Solution

$$\left[ \begin{array}{ccc|ccc} 1 & 2 & -1 & 1 & 0 & 0 \\ -2 & 0 & 1 & 0 & 1 & 0 \\ 1 & -1 & 0 & 0 & 0 & 1 \end{array} \right] \begin{array}{l} \\ R_2 + 2R_1 \\ R_3 - R_1 \end{array}$$

$$\begin{array}{cccccc} -2 & 0 & 1 & 0 & 1 & 0 \\ 2 & 4 & -2 & 2 & 0 & 0 \\ 0 & 4 & -1 & 2 & 1 & 0 \end{array} \quad \begin{array}{cccccc} 1 & -1 & 0 & 0 & 0 & 1 \\ -1 & -2 & 1 & -1 & 0 & 0 \\ 0 & -3 & 1 & -1 & 0 & 1 \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & 2 & -1 & 1 & 0 & 0 \\ 0 & 4 & -1 & 2 & 1 & 0 \\ 0 & -3 & 1 & -1 & 0 & 1 \end{array} \right] \frac{1}{4}R_2$$

$$0 \quad 1 \quad -\frac{1}{4} \quad \frac{1}{2} \quad \frac{1}{4} \quad 0$$

$$\left[ \begin{array}{ccc|ccc} 1 & 2 & -1 & 1 & 0 & 0 \\ 0 & 1 & -\frac{1}{4} & \frac{1}{2} & \frac{1}{4} & 0 \\ 0 & -3 & 1 & -1 & 0 & 1 \end{array} \right] \begin{array}{l} R_1 - 2R_2 \\ \\ R_3 + 3R_2 \end{array}$$

$$\begin{array}{cccccc} 0 & -3 & 1 & -1 & 0 & 1 \\ 0 & 3 & -\frac{3}{4} & \frac{3}{2} & \frac{3}{4} & 0 \\ 0 & 0 & \frac{1}{4} & \frac{1}{2} & \frac{3}{4} & 1 \end{array} \quad \begin{array}{cccccc} 1 & 2 & -1 & 1 & 0 & 0 \\ 0 & -2 & \frac{1}{2} & -1 & -\frac{1}{2} & 0 \\ 1 & 0 & -\frac{1}{2} & 0 & -\frac{1}{2} & 0 \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & -\frac{1}{2} & 0 & -\frac{1}{2} & 0 \\ 0 & 1 & -\frac{1}{4} & \frac{1}{2} & \frac{1}{4} & 0 \\ 0 & 0 & \frac{1}{4} & \frac{1}{2} & \frac{3}{4} & 1 \end{array} \right] 4R_3$$

$$0 \quad 0 \quad 1 \quad 2 \quad 3 \quad 4$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & -\frac{1}{2} & 0 & -\frac{1}{2} & 0 \\ 0 & 1 & -\frac{1}{4} & \frac{1}{2} & \frac{1}{4} & 0 \\ 0 & 0 & 1 & 2 & 3 & 4 \end{array} \right] \begin{array}{l} R_1 + \frac{1}{2}R_3 \\ R_2 + \frac{1}{4}R_3 \\ \end{array}$$

$$\begin{array}{cccccc} 1 & 0 & -\frac{1}{2} & 0 & -\frac{1}{2} & 0 \\ 0 & 0 & \frac{1}{2} & 1 & \frac{3}{2} & 2 \\ 1 & 0 & 0 & 1 & 1 & 2 \end{array} \quad \begin{array}{cccccc} 0 & 1 & -\frac{1}{4} & \frac{1}{2} & \frac{1}{4} & 0 \\ 0 & 0 & \frac{1}{4} & \frac{1}{2} & \frac{3}{4} & 1 \\ 0 & 1 & 0 & 1 & 1 & 1 \end{array}$$

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

$$A^{-1} = \begin{bmatrix} 1 & 1 & 2 \\ 1 & 1 & 1 \\ 2 & 3 & 4 \end{bmatrix}$$

### Exercise

Find  $A^{-1}$ , where  $A = \begin{bmatrix} -2 & 5 & 3 \\ 4 & -1 & 3 \\ 7 & -2 & 5 \end{bmatrix}$

### Solution

$$\left[ \begin{array}{ccc|ccc} -2 & 5 & 3 & 1 & 0 & 0 \\ 4 & -1 & 3 & 0 & 1 & 0 \\ 7 & -2 & 5 & 0 & 0 & 1 \end{array} \right] \quad \frac{1}{-2}R_1 \quad \begin{array}{cccccc} 1 & -\frac{5}{2} & -\frac{3}{2} & -\frac{1}{2} & 0 & 0 \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & -\frac{5}{2} & -\frac{3}{2} & -\frac{1}{2} & 0 & 0 \\ 4 & -1 & 3 & 0 & 1 & 0 \\ 7 & -2 & 5 & 0 & 0 & 1 \end{array} \right] \quad R_2 - 4R_1 \quad \begin{array}{cccccc} 4 & -1 & 3 & 0 & 1 & 0 \\ -4 & 10 & 6 & 2 & 0 & 0 \\ \hline 0 & 9 & 9 & 2 & 1 & 0 \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & -\frac{5}{2} & -\frac{3}{2} & -\frac{1}{2} & 0 & 0 \\ 0 & 9 & 9 & 2 & 1 & 0 \\ 7 & -2 & 5 & 0 & 0 & 1 \end{array} \right] \quad R_3 - 7R_1 \quad \begin{array}{cccccc} 7 & -2 & 5 & 0 & 0 & 1 \\ -7 & \frac{35}{2} & \frac{21}{2} & \frac{7}{2} & 0 & 0 \\ \hline 0 & \frac{31}{2} & \frac{31}{2} & \frac{7}{2} & 0 & 1 \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & -\frac{5}{2} & -\frac{3}{2} & -\frac{1}{2} & 0 & 0 \\ 0 & 9 & 9 & 2 & 1 & 0 \\ 0 & \frac{31}{2} & \frac{31}{2} & \frac{7}{2} & 0 & 1 \end{array} \right] \quad \frac{1}{9}R_2 \quad \begin{array}{cccccc} 0 & 1 & 1 & \frac{2}{9} & \frac{1}{9} & 0 \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & -\frac{5}{2} & -\frac{3}{2} & \frac{1}{2} & 0 & 0 \\ 0 & 1 & 1 & \frac{2}{9} & \frac{1}{9} & 0 \\ 0 & \frac{31}{2} & \frac{31}{2} & \frac{7}{2} & 0 & 1 \end{array} \right] \quad R_3 - \frac{31}{2}R_2 \quad \begin{array}{cccccc} 0 & \frac{31}{2} & \frac{31}{2} & \frac{7}{2} & 0 & 1 \\ 0 & -\frac{31}{2} & -\frac{31}{2} & -\frac{31}{9} & -\frac{31}{18} & 0 \\ \hline 0 & 0 & 0 & \frac{1}{18} & -\frac{31}{18} & 1 \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & -\frac{5}{2} & -\frac{3}{2} & \frac{1}{2} & 0 & 0 \\ 0 & 1 & 1 & \frac{2}{9} & \frac{1}{9} & 0 \\ 0 & 0 & 0 & \frac{1}{18} & -\frac{31}{18} & 1 \end{array} \right]$$

$\therefore$  The inverse matrix ***doesn't exist***

### Exercise

Find the inverse, if exists, of  $A = \begin{pmatrix} 1 & 1 & 0 \\ -1 & 3 & 4 \\ 0 & 4 & 3 \end{pmatrix}$

### Solution

$$\left( \begin{array}{ccc|ccc} 1 & 1 & 0 & 1 & 0 & 0 \\ -1 & 3 & 4 & 0 & 1 & 0 \\ 0 & 4 & 3 & 0 & 0 & 1 \end{array} \right) \begin{array}{l} \\ R_2 + R_1 \\ \end{array} \quad \begin{array}{cccccc} 1 & 1 & 0 & 1 & 0 & 0 \\ -1 & 3 & 4 & 0 & 1 & 0 \\ \hline 0 & 4 & 4 & 1 & 1 & 0 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 4 & 4 & 1 & 1 & 0 \\ 0 & 4 & 3 & 0 & 0 & 1 \end{array} \right) \frac{1}{4} R_2$$

$$\left( \begin{array}{ccc|ccc} 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & \frac{1}{4} & \frac{1}{4} & 0 \\ 0 & 4 & 3 & 0 & 0 & 1 \end{array} \right) \begin{array}{l} \\ R_1 - R_2 \\ R_3 - 4R_2 \end{array} \quad \begin{array}{cccccc} 0 & 4 & 3 & 0 & 0 & 1 \\ 0 & -4 & -4 & -1 & -1 & 0 \\ \hline 0 & 0 & -1 & -1 & -1 & 1 \end{array} \quad \begin{array}{cccccc} 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & -1 & -1 & -\frac{1}{4} & -\frac{1}{4} & 0 \\ \hline 1 & 0 & -1 & \frac{3}{4} & -\frac{1}{4} & 0 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & -1 & \frac{3}{4} & -\frac{1}{4} & 0 \\ 0 & 1 & 1 & \frac{1}{4} & \frac{1}{4} & 0 \\ 0 & 0 & -1 & -1 & -1 & 1 \end{array} \right) -R_3$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & -1 & \frac{3}{4} & -\frac{1}{4} & 0 \\ 0 & 1 & 1 & \frac{1}{4} & \frac{1}{4} & 0 \\ 0 & 0 & 1 & 1 & 1 & -1 \end{array} \right) \begin{array}{l} R_1 + R_3 \\ R_2 - R_3 \\ \end{array} \quad \begin{array}{cccccc} 1 & 0 & -1 & \frac{3}{4} & -\frac{1}{4} & 0 \\ 0 & 0 & 1 & 1 & 1 & -1 \\ \hline 1 & 0 & 0 & \frac{7}{4} & \frac{3}{4} & -1 \end{array} \quad \begin{array}{cccccc} 0 & 1 & 1 & \frac{1}{4} & \frac{1}{4} & 0 \\ 0 & 0 & -1 & -1 & -1 & 1 \\ \hline 0 & 1 & 0 & -\frac{3}{4} & -\frac{3}{4} & 1 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & 0 & \frac{7}{4} & \frac{3}{4} & -1 \\ 0 & 1 & 0 & -\frac{3}{4} & -\frac{3}{4} & 1 \\ 0 & 0 & 1 & 1 & 1 & -1 \end{array} \right)$$

$$A^{-1} = \begin{pmatrix} \frac{7}{4} & \frac{3}{4} & -1 \\ -\frac{3}{4} & -\frac{3}{4} & 1 \\ 1 & 1 & -1 \end{pmatrix}$$

### Exercise

Find the inverse, if exists, of  $A = \begin{pmatrix} 1 & -1 & 1 \\ 0 & -2 & 1 \\ -2 & -3 & 0 \end{pmatrix}$

### Solution

$$\left( \begin{array}{ccc|ccc} 1 & -1 & 1 & 1 & 0 & 0 \\ 0 & -2 & 1 & 0 & 1 & 0 \\ -2 & -3 & 0 & 0 & 0 & 1 \end{array} \right) \begin{array}{l} \\ R_3 + 2R_1 \end{array} \quad \begin{array}{cccccc} -2 & -3 & 0 & 0 & 0 & 1 \\ 2 & -2 & 2 & 2 & 0 & 0 \\ \hline 0 & -5 & 2 & 2 & 0 & 1 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & -1 & 1 & 1 & 0 & 0 \\ 0 & -2 & 1 & 0 & 1 & 0 \\ 0 & -5 & 2 & 2 & 0 & 1 \end{array} \right) -\frac{1}{2}R_2$$

$$\left( \begin{array}{ccc|ccc} 1 & -1 & 1 & 1 & 0 & 0 \\ 0 & 1 & -\frac{1}{2} & 0 & -\frac{1}{2} & 0 \\ 0 & -5 & 2 & 2 & 0 & 1 \end{array} \right) \begin{array}{l} R_1 + R_2 \\ R_3 + 5R_2 \end{array} \quad \begin{array}{cccccc} 1 & -1 & 1 & 1 & 0 & 0 \\ 0 & 1 & -\frac{1}{2} & 0 & -\frac{1}{2} & 0 \\ \hline 1 & 0 & \frac{1}{2} & 1 & -\frac{1}{2} & 0 \end{array} \quad \begin{array}{cccccc} 0 & -5 & 2 & 2 & 0 & 1 \\ 0 & 5 & -\frac{5}{2} & 0 & -\frac{5}{2} & 0 \\ \hline 0 & 0 & -\frac{1}{2} & 2 & -\frac{5}{2} & 1 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & \frac{1}{2} & 1 & -\frac{1}{2} & 0 \\ 0 & 1 & -\frac{1}{2} & 0 & -\frac{1}{2} & 0 \\ 0 & 0 & -\frac{1}{2} & 2 & -\frac{5}{2} & 1 \end{array} \right) -2R_3$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & \frac{1}{2} & 1 & -\frac{1}{2} & 0 \\ 0 & 1 & -\frac{1}{2} & 0 & -\frac{1}{2} & 0 \\ 0 & 0 & 1 & -4 & 5 & -2 \end{array} \right) \begin{array}{l} R_1 - \frac{1}{2}R_3 \\ R_2 + \frac{1}{2}R_3 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & 0 & 3 & -3 & 1 \\ 0 & 1 & 0 & -2 & 2 & -1 \\ 0 & 0 & 1 & -4 & 5 & -2 \end{array} \right)$$

$$A^{-1} = \begin{pmatrix} 3 & -3 & 1 \\ -2 & 2 & -1 \\ -4 & 5 & -2 \end{pmatrix}$$

**Exercise**

Find the inverse, if exists, of  $A = \begin{pmatrix} 1 & 0 & 2 \\ -1 & 2 & 3 \\ 1 & -1 & 0 \end{pmatrix}$

**Solution**

$$\left( \begin{array}{ccc|ccc} 1 & 0 & 2 & 1 & 0 & 0 \\ -1 & 2 & 3 & 0 & 1 & 0 \\ 1 & -1 & 0 & 0 & 0 & 1 \end{array} \right) \begin{array}{l} \\ R_2 + R_1 \\ R_3 - R_1 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & 2 & 1 & 0 & 0 \\ 0 & 2 & 5 & 1 & 1 & 0 \\ 0 & -1 & -2 & -1 & 0 & 1 \end{array} \right) \frac{1}{2}R_2$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & 2 & 1 & 0 & 0 \\ 0 & 1 & \frac{5}{2} & \frac{1}{2} & \frac{1}{2} & 0 \\ 0 & -1 & -2 & -1 & 0 & 1 \end{array} \right) R_3 + R_2$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & 2 & 1 & 0 & 0 \\ 0 & 1 & \frac{5}{2} & \frac{1}{2} & \frac{1}{2} & 0 \\ 0 & 0 & \frac{1}{2} & -\frac{1}{2} & \frac{1}{2} & 1 \end{array} \right) 2R_3$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & 2 & 1 & 0 & 0 \\ 0 & 1 & \frac{5}{2} & \frac{1}{2} & \frac{1}{2} & 0 \\ 0 & 0 & 1 & -1 & 1 & 2 \end{array} \right) \begin{array}{l} R_1 - 2R_3 \\ R_2 - \frac{5}{2}R_3 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & 0 & 3 & -2 & -4 \\ 0 & 1 & 0 & 3 & -2 & -5 \\ 0 & 0 & 1 & -1 & 1 & 2 \end{array} \right)$$

$$A^{-1} = \begin{pmatrix} 3 & -2 & -4 \\ 3 & -2 & -5 \\ -1 & 1 & 2 \end{pmatrix}$$

### Exercise

Find the inverse, if exists, of  $A = \begin{pmatrix} 1 & 1 & 1 \\ 3 & 2 & -1 \\ 3 & 1 & 2 \end{pmatrix}$

### Solution

$$\left( \begin{array}{ccc|ccc} 1 & 1 & 1 & 1 & 0 & 0 \\ 3 & 2 & -1 & 0 & 1 & 0 \\ 3 & 1 & 2 & 0 & 0 & 1 \end{array} \right) \begin{array}{l} \\ R_2 - 3R_1 \\ R_3 - 3R_1 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & -1 & -4 & -3 & 1 & 0 \\ 0 & -2 & -1 & -3 & 0 & 1 \end{array} \right) -R_2$$

$$\left( \begin{array}{ccc|ccc} 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 4 & 3 & -1 & 0 \\ 0 & -2 & -1 & -3 & 0 & 1 \end{array} \right) \begin{array}{l} R_1 - R_2 \\ \\ R_3 + 2R_2 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & -3 & -2 & 1 & 0 \\ 0 & 1 & 4 & 3 & -1 & 0 \\ 0 & 0 & 7 & 3 & -2 & 1 \end{array} \right) \frac{1}{7}R_3$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & -3 & -2 & 1 & 0 \\ 0 & 1 & 4 & 3 & -1 & 0 \\ 0 & 0 & 1 & \frac{3}{7} & -\frac{2}{7} & \frac{1}{7} \end{array} \right) \begin{array}{l} R_1 + 3R_3 \\ R_2 - 4R_3 \\ \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & 0 & -\frac{5}{7} & \frac{1}{7} & \frac{3}{7} \\ 0 & 1 & 0 & \frac{9}{7} & \frac{1}{7} & -\frac{4}{7} \\ 0 & 0 & 1 & \frac{3}{7} & -\frac{2}{7} & \frac{1}{7} \end{array} \right)$$

$$A^{-1} = \begin{pmatrix} -\frac{5}{7} & \frac{1}{7} & \frac{3}{7} \\ \frac{9}{7} & \frac{1}{7} & -\frac{4}{7} \\ \frac{3}{7} & -\frac{2}{7} & \frac{1}{7} \end{pmatrix}$$

### Exercise

Find the inverse, if exists, of  $A = \begin{pmatrix} 3 & 3 & 1 \\ 1 & 2 & 1 \\ 2 & -1 & 1 \end{pmatrix}$

### Solution

$$\left( \begin{array}{ccc|ccc} 3 & 3 & 1 & 1 & 0 & 0 \\ 1 & 2 & 1 & 0 & 1 & 0 \\ 2 & -1 & 1 & 0 & 0 & 1 \end{array} \right) \frac{1}{3}R_1$$

$$\left( \begin{array}{ccc|ccc} 1 & 1 & \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ 1 & 2 & 1 & 0 & 1 & 0 \\ 2 & -1 & 1 & 0 & 0 & 1 \end{array} \right) \begin{array}{l} R_2 - R_1 \\ R_3 - 2R_1 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 1 & \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ 0 & 1 & \frac{2}{3} & -\frac{1}{3} & 1 & 0 \\ 0 & -3 & \frac{1}{3} & -\frac{2}{3} & 0 & 1 \end{array} \right) \begin{array}{l} R_1 - R_2 \\ R_3 + 3R_2 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & -\frac{1}{3} & \frac{2}{3} & -1 & 0 \\ 0 & 1 & \frac{2}{3} & -\frac{1}{3} & 1 & 0 \\ 0 & 0 & \frac{7}{3} & -\frac{5}{3} & 3 & 1 \end{array} \right) \frac{3}{7}R_3$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & -\frac{1}{3} & \frac{2}{3} & -1 & 0 \\ 0 & 1 & \frac{2}{3} & -\frac{1}{3} & 1 & 0 \\ 0 & 0 & 1 & -\frac{5}{7} & \frac{9}{7} & \frac{3}{7} \end{array} \right) \begin{array}{l} R_1 + \frac{1}{3}R_3 \\ R_2 - \frac{2}{3}R_3 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & 0 & \frac{3}{7} & -\frac{4}{7} & \frac{1}{7} \\ 0 & 1 & 0 & \frac{1}{7} & \frac{1}{7} & -\frac{2}{7} \\ 0 & 0 & 1 & -\frac{5}{7} & \frac{9}{7} & \frac{3}{7} \end{array} \right)$$

$$A^{-1} = \begin{pmatrix} \frac{3}{7} & -\frac{4}{7} & \frac{1}{7} \\ \frac{1}{7} & \frac{1}{7} & -\frac{2}{7} \\ -\frac{5}{7} & \frac{9}{7} & \frac{3}{7} \end{pmatrix}$$

### Exercise

Find the inverse, if exists, of  $A = \begin{pmatrix} -3 & 1 & -1 \\ 1 & -4 & -7 \\ 1 & 2 & 5 \end{pmatrix}$

### Solution

$$\left( \begin{array}{ccc|ccc} -3 & 1 & -1 & 1 & 0 & 0 \\ 1 & -4 & -7 & 0 & 1 & 0 \\ 1 & 2 & 5 & 0 & 0 & 1 \end{array} \right) \quad -\frac{1}{3}R_1$$

$$\left( \begin{array}{ccc|ccc} 1 & -\frac{1}{3} & \frac{1}{3} & -\frac{1}{3} & 0 & 0 \\ 1 & -4 & -7 & 0 & 1 & 0 \\ 1 & 2 & 5 & 0 & 0 & 1 \end{array} \right) \quad \begin{array}{l} R_2 - R_1 \\ R_3 - R_1 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & -\frac{1}{3} & \frac{1}{3} & -\frac{1}{3} & 0 & 0 \\ 0 & -\frac{11}{3} & -\frac{22}{3} & \frac{1}{3} & 1 & 0 \\ 0 & \frac{7}{3} & \frac{14}{3} & \frac{1}{3} & 0 & 1 \end{array} \right) \quad -\frac{3}{11}R_2$$

$$\left( \begin{array}{ccc|ccc} 1 & -\frac{1}{3} & \frac{1}{3} & -\frac{1}{3} & 0 & 0 \\ 0 & 1 & 2 & -\frac{1}{11} & -\frac{3}{11} & 0 \\ 0 & \frac{7}{3} & \frac{14}{3} & \frac{1}{3} & 0 & 1 \end{array} \right) \quad R_3 - \frac{7}{3}R_2$$

$$\left( \begin{array}{ccc|ccc} 1 & -\frac{1}{3} & \frac{1}{3} & -\frac{1}{3} & 0 & 0 \\ 0 & 1 & 2 & -\frac{1}{11} & -\frac{3}{11} & 0 \\ 0 & 0 & 0 & -\frac{1}{11} & -\frac{3}{11} & 0 \end{array} \right)$$

$\therefore$  Inverse **does not exist**



### Exercise

Find the inverse, if exists, of  $A = \begin{pmatrix} 1 & 1 & -3 \\ 2 & -4 & 1 \\ -5 & 7 & 1 \end{pmatrix}$

### Solution

$$\left( \begin{array}{ccc|ccc} 1 & 1 & -3 & 1 & 0 & 0 \\ 2 & -4 & 1 & 0 & 1 & 0 \\ -5 & 7 & 1 & 0 & 0 & 1 \end{array} \right) \begin{array}{l} \\ R_2 - 2R_1 \\ R_3 + 5R_1 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 1 & -3 & 1 & 0 & 0 \\ 0 & -6 & 7 & -2 & 1 & 0 \\ 0 & 12 & -14 & 5 & 0 & 1 \end{array} \right) -\frac{1}{6}R_2$$

$$\left( \begin{array}{ccc|ccc} 1 & 1 & -3 & 1 & 0 & 0 \\ 0 & 1 & -\frac{7}{6} & \frac{1}{3} & -\frac{1}{6} & 0 \\ 0 & 12 & -14 & 5 & 0 & 1 \end{array} \right) \begin{array}{l} R_1 - R_2 \\ \\ R_3 - 12R_2 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & -3 & 1 & 0 & 0 \\ 0 & 1 & -\frac{7}{6} & \frac{1}{3} & -\frac{1}{6} & 0 \\ 0 & 0 & 0 & \frac{1}{3} & -\frac{1}{6} & 0 \end{array} \right)$$

$\therefore$  Inverse **does not exist**

### Exercise

Find the inverse, if exists, of  $A = \begin{pmatrix} 1 & 2 & -1 \\ 3 & 5 & 3 \\ 2 & 4 & 3 \end{pmatrix}$

### Solution

$$\left( \begin{array}{ccc|ccc} 1 & 2 & -1 & 1 & 0 & 0 \\ 3 & 5 & 3 & 0 & 1 & 0 \\ 2 & 4 & 3 & 0 & 0 & 1 \end{array} \right) \begin{array}{l} \\ R_3 - 3R_1 \\ R_3 - 2R_1 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 2 & -1 & 1 & 0 & 0 \\ 0 & -1 & 6 & -3 & 1 & 0 \\ 0 & 0 & 5 & -2 & 0 & 1 \end{array} \right) -R_2$$

$$\left( \begin{array}{ccc|ccc} 1 & 2 & -1 & 1 & 0 & 0 \\ 0 & 1 & -6 & 3 & -1 & 0 \\ 0 & 0 & 5 & -2 & 0 & 1 \end{array} \right) R_1 - 2R_2$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & 11 & -5 & 2 & 0 \\ 0 & 1 & -6 & 3 & -1 & 0 \\ 0 & 0 & 5 & -2 & 0 & 1 \end{array} \right) \frac{1}{5}R_3$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & 11 & -5 & 2 & 0 \\ 0 & 1 & -6 & 3 & -1 & 0 \\ 0 & 0 & 1 & -\frac{2}{5} & 0 & \frac{1}{5} \end{array} \right) \begin{array}{l} R_1 - 11R_3 \\ R_2 + 6R_3 \end{array}$$

$$\left( \begin{array}{ccc|ccc} 1 & 0 & 0 & -\frac{3}{5} & 2 & -\frac{11}{5} \\ 0 & 1 & 0 & \frac{3}{5} & -1 & \frac{6}{5} \\ 0 & 0 & 1 & -\frac{2}{5} & 0 & \frac{1}{5} \end{array} \right)$$

$$A^{-1} = \begin{pmatrix} -\frac{3}{5} & 2 & -\frac{11}{5} \\ \frac{3}{5} & -1 & \frac{6}{5} \\ -\frac{2}{5} & 0 & \frac{1}{5} \end{pmatrix}$$

### ***Exercise***

Find the inverse, if exists of  $A = \begin{pmatrix} 1 & 0 & 1 \\ 0 & 1 & 1 \\ 1 & 1 & 0 \end{pmatrix}$

### **Solution**

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 & 1 \end{array} \right] R_3 - R_1$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & -1 & -1 & 0 & 1 \end{array} \right] R_3 - R_2$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & -2 & -1 & -1 & 1 \end{array} \right] -\frac{1}{2}R_3$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & \frac{1}{2} & \frac{1}{2} & -\frac{1}{2} \end{array} \right] \begin{array}{l} R_1 - R_3 \\ R_2 - R_3 \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 0 & \frac{1}{2} & -\frac{1}{2} & \frac{1}{2} \\ 0 & 1 & 0 & -\frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ 0 & 0 & 1 & \frac{1}{2} & \frac{1}{2} & -\frac{1}{2} \end{array} \right]$$

$$A^{-1} = \begin{bmatrix} \frac{1}{2} & -\frac{1}{2} & \frac{1}{2} \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{2} \end{bmatrix}$$

### ***Exercise***

Find the inverse, if exists of  $A = \begin{pmatrix} \frac{1}{5} & \frac{1}{5} & -\frac{2}{5} \\ \frac{1}{5} & \frac{1}{5} & \frac{1}{10} \\ \frac{1}{5} & -\frac{4}{5} & \frac{1}{10} \end{pmatrix}$

### **Solution**

$$\left[ \begin{array}{ccc|ccc} \frac{1}{5} & \frac{1}{5} & -\frac{2}{5} & 1 & 0 & 0 \\ \frac{1}{5} & \frac{1}{5} & \frac{1}{10} & 0 & 1 & 0 \\ \frac{1}{5} & -\frac{4}{5} & \frac{1}{10} & 0 & 0 & 1 \end{array} \right] \begin{array}{l} 5R_1 \\ 10R_2 \\ 10R_3 \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & 1 & -2 & 5 & 0 & 0 \\ 2 & 2 & 1 & 0 & 10 & 0 \\ 2 & -8 & 1 & 0 & 0 & 10 \end{array} \right] \begin{array}{l} \\ R_2 - 2R_1 \\ R_3 - 2R_1 \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & 1 & -2 & 5 & 0 & 0 \\ 0 & 0 & 5 & -10 & 10 & 0 \\ 0 & -10 & 5 & -10 & 0 & 10 \end{array} \right] \begin{array}{l} \\ R_2 - \frac{1}{10}R_3 \\ \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & 1 & -2 & 5 & 0 & 0 \\ 0 & 1 & \frac{9}{2} & -9 & 10 & -1 \\ 0 & -10 & 5 & -10 & 0 & 10 \end{array} \right] \begin{array}{l} R_1 - R_2 \\ \\ R_3 + 10R_2 \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & -\frac{13}{2} & 14 & -10 & 1 \\ 0 & 1 & \frac{9}{2} & -9 & 10 & -1 \\ 0 & 0 & 50 & -100 & 100 & 0 \end{array} \right] \frac{1}{50}R_3$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & -\frac{13}{2} & 14 & -10 & 1 \\ 0 & 1 & \frac{9}{2} & -9 & 10 & -1 \\ 0 & 0 & 1 & -2 & 2 & 0 \end{array} \right] \quad \begin{array}{l} R_1 + \frac{13}{2}R_3 \\ R_2 - \frac{9}{2}R_3 \end{array}$$

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

$$A^{-1} = \begin{bmatrix} 1 & 3 & 1 \\ 0 & 1 & -1 \\ -2 & 2 & 0 \end{bmatrix}$$

### ***Exercise***

Find the inverse, if exists of  $A = \begin{pmatrix} \sqrt{2} & 3\sqrt{2} & 0 \\ -4\sqrt{2} & \sqrt{2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$

### **Solution**

$$\left[ \begin{array}{ccc|ccc} \sqrt{2} & 3\sqrt{2} & 0 & 1 & 0 & 0 \\ -4\sqrt{2} & \sqrt{2} & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \end{array} \right] \quad R_2 + 4R_1$$

$$\left[ \begin{array}{ccc|ccc} \sqrt{2} & 3\sqrt{2} & 0 & 1 & 0 & 0 \\ 0 & 13\sqrt{2} & 0 & 4 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \end{array} \right] \quad 13R_1 - 3R_2$$

$$\left[ \begin{array}{ccc|ccc} 13\sqrt{2} & 0 & 0 & 1 & -3 & 0 \\ 0 & 13\sqrt{2} & 0 & 4 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \end{array} \right] \quad \begin{array}{l} \frac{1}{13\sqrt{2}}R_1 \\ \frac{1}{13\sqrt{2}}R_2 \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 0 & \frac{1}{13\sqrt{2}} & -\frac{3}{13\sqrt{2}} & 0 \\ 0 & 1 & 0 & \frac{4}{13\sqrt{2}} & \frac{1}{13\sqrt{2}} & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \end{array} \right]$$

$$A^{-1} = \begin{pmatrix} \frac{\sqrt{2}}{26} & -\frac{3\sqrt{2}}{26} & 0 \\ \frac{2\sqrt{2}}{13} & \frac{\sqrt{2}}{26} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

### Exercise

Find the inverse, if exists of  $A = \begin{pmatrix} -8 & 17 & 2 & \frac{1}{3} \\ 4 & 0 & \frac{2}{5} & -9 \\ 0 & 0 & 0 & 0 \\ -1 & 13 & 4 & 2 \end{pmatrix}$

### Solution

$$\begin{bmatrix} -8 & 17 & 2 & \frac{1}{3} \\ 4 & 0 & \frac{2}{5} & -9 \\ 0 & 0 & 0 & 0 \\ -1 & 13 & 4 & 2 \end{bmatrix}^{-1} = \text{doesn't exist}$$

Since this matrix is *singular*, row 3 all zeros.

### Exercise

Find the inverse, if exists, of  $A = \begin{bmatrix} -2 & -3 & 4 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 4 & -6 & 1 \\ -2 & -2 & 5 & 1 \end{bmatrix}$

### Solution

$$\left[ \begin{array}{cccc|cccc} -2 & -3 & 4 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 4 & -6 & 1 & 0 & 0 & 1 & 0 \\ -2 & -2 & 5 & 1 & 0 & 0 & 0 & 1 \end{array} \right] \quad -\frac{1}{2}R_1$$

$$\left[ \begin{array}{cccc|cccc} 1 & \frac{3}{2} & -2 & -\frac{1}{2} & -\frac{1}{2} & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 4 & -6 & 1 & 0 & 0 & 1 & 0 \\ -2 & -2 & 5 & 1 & 0 & 0 & 0 & 1 \end{array} \right] \quad R_4 + 2R_1$$

$$\left[ \begin{array}{cccc|cccc} 1 & \frac{3}{2} & -2 & -\frac{1}{2} & -\frac{1}{2} & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 4 & -6 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 \end{array} \right] R_4 - R_2$$

$$\left[ \begin{array}{cccc|cccc} 1 & \frac{3}{2} & -2 & -\frac{1}{2} & -\frac{1}{2} & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 4 & -6 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{array} \right]$$

$\therefore$  Inverse *does not exist*

### Exercise

Find the inverse, if exists, of  $A = \begin{bmatrix} 1 & -14 & 7 & 38 \\ -1 & 2 & 1 & -2 \\ 1 & 2 & -1 & -6 \\ 1 & -2 & 3 & 6 \end{bmatrix}$

### Solution

$$\left[ \begin{array}{cccc|cccc} 1 & -14 & 7 & 38 & 1 & 0 & 0 & 0 \\ -1 & 2 & 1 & -2 & 0 & 1 & 0 & 0 \\ 1 & 2 & -1 & -6 & 0 & 0 & 1 & 0 \\ 1 & -2 & 3 & 6 & 0 & 0 & 0 & 1 \end{array} \right] \begin{array}{l} R_2 + R_1 \\ R_3 - R_1 \\ R_4 - R_1 \end{array}$$

$$\left[ \begin{array}{cccc|cccc} 1 & -14 & 7 & 38 & 1 & 0 & 0 & 0 \\ 0 & -12 & 8 & 36 & 1 & 1 & 0 & 0 \\ 0 & 16 & -8 & -44 & -1 & 0 & 1 & 0 \\ 0 & 12 & -4 & -32 & -1 & 0 & 0 & 1 \end{array} \right] -\frac{1}{12}R_2$$

$$\left[ \begin{array}{cccc|cccc} 1 & -14 & 7 & 38 & 1 & 0 & 0 & 0 \\ 0 & 1 & -\frac{2}{3} & -3 & -\frac{1}{12} & -\frac{1}{12} & 0 & 0 \\ 0 & 16 & -8 & -44 & -1 & 0 & 1 & 0 \\ 0 & 12 & -4 & -32 & -1 & 0 & 0 & 1 \end{array} \right] \begin{array}{l} R_1 + 14R_2 \\ R_3 - 16R_2 \\ R_4 - 12R_2 \end{array}$$

$$\left[ \begin{array}{cccc|cccc} 1 & 0 & -\frac{7}{3} & -4 & -\frac{1}{6} & -\frac{7}{6} & 0 & 0 \\ 0 & 1 & -\frac{2}{3} & -3 & -\frac{1}{12} & -\frac{1}{12} & 0 & 0 \\ 0 & 0 & \frac{8}{3} & 4 & \frac{1}{3} & \frac{4}{3} & 1 & 0 \\ 0 & 0 & 4 & 4 & 0 & 1 & 0 & 1 \end{array} \right] \frac{3}{8}R_3$$

$$\left[ \begin{array}{cccc|cccc} 1 & 0 & -\frac{7}{3} & -4 & -\frac{1}{6} & -\frac{7}{6} & 0 & 0 \\ 0 & 1 & -\frac{2}{3} & -3 & -\frac{1}{12} & -\frac{1}{12} & 0 & 0 \\ 0 & 0 & 1 & \frac{3}{2} & \frac{1}{8} & \frac{1}{2} & \frac{3}{8} & 0 \\ 0 & 0 & 4 & 4 & 0 & 1 & 0 & 1 \end{array} \right] \begin{array}{l} R_1 + \frac{7}{3}R_3 \\ R_2 + \frac{2}{3}R_3 \\ \\ R_4 - 4R_3 \end{array}$$

$$\left[ \begin{array}{cccc|cccc} 1 & 0 & 0 & -\frac{1}{2} & \frac{1}{8} & 0 & \frac{7}{8} & 0 \\ 0 & 1 & 0 & -2 & 0 & \frac{1}{4} & \frac{1}{4} & 0 \\ 0 & 0 & 1 & \frac{3}{2} & \frac{1}{8} & \frac{1}{2} & \frac{3}{8} & 0 \\ 0 & 0 & 0 & -2 & -\frac{1}{2} & -1 & -\frac{3}{2} & 1 \end{array} \right] -\frac{1}{2}R_4$$

$$\left[ \begin{array}{cccc|cccc} 1 & 0 & 0 & -\frac{1}{2} & \frac{1}{8} & 0 & \frac{7}{8} & 0 \\ 0 & 1 & 0 & -2 & 0 & \frac{1}{4} & \frac{1}{4} & 0 \\ 0 & 0 & 1 & \frac{3}{2} & \frac{1}{8} & \frac{1}{2} & \frac{3}{8} & 0 \\ 0 & 0 & 0 & 1 & \frac{1}{4} & \frac{1}{2} & \frac{3}{4} & -\frac{1}{2} \end{array} \right] \begin{array}{l} R_1 + \frac{1}{2}R_4 \\ R_2 + 2R_4 \\ R_3 - \frac{3}{2}R_4 \\ \end{array}$$

$$\left[ \begin{array}{cccc|cccc} 1 & 0 & 0 & 0 & \frac{1}{4} & \frac{1}{4} & \frac{5}{4} & -\frac{1}{4} \\ 0 & 1 & 0 & 0 & \frac{1}{2} & \frac{5}{4} & \frac{7}{4} & -1 \\ 0 & 0 & 1 & 0 & -\frac{1}{4} & -\frac{1}{4} & -\frac{3}{4} & \frac{3}{4} \\ 0 & 0 & 0 & 1 & \frac{1}{4} & \frac{1}{2} & \frac{3}{4} & -\frac{1}{2} \end{array} \right]$$

$$A^{-1} = \begin{bmatrix} \frac{1}{4} & \frac{1}{4} & \frac{5}{4} & -\frac{1}{4} \\ \frac{1}{2} & \frac{5}{4} & \frac{7}{4} & -1 \\ -\frac{1}{4} & -\frac{1}{4} & -\frac{3}{4} & \frac{3}{4} \\ \frac{1}{4} & \frac{1}{2} & \frac{3}{4} & -\frac{1}{2} \end{bmatrix}$$

### Exercise

Find the inverse, if exists, of  $A = \begin{bmatrix} 10 & 20 & -30 & 15 \\ 3 & -7 & 14 & -8 \\ -7 & -2 & -1 & 2 \\ 4 & 4 & -3 & 1 \end{bmatrix}$

### Solution

$$\left[ \begin{array}{cccc|cccc} 10 & 20 & -30 & 15 & 1 & 0 & 0 & 0 \\ 3 & -7 & 14 & -8 & 0 & 1 & 0 & 0 \\ -7 & -2 & -1 & 2 & 0 & 0 & 1 & 0 \\ 4 & 4 & -3 & 1 & 0 & 0 & 0 & 1 \end{array} \right] \quad \frac{1}{10}R_1$$

$$\left[ \begin{array}{cccc|cccc} 1 & 2 & -3 & \frac{3}{2} & \frac{1}{10} & 0 & 0 & 0 \\ 3 & -7 & 14 & -8 & 0 & 1 & 0 & 0 \\ -7 & -2 & -1 & 2 & 0 & 0 & 1 & 0 \\ 4 & 4 & -3 & 1 & 0 & 0 & 0 & 1 \end{array} \right] \quad \begin{array}{l} R_2 - 3R_1 \\ R_3 + 7R_1 \\ R_4 - 4R_1 \end{array}$$

$$\left[ \begin{array}{cccc|cccc} 1 & 2 & -3 & \frac{3}{2} & \frac{1}{10} & 0 & 0 & 0 \\ 0 & -13 & 23 & -\frac{25}{2} & -\frac{3}{10} & 1 & 0 & 0 \\ 0 & 12 & -22 & \frac{25}{2} & \frac{7}{10} & 0 & 1 & 0 \\ 0 & -4 & 9 & -5 & -\frac{2}{5} & 0 & 0 & 1 \end{array} \right] \quad -\frac{1}{13}R_2$$

$$\left[ \begin{array}{cccc|cccc} 1 & 2 & -3 & \frac{3}{2} & \frac{1}{10} & 0 & 0 & 0 \\ 0 & 1 & -\frac{23}{13} & \frac{25}{26} & \frac{3}{130} & -\frac{1}{13} & 0 & 0 \\ 0 & 12 & -22 & \frac{25}{2} & \frac{7}{10} & 0 & 1 & 0 \\ 0 & -4 & 9 & -5 & -\frac{2}{5} & 0 & 0 & 1 \end{array} \right] \quad \begin{array}{l} R_1 - 2R_2 \\ R_3 - 12R_2 \\ R_4 + 4R_2 \end{array}$$

$$\left[ \begin{array}{cccc|cccc} 1 & 0 & \frac{7}{13} & -\frac{11}{26} & \frac{7}{130} & \frac{2}{13} & 0 & 0 \\ 0 & 1 & -\frac{23}{13} & \frac{25}{26} & \frac{3}{130} & -\frac{1}{13} & 0 & 0 \\ 0 & 0 & -\frac{10}{13} & \frac{25}{26} & \frac{11}{26} & \frac{12}{13} & 1 & 0 \\ 0 & 0 & \frac{25}{13} & -\frac{15}{13} & -\frac{4}{13} & -\frac{4}{13} & 0 & 1 \end{array} \right] \quad -\frac{13}{10}R_3$$



$$\left[ \begin{array}{cccc|cccc} 1 & 0 & \frac{7}{13} & -\frac{11}{26} & \frac{7}{130} & \frac{2}{13} & 0 & 0 \\ 0 & 1 & -\frac{23}{13} & \frac{25}{26} & \frac{3}{130} & -\frac{1}{13} & 0 & 0 \\ 0 & 0 & 1 & -\frac{5}{4} & -\frac{11}{20} & -\frac{6}{5} & -\frac{13}{10} & 0 \\ 0 & 0 & \frac{25}{13} & -\frac{15}{13} & -\frac{4}{13} & -\frac{4}{13} & 0 & 1 \end{array} \right] \quad \begin{array}{l} R_1 - \frac{7}{13}R_3 \\ R_2 + \frac{23}{13}R_3 \\ R_4 - \frac{25}{13}R_3 \end{array}$$

$$\left[ \begin{array}{cccc|cccc} 1 & 0 & 0 & \frac{1}{4} & \frac{7}{20} & \frac{4}{5} & \frac{7}{10} & 0 \\ 0 & 1 & 0 & -\frac{5}{4} & -\frac{19}{20} & -\frac{11}{5} & -\frac{23}{10} & 0 \\ 0 & 0 & 1 & -\frac{5}{4} & -\frac{11}{20} & -\frac{6}{5} & -\frac{13}{10} & 0 \\ 0 & 0 & 0 & \frac{5}{4} & \frac{3}{4} & 2 & \frac{5}{2} & 1 \end{array} \right] \quad \begin{array}{l} R_2 + R_4 \\ R_3 + R_4 \end{array}$$

$$\left[ \begin{array}{cccc|cccc} 1 & 0 & 0 & \frac{1}{4} & \frac{7}{20} & \frac{4}{5} & \frac{7}{10} & 0 \\ 0 & 1 & 0 & 0 & -\frac{4}{5} & -\frac{1}{5} & \frac{1}{5} & 1 \\ 0 & 0 & 1 & 0 & \frac{1}{5} & \frac{4}{5} & \frac{6}{5} & 1 \\ 0 & 0 & 0 & \frac{5}{4} & \frac{3}{4} & 2 & \frac{5}{2} & 1 \end{array} \right] \quad \frac{4}{5}R_4$$

$$\left[ \begin{array}{cccc|cccc} 1 & 0 & 0 & \frac{1}{4} & \frac{7}{20} & \frac{4}{5} & \frac{7}{10} & 0 \\ 0 & 1 & 0 & 0 & -\frac{4}{5} & -\frac{1}{5} & \frac{1}{5} & 1 \\ 0 & 0 & 1 & 0 & \frac{1}{5} & \frac{4}{5} & \frac{6}{5} & 1 \\ 0 & 0 & 0 & 1 & \frac{3}{5} & \frac{8}{5} & 2 & \frac{4}{5} \end{array} \right] \quad R_1 - \frac{1}{4}R_4$$

$$\left[ \begin{array}{cccc|cccc} 1 & 0 & 0 & 0 & \frac{1}{5} & \frac{2}{5} & \frac{1}{5} & -\frac{1}{5} \\ 0 & 1 & 0 & 0 & -\frac{4}{5} & -\frac{1}{5} & \frac{1}{5} & 1 \\ 0 & 0 & 1 & 0 & \frac{1}{5} & \frac{4}{5} & \frac{6}{5} & 1 \\ 0 & 0 & 0 & 1 & \frac{3}{5} & \frac{8}{5} & 2 & \frac{4}{5} \end{array} \right]$$

$$A^{-1} = \begin{bmatrix} \frac{1}{5} & \frac{2}{5} & \frac{1}{5} & -\frac{1}{5} \\ -\frac{4}{5} & -\frac{1}{5} & \frac{1}{5} & 1 \\ \frac{1}{5} & \frac{4}{5} & \frac{6}{5} & 1 \\ \frac{3}{5} & \frac{8}{5} & 2 & \frac{4}{5} \end{bmatrix}$$

### Exercise

Show that  $A$  is not invertible for any values of the entries

$$A = \begin{bmatrix} 0 & a & 0 & 0 & 0 \\ b & 0 & c & 0 & 0 \\ 0 & d & 0 & e & 0 \\ 0 & 0 & f & 0 & g \\ 0 & 0 & 0 & h & 0 \end{bmatrix}$$

### Solution

Since the matrix  $A$  had zero's on its diagonals, therefore  $A$  is not invertible.

### Exercise

Prove that if  $A$  is an invertible matrix and  $B$  is row equivalent to  $A$ , then  $B$  is also invertible.

### Solution

Since  $B$  is row equivalent to  $A$ , there exist some elementary matrices  $E_1, E_2, \dots, E_n$  such that  $B = E_n \dots E_1 A$ . Because  $E_1, E_2, \dots, E_n$  and  $A$  are invertible, then  $B$  is also invertible.

### Exercise

Determine if the given matrix has an inverse, and find the inverse if it exists. Check your answer by multiplying  $A \cdot A^{-1} = I$

$$a) \begin{bmatrix} 2 & 3 \\ -3 & -5 \end{bmatrix} \quad b) \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 1 \\ 2 & 3 & 5 \end{bmatrix}$$

### Solution

$$a) \quad 2(-5) - 3(-3) = -10 + 9 = -1$$

$$A^{-1} = \frac{1}{-1} \begin{bmatrix} -5 & -3 \\ 3 & 2 \end{bmatrix} = \begin{bmatrix} 5 & 3 \\ -3 & -2 \end{bmatrix}$$

$$AA^{-1} = \begin{pmatrix} 2 & 3 \\ -3 & -5 \end{pmatrix} \begin{pmatrix} 5 & 3 \\ -3 & -2 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = I$$

$$b) \quad \left[ \begin{array}{ccc|ccc} 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 2 & 3 & 5 & 0 & 0 & 1 \end{array} \right] \quad R_3 - 2R_1$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 3 & 3 & -2 & 0 & 1 \end{array} \right] \quad R_3 - 3R_2$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & * & * & * \end{array} \right]$$

The inverse matrix doesn't exist

### Exercise

Show that the inverse of  $\begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}$  is  $\begin{bmatrix} \cos(-\theta) & \sin(-\theta) \\ -\sin(-\theta) & \cos(-\theta) \end{bmatrix}$

### Solution

$$\begin{aligned} & \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} \cos(-\theta) & \sin(-\theta) \\ -\sin(-\theta) & \cos(-\theta) \end{bmatrix} \\ &= \begin{bmatrix} (\cos \theta)\cos(-\theta) - (\sin \theta)\sin(-\theta) & (\cos \theta)\sin(-\theta) - (\sin \theta)\cos(-\theta) \\ (-\sin \theta)\cos(-\theta) - (\cos \theta)\sin(-\theta) & (-\sin \theta)\sin(-\theta) + (\cos \theta)\cos(-\theta) \end{bmatrix} \\ &= \begin{bmatrix} \cos \theta \cos \theta + \sin \theta \sin \theta & -\cos \theta \sin \theta - \sin \theta \cos \theta \\ -\sin \theta \cos \theta + \cos \theta \sin \theta & \sin \theta \sin \theta + \cos \theta \cos \theta \end{bmatrix} \quad \begin{cases} \cos(-\theta) = \cos \theta & (\text{even}) \\ \sin(-\theta) = -\sin \theta & (\text{odd}) \end{cases} \\ &= \begin{bmatrix} \cos^2 \theta + \sin^2 \theta & 0 \\ 0 & \sin^2 \theta + \cos^2 \theta \end{bmatrix} \\ &= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\ &= \underline{I} \end{aligned}$$

### Exercise

If the product  $C = AB$  is invertible (and  $A$  &  $B$  are square matrices), find a formula for  $A^{-1}$  that involves  $C^{-1}$  and  $B$ .

Hence, it is not possible to multiply a non-invertible matrix by another matrix and obtain an invertible matrix as a result.

### Solution

Since  $C = AB$  is invertible, the  $CC^{-1} = C^{-1}C = I$

$$CC^{-1} = I$$

$$(AB)C^{-1} = I$$

$$A(BC^{-1}) = I$$

$$A^{-1}A(BC^{-1}) = A^{-1}I$$

$$I(BC^{-1}) = A^{-1}$$

$$\underline{BC^{-1} = A^{-1}} \quad \checkmark$$

### Exercise

Prove that if  $A$  is an  $m \times n$  matrix, there is an invertible matrix  $C$  such that  $CA$  is in reduced row-echelon form.

### Solution

The reduced row-echelon form of  $A$  can be written in the form  $E_n \dots E_2 E_1 A$  where

$E_1, E_2, \dots, E_n$  are elementary matrices.

Let  $C = E_n \dots E_2 E_1$ , then  $C$  is invertible since  $E_1, E_2, \dots, E_n$  are invertible.

Hence, there exists such a matrix  $C$ .

### Exercise

Prove that 2  $m \times n$  matrices  $A$  and  $B$  are row equivalent if and only if there exists a nonsingular matrix  $P$  such that  $B = PA$

### Solution

Suppose that  $A \sim B$ , then there exist elementary matrices  $E_1, E_2, \dots, E_n$  such that

$$B = E_n \dots E_2 E_1 A.$$

Let  $P = E_n \dots E_2 E_1 \Rightarrow$  by the theorem,  $P$  is nonsingular.

Suppose that  $B = PA$ , for some nonsingular matrix  $P$ . By the theorem,  $P$  is row equivalent to  $I_k$ .

That is,  $I_k = E_n \dots E_2 E_1 P$ .

Thus,  $B = E_n^{-1} E_{n-1}^{-1} \dots E_1^{-1} A$  and this implies that  $A$  is row equivalent to  $B$ .

### Exercise

Let  $A$  and  $B$  be 2  $m \times n$  matrices. Suppose  $A$  is row equivalent to  $B$ . Prove that  $A$  is nonsingular if and only if  $B$  is nonsingular.

### Solution

Suppose that  $A$  is row equivalent to  $B$ . Then, there exists a nonsingular matrix  $P$  such that  $B = PA$ .

If  $A$  is nonsingular then  $B$  is nonsingular.

Conversely, if  $B$  is nonsingular then  $A = P^{-1}B$  is nonsingular.

### Exercise

Show that if  $A$  and  $B$  are two  $n \times n$  invertible matrices then  $A$  is row equivalent to  $B$ .

### Solution

Since  $A$  is invertible, then  $A$  is row equivalent to  $I_n$ . That is, there exist elementary matrices

$$E_1, E_2, \dots, E_k \text{ such that } I_n = E_k E_{k-1} \cdots E_1 A.$$

Similarly, there exist elementary matrices  $F_1, F_2, \dots, F_k$  such that  $I_n = F_i F_{i-1} \cdots F_1 B$ .

$$\begin{aligned} \text{Hence, } A &= E_1^{-1} E_2^{-1} \cdots E_k^{-1} I_n \\ &= E_1^{-1} E_2^{-1} \cdots E_k^{-1} (F_i F_{i-1} \cdots F_1 B) \\ &= (E_1^{-1} E_2^{-1} \cdots E_k^{-1} F_i F_{i-1} \cdots F_1 B) \end{aligned}$$

That is,  $A$  row equivalent to  $B$ .

### Exercise

Prove that a square matrix  $A$  is nonsingular if and only if  $A$  is a product of elementary matrices.

### Solution

Suppose that  $A$  is nonsingular. Then  $A$  is row equivalent to  $I_n$ . That is, there exist elementary

$$\text{matrices } E_1, E_2, \dots, E_k \text{ such that } I_n = E_k E_{k-1} \cdots E_1 A \rightarrow A = E_1^{-1} E_2^{-1} \cdots E_k^{-1} I_n.$$

But each  $E_i^{-1}$  is an elementary matrix.

$$\text{Conversely, suppose that } A = E_1 E_2 \cdots E_k, \text{ then } (E_1 E_2 \cdots E_k)^{-1} A = I_n$$

That is,  $A$  is nonsingular.

### Exercise

Show that if  $A \sim B$  (that is, if they are row equivalent), then  $EA = B$  for some matrix  $E$  which is a product of elementary matrices.

### Solution

If  $A \sim B$ , there is some sequence of elementary row operations which, when performed on  $A$ , produce  $B$ .

Further, multiplying on the left by the corresponding elementary matrix is the same as performing that row operation. So we have

$$\begin{aligned} A &\sim E_1 A \\ &\sim E_2 E_1 A \end{aligned}$$

$$\sim E_k E_{k-1} \dots E_2 E_1 A$$

$$= B$$

Thus, if  $E = E_k \dots E_1$ , then we have  $EA = B$

### Exercise

Show that if  $EA = B$  for some matrix  $E$  which is a product of elementary matrices, then  $AC \sim BC$  for every  $n \times n$  matrix  $C$ .

### Solution

Let  $E = E_k E_{k-1} \dots E_1$ , where each  $E_i$  is an elementary matrix.

$$\begin{aligned} AC &\sim E_1 AC \\ &\sim E_2 E_1 AC \\ &\sim E_k E_{k-1} \dots E_2 E_1 AC \\ &= EAC && \text{since } EA = B \\ &= BC \end{aligned}$$

Therefore;  $AC \sim BC$

### Exercise

Let  $A\vec{x} = 0$  be a homogeneous system of  $n$  linear equations in  $n$  unknowns that has only the trivial solution. Show that if  $k$  is any positive integer, then the system  $A^k \vec{x} = 0$  also has only trivial solution.

### Solution

Since  $A$  is a square matrix, thus  $A$  has only the trivial solution. That implies that  $A$  is invertible.

But  $A^k$  is also invertible so  $A^k \vec{x} = 0$  has only trivial solution.

### Exercise

Let  $A\vec{x} = 0$  be a homogeneous system of  $n$  linear equations in  $n$  unknowns, and let  $Q$  be an invertible  $n \times n$  matrix. Show that  $A\vec{x} = 0$  has just trivial solution if and only if  $(QA)\vec{x} = 0$  has just trivial solution.

### Solution

$A$  is a square  $(n \times n)$  matrix. If  $A\vec{x} = 0$  has just a trivial solution, then  $A$  is invertible. Since  $Q$  is an invertible  $n \times n$  matrix, then  $QA$  is also invertible.

Thus,  $(QA)\vec{x} = 0$  has trivial solution.

On the other hand, if  $(QA)\vec{x} = 0$  has trivial solution, then  $QA$  is also invertible.

Since  $Q$  is invertible, then  $Q^{-1}$  is also invertible.

Thus,  $A = Q^{-1}QA$  is invertible, i.e.  $A\vec{x} = 0$  has just trivial solution, equivalent  $A\vec{x} = 0$  has just trivial solution if and only if  $(QA)\vec{x} = 0$  has just trivial solution.

### ***Exercise***

Let  $A\vec{x} = b$  be any consistent system of linear equations, and let  $\vec{x}_1$  be a fixed solution. Show that every solution to the system can be written in the form  $\vec{x} = \vec{x}_1 + \vec{x}_0$  where  $\vec{x}_0$  is a solution to  $A\vec{x} = 0$ . Show also that every matrix of this form is a solution.

### ***Solution***

Since  $\vec{x}_0$  is a solution to  $A\vec{x} = 0$ , we have  $A\vec{x}_0 = 0$ .

Adding  $A\vec{x}_0 = 0$  to  $A\vec{x} = b$ , then

$$A\vec{x} + A\vec{x}_0 = b + 0$$

$$A(\vec{x} + \vec{x}_0) = b$$

As adding an equation to the original equation does not affect the solution.

If we let  $\vec{x}_1$  be a fixed solution, then every solution to  $A\vec{x} = b$  is  $\vec{x} = \vec{x}_1 + \vec{x}_0$ .

Besides,

$$\begin{aligned} A(\vec{x} + \vec{x}_0) &= A\vec{x} + A\vec{x}_0 \\ &= b + 0 \\ &= b \end{aligned}$$

So, every matrix (vector) in the form  $\vec{x}_1 + \vec{x}_0$  is a solution to  $A\vec{x} = b$

### ***Exercise***

If  $A$  and  $B$  are  $n \times n$  matrices satisfying  $A^2 = B^2 = (AB)^2 = I_n$ . Prove that  $AB = BA$ .

### ***Solution***

Since  $A^2 = B^2 = (AB)^2 = I_n$ , then  $A, B, AB$  are nonsingular.

$$A^2 = I \rightarrow A = A^{-1}$$

$$B^2 = I \rightarrow B = B^{-1}$$

$$(AB)^2 = I \rightarrow AB = (AB)^{-1}$$

$$\begin{aligned}
 AB &= (AB)^{-1} \\
 &= B^{-1}A^{-1} \\
 &= \underline{BA} \quad \checkmark
 \end{aligned}$$

### Exercise

Let  $A = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 5 & 0 & 0 \end{pmatrix}$ . Verify that  $A^3 = 5I$ , then find  $A^{-1}$  in term of  $A$ .

### Solution

$$\begin{aligned}
 A^2 &= \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 5 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 5 & 0 & 0 \end{pmatrix} \\
 &= \begin{pmatrix} 0 & 0 & 1 \\ 5 & 0 & 0 \\ 0 & 5 & 0 \end{pmatrix}
 \end{aligned}$$

$$\begin{aligned}
 A^3 &= AA^2 \\
 &= \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 5 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 1 \\ 5 & 0 & 0 \\ 0 & 5 & 0 \end{pmatrix} \\
 &= \begin{pmatrix} 5 & 0 & 0 \\ 0 & 5 & 0 \\ 0 & 0 & 5 \end{pmatrix} \\
 &= 5 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \\
 &= \underline{5I}
 \end{aligned}$$

Since  $A^3 = AA^2 = 5I$

$$\frac{1}{5}(AA^2) = I$$

$$A\left(\frac{1}{5}A^2\right) = I$$

$$\underline{A^{-1} = \frac{1}{5}A^2}$$



### Exercise

Consider  $B(A, I) = (BA, B)$ , thus if  $B$  is the inverse of  $A$ , then  $(BA, B)$  becomes  $(I, A^{-1})$ . On the other hand  $B$  is a product of elementary matrices since it is invertible. This indicates that the inverse of  $A$  can be obtained by applying elementary row operations to  $(A, I)$  to get  $(I, A^{-1})$ .

Find the inverses of

$$a) \quad A = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ a & b & 1 \end{pmatrix}$$

$$b) \quad B = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ a & b & c & d \end{pmatrix}$$

### Solution

$$a) \quad \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ a & b & 1 \end{pmatrix} \xrightarrow{R_3 - aR_1} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & b & 1 \end{pmatrix} \quad E_{31} = -a$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & b & 1 \end{pmatrix} \xrightarrow{R_3 - bR_2} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad E_{32} = -b$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} = I$$

$$A^{-1} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -a & -b & 1 \end{pmatrix}$$

b) First, we have move row 4 to row 1, for the calculation

$$\begin{pmatrix} a & b & c & d \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \xrightarrow{\frac{1}{a}R_1} \begin{pmatrix} 1 & \frac{b}{a} & \frac{c}{a} & \frac{d}{a} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad E_{11} = \frac{1}{a}$$

$$\begin{pmatrix} 1 & \frac{b}{a} & \frac{c}{a} & \frac{d}{a} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \xrightarrow{R_1 - \frac{b}{a}R_2} \begin{pmatrix} 1 & 0 & \frac{c}{a} & \frac{d}{a} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad E_{12} = -\frac{b}{a}$$

$$\begin{pmatrix} 1 & 0 & \frac{c}{a} & \frac{d}{a} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad R_1 - \frac{c}{a}R_3 \quad E_{13} = -\frac{c}{a}$$

$$\begin{pmatrix} 1 & 0 & 0 & \frac{d}{a} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad R_1 - \frac{d}{a}R_4 \quad E_{14} = -\frac{d}{a}$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} = I$$

$$E = \begin{pmatrix} \frac{1}{a} & -\frac{b}{a} & -\frac{c}{a} & -\frac{d}{a} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Since we move Row 4 to Row 1, we must move Column 1 to Column 4 to get the inverse matrix.

$$B^{-1} = \begin{pmatrix} -\frac{b}{a} & -\frac{c}{a} & -\frac{d}{a} & \frac{1}{a} \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

### ***Exercise***

Let  $A, B, C, X, Y, Z \in M_n(\mathbb{C})$ ,  $A$  and  $C$  are invertible. Find

$$a) \begin{pmatrix} A & B \\ 0 & C \end{pmatrix}^{-1}$$

$$b) \begin{pmatrix} I & X & Y \\ 0 & I & Z \\ 0 & 0 & I \end{pmatrix}^{-1}$$

### **Solution**

$$a) \left( A \ B \mid I \ 0 \right) \quad A^{-1}R_1$$

$$\left( \begin{array}{cc|cc} A^{-1}A & A^{-1}B & A^{-1}I & 0 \\ 0 & C & 0 & I \end{array} \right)$$

$$\left( \begin{array}{cc|cc} I & A^{-1}B & A^{-1} & 0 \\ 0 & C & 0 & I \end{array} \right) \quad \textcolor{red}{C}^{-1}R_2$$

$$\left( \begin{array}{cc|cc} I & A^{-1}B & A^{-1} & 0 \\ 0 & C^{-1}C & 0 & C^{-1}I \end{array} \right)$$

$$\left( \begin{array}{cc|cc} I & A^{-1}B & A^{-1} & 0 \\ 0 & I & 0 & C^{-1} \end{array} \right) \quad R_1 - \textcolor{red}{A}^{-1}\textcolor{red}{B}R_2$$

$$\left( \begin{array}{cc|cc} I & A^{-1}B - A^{-1}BI & A^{-1} & -A^{-1}BC^{-1} \\ 0 & I & 0 & C^{-1} \end{array} \right)$$

$$\left( \begin{array}{cc|cc} I & A^{-1}B - A^{-1}B & A^{-1} & -A^{-1}BC^{-1} \\ 0 & I & 0 & C^{-1} \end{array} \right)$$

$$\left( \begin{array}{cc|cc} I & 0 & A^{-1} & -A^{-1}BC^{-1} \\ 0 & I & 0 & C^{-1} \end{array} \right)$$

$$\begin{pmatrix} A & B \\ 0 & C \end{pmatrix}^{-1} = \begin{pmatrix} \textcolor{blue}{A}^{-1} & -\textcolor{blue}{A}^{-1}\textcolor{blue}{B}C^{-1} \\ \textcolor{blue}{0} & \textcolor{blue}{C}^{-1} \end{pmatrix}$$

$$b) \left( \begin{array}{ccc|ccc} I & X & Y & I & 0 & 0 \\ 0 & I & Z & 0 & I & 0 \\ 0 & 0 & I & 0 & 0 & I \end{array} \right) \quad R_1 - \textcolor{red}{X}R_2$$

$$\left( \begin{array}{ccc|ccc} I & 0 & Y - XZ & I & -X & 0 \\ 0 & I & Z & 0 & I & 0 \\ 0 & 0 & I & 0 & 0 & I \end{array} \right) \quad \begin{array}{l} R_1 - (\textcolor{red}{Y} - \textcolor{red}{X}\textcolor{red}{Z})R_3 \\ R_2 - \textcolor{red}{Z}R_3 \end{array}$$

$$\left( \begin{array}{ccc|ccc} I & 0 & 0 & I & -X & XZ - Y \\ 0 & I & 0 & 0 & I & -Z \\ 0 & 0 & I & 0 & 0 & I \end{array} \right)$$

$$\begin{pmatrix} I & X & Y \\ 0 & I & Z \\ 0 & 0 & I \end{pmatrix}^{-1} = \begin{pmatrix} \textcolor{blue}{I} & -\textcolor{blue}{X} & \textcolor{blue}{X}Z - \textcolor{blue}{Y} \\ \textcolor{blue}{0} & \textcolor{blue}{I} & -\textcolor{blue}{Z} \\ \textcolor{blue}{0} & \textcolor{blue}{0} & \textcolor{blue}{I} \end{pmatrix}$$

### Exercise

Suppose that  $A$ ,  $B$ , and  $A - B$  are invertible  $n \times n$  matrices. Show that

$$(A - B)^{-1} = A^{-1} + A^{-1}(B^{-1} - A^{-1})^{-1}A^{-1}$$

### Solution

$A$ ,  $B$ , and  $A - B$  are invertible Then

$$AA^{-1} = A^{-1}A = I \quad BB^{-1} = B^{-1}B = I$$

$$(A - B)(A - B)^{-1} = (A - B)^{-1}(A - B) = I$$

Let:

$$(A - B)^{-1}(A - B) = I$$

Then, we need to prove that

$$\left( A^{-1} + A^{-1}(B^{-1} - A^{-1})^{-1}A^{-1} \right)(A - B) \stackrel{?}{=} I$$

$$\begin{aligned} \left( A^{-1} + A^{-1}(B^{-1} - A^{-1})^{-1}A^{-1} \right)(A - B) &= \left( A^{-1} + A^{-1} \left( A(B^{-1} - A^{-1}) \right)^{-1} \right)(A - B) \\ & \qquad \qquad \qquad \left( A(B^{-1} - A^{-1}) \right)^{-1} = (B^{-1} - A^{-1})^{-1}A^{-1} \end{aligned}$$

$$= \left( A^{-1} + A^{-1} \left( AB^{-1} - AA^{-1} \right)^{-1} \right)(A - B)$$

$$= \left( A^{-1} + A^{-1} \left( AB^{-1} - I \right)^{-1} \right)(A - B)$$

$$= \left( A^{-1} + A^{-1} \left( AB^{-1} - \textcolor{red}{BB}^{-1} \right)^{-1} \right)(A - B)$$

$$= \left( A^{-1} + A^{-1} \left( (A - B)B^{-1} \right)^{-1} \right)(A - B)$$

$$\left( (A - B)B^{-1} \right)^{-1} = B(A - B)^{-1}$$

$$= \left( A^{-1} + A^{-1} \left( B(A - B)^{-1} \right) \right)(A - B)$$

$$= \left( A^{-1} + A^{-1}B(A - B)^{-1} \right)(A - B)$$

$$= A^{-1}(A - B) + A^{-1}B(A - B)^{-1}(A - B)$$

$$= A^{-1}A - A^{-1}B + A^{-1}B \textcolor{red}{I}$$

$$= I - A^{-1}B + A^{-1}B$$

$$= I \quad \checkmark$$

$$\text{Therefore; } (A - B)^{-1} = A^{-1} + A^{-1} (B^{-1} - A^{-1})^{-1} A^{-1}$$

### Exercise

Suppose  $P$  is invertible and  $A = PBP^{-1}$ . Solve for  $B$  in terms of  $A$ .

### Solution

Since  $P$  is invertible, then  $PP^{-1} = P^{-1}P = I$

$$A = PBP^{-1}$$

$$P^{-1}AP = P^{-1}PBP^{-1}P \quad PP^{-1} = P^{-1}P = I$$

$$P^{-1}AP = IBI \quad BI = B$$

$$\underline{P^{-1}AP = B} \quad \checkmark$$

### Exercise

Suppose  $(A - B)C = 0$ , where  $A$  and  $B$  are  $m \times n$  matrices and  $C$  is invertible. Show that  $A = B$ .

### Solution

Since  $C$  is invertible, then  $CC^{-1} = C^{-1}C = I$

$$(A - B)C = 0$$

$$(A - B)CC^{-1} = 0C^{-1}$$

$$(A - B)I = 0$$

$$A - B = 0$$

$$A - B + B = 0 + B$$

$$\underline{A = B} \quad \checkmark$$

# ***Solution***      **Section 1.5 – Transpose, Diagonal, Triangular, and Symmetric Matrices**

## ***Exercise***

Solve  $Lc = b$  to find  $c$ . Then solve  $Ux = c$  to find  $x$ . What was  $A$ ?

$$L = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix} \quad U = \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix} \quad b = \begin{bmatrix} 4 \\ 5 \\ 6 \end{bmatrix}$$

## **Solution**

$$Lc = b$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \\ c_3 \end{pmatrix} = \begin{pmatrix} 4 \\ 5 \\ 6 \end{pmatrix}$$

$$\rightarrow \begin{cases} c_1 = 4 \\ c_1 + c_2 = 5 \Rightarrow c_2 = 5 - 4 = 1 \\ c_1 + c_2 + c_3 = 6 \Rightarrow c_3 = 6 - 4 - 1 = 1 \end{cases} \quad c = \begin{pmatrix} 4 \\ 1 \\ 1 \end{pmatrix}$$

$$Ux = c$$

$$\begin{pmatrix} 1 & 1 & 1 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} 4 \\ 1 \\ 1 \end{pmatrix}$$

$$\Rightarrow \begin{cases} x + y + z = 4 \\ y + z = 1 \\ z = 1 \end{cases} \rightarrow \begin{cases} x = 3 \\ y = 0 \end{cases} \quad x = \begin{pmatrix} 3 \\ 0 \\ 1 \end{pmatrix}$$

$$Lc = b \Rightarrow LUx = b$$

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 & 1 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix}}_A \underbrace{\begin{pmatrix} 3 \\ 0 \\ 1 \end{pmatrix}}_x = \underbrace{\begin{pmatrix} 4 \\ 5 \\ 6 \end{pmatrix}}_b$$

### Exercise

Find  $L$  and  $U$  for the symmetric matrix

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

Find four conditions on  $a, b, c, d$  to get  $A = LU$  with four pivots

### Solution

$$A = \begin{bmatrix} a & a & a & a \\ a & b & b & b \\ a & b & c & c \\ a & b & c & d \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} a & a & a & a \\ 0 & b-a & b-a & b-a \\ 0 & 0 & c-b & c-b \\ 0 & 0 & 0 & d-c \end{bmatrix}$$

### Exercise

Determine whether the given matrix is invertible

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

### Solution

The matrix is a diagonal matrix with nonzero entries on the diagonal, so it is invertible.

$$\begin{pmatrix} -1 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & \frac{1}{3} \end{pmatrix}^{-1} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & \frac{1}{2} & 0 \\ 0 & 0 & 3 \end{bmatrix}$$

### Exercise

Find  $A^2$ ,  $A^{-2}$ , and  $A^{-k}$  by inspection  $A = \begin{bmatrix} 1 & 0 \\ 0 & -2 \end{bmatrix}$

### Solution

$$A^2 = \begin{bmatrix} 1^2 & 0 \\ 0 & (-2)^2 \end{bmatrix} \\ = \begin{bmatrix} 1 & 0 \\ 0 & 4 \end{bmatrix}$$

$$A^{-2} = \begin{bmatrix} 1^{-2} & 0 \\ 0 & (-2)^{-2} \end{bmatrix} \\ = \begin{bmatrix} 1 & 0 \\ 0 & \frac{1}{4} \end{bmatrix}$$

$$A^{-k} = \begin{bmatrix} 1^{-k} & 0 \\ 0 & (-2)^{-k} \end{bmatrix} \\ = \begin{bmatrix} 1 & 0 \\ 0 & \frac{1}{(-2)^k} \end{bmatrix}$$

### ***Exercise***

Find  $A^2$ ,  $A^{-2}$ , and  $A^{-k}$  by inspection  $A = \begin{bmatrix} \frac{1}{2} & 0 & 0 \\ 0 & \frac{1}{3} & 0 \\ 0 & 0 & \frac{1}{4} \end{bmatrix}$

### **Solution**

$$A^2 = \begin{bmatrix} \left(\frac{1}{2}\right)^2 & 0 & 0 \\ 0 & \left(\frac{1}{3}\right)^2 & 0 \\ 0 & 0 & \left(\frac{1}{4}\right)^2 \end{bmatrix} \\ = \begin{bmatrix} \frac{1}{4} & 0 & 0 \\ 0 & \frac{1}{9} & 0 \\ 0 & 0 & \frac{1}{16} \end{bmatrix}$$



$$A^{-2} = \begin{bmatrix} \left(\frac{1}{2}\right)^{-2} & 0 & 0 \\ 0 & \left(\frac{1}{3}\right)^{-2} & 0 \\ 0 & 0 & \left(\frac{1}{4}\right)^{-2} \end{bmatrix}$$

$$= \begin{bmatrix} 4 & 0 & 0 \\ 0 & 9 & 0 \\ 0 & 0 & 16 \end{bmatrix}$$

$$A^{-k} = \begin{bmatrix} \left(\frac{1}{2}\right)^{-k} & 0 & 0 \\ 0 & \left(\frac{1}{3}\right)^{-k} & 0 \\ 0 & 0 & \left(\frac{1}{4}\right)^{-k} \end{bmatrix}$$

$$= \begin{bmatrix} 2^k & 0 & 0 \\ 0 & 3^k & 0 \\ 0 & 0 & 4^k \end{bmatrix}$$

### ***Exercise***

Find  $A^2$ ,  $A^{-2}$ , and  $A^{-k}$  by inspection  $A = \begin{bmatrix} -2 & 0 & 0 & 0 \\ 0 & -4 & 0 & 0 \\ 0 & 0 & -3 & 0 \\ 0 & 0 & 0 & 2 \end{bmatrix}$

### **Solution**

$$A^2 = \begin{bmatrix} 4 & 0 & 0 & 0 \\ 0 & 16 & 0 & 0 \\ 0 & 0 & 9 & 0 \\ 0 & 0 & 0 & 4 \end{bmatrix}$$

$$A^{-2} = \begin{bmatrix} \frac{1}{4} & 0 & 0 & 0 \\ 0 & \frac{1}{16} & 0 & 0 \\ 0 & 0 & \frac{1}{9} & 0 \\ 0 & 0 & 0 & \frac{1}{4} \end{bmatrix}$$

$$A^{-k} = \begin{bmatrix} (-2)^{-k} & 0 & 0 & 0 \\ 0 & (-4)^{-k} & 0 & 0 \\ 0 & 0 & (-3)^{-k} & 0 \\ 0 & 0 & 0 & (2)^{-k} \end{bmatrix}$$

### Exercise

Decide whether the given matrix is symmetric  $\begin{bmatrix} 2 & -1 \\ 1 & 2 \end{bmatrix}$

### Solution

Not *symmetric*, since  $a_{12} \neq a_{21}$  ( $1 \neq -1$ )

### Exercise

Decide whether the given matrix is symmetric  $\begin{bmatrix} 2 & -1 & 3 \\ -1 & 5 & 1 \\ 3 & 1 & 7 \end{bmatrix}$

### Solution

*Symmetric*

### Exercise

Decide whether the given matrix is symmetric  $\begin{bmatrix} 0 & 0 & 1 \\ 0 & 2 & 0 \\ 3 & 0 & 0 \end{bmatrix}$

### Solution

Not *symmetric*, since  $a_{13} = 1 \neq 3 = a_{31}$

### Exercise

Find all values of the unknown constant(s) in order for  $A$  to be symmetric

$$A = \begin{bmatrix} 2 & a - 2b + 2c & 2a + b + c \\ 3 & 5 & a + c \\ 0 & -2 & 7 \end{bmatrix}$$

### Solution

$$\begin{cases} a - 2b + 2c = 3 \\ 2a + b + c = 0 \\ a + c = -2 \end{cases} \rightarrow a = 11, \quad b = 9, \quad c = -13$$

### ***Exercise***

Find a diagonal matrix  $A$  that satisfies the given condition  $A^{-2} = \begin{bmatrix} 9 & 0 & 0 \\ 0 & 4 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

### ***Solution***

$$\begin{aligned} \begin{pmatrix} a & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & c \end{pmatrix}^{-2} &= \begin{pmatrix} a^{-2} & 0 & 0 \\ 0 & b^{-2} & 0 \\ 0 & 0 & c^{-2} \end{pmatrix} \\ &= \begin{bmatrix} 9 & 0 & 0 \\ 0 & 4 & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{aligned}$$

$$\rightarrow \begin{cases} a^{-2} = 9 \Rightarrow a = \pm 9^{-1/2} = \pm \frac{1}{3} \\ b^{-2} = 4 \Rightarrow b = \pm 2^{-1/2} = \pm \frac{1}{2} \\ c^{-2} = 1 \Rightarrow c = \pm 1^{-1/2} = \pm 1 \end{cases}$$

$$A = \begin{pmatrix} -\frac{1}{3} & 0 & 0 \\ 0 & \frac{1}{2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad A = \begin{pmatrix} -\frac{1}{3} & 0 & 0 \\ 0 & -\frac{1}{2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad A = \begin{pmatrix} -\frac{1}{3} & 0 & 0 \\ 0 & -\frac{1}{2} & 0 \\ 0 & 0 & -1 \end{pmatrix} \quad \dots$$

$$A = \begin{pmatrix} \pm \frac{1}{3} & 0 & 0 \\ 0 & \pm \frac{1}{2} & 0 \\ 0 & 0 & \pm 1 \end{pmatrix}$$

### Exercise

Let  $A$  be an  $n \times n$  symmetric matrix

- a) Show that  $A^2$  is symmetric
- b) Show that  $2A^2 - 3A + I$  is symmetric

### Solution

- a) The property of the transpose states that  $(AB)^T = B^T A^T$

$$\begin{aligned}(A^2)^T &= (AA)^T \\ &= A^T A^T \\ &= (A^T)^2 \quad \text{A is symmetric} \\ &= A^2\end{aligned}$$

$\therefore A^2$  is symmetric

$$\begin{aligned}b) \quad (2A^2 - 3A + I)^T &= 2(A^2)^T - 3(A)^T + (I)^T \\ &= 2(A^T)^2 - 3A^T + (I)^T \quad \text{A and I are symmetric} \\ &= 2A^2 - 3A + I \\ \therefore 2A^2 - 3A + I &\text{ is Symmetric}\end{aligned}$$

### Exercise

Prove if  $A^T A = A$ , then  $A$  is symmetric and  $A = A^2$

### Solution

If  $A^T A = A$ , then

$$\begin{aligned}A^T &= \left( \begin{matrix} \textcolor{red}{A}^T & \textcolor{blue}{A} \end{matrix} \right)^T \\ &= \textcolor{blue}{A}^T \left( \begin{matrix} \textcolor{red}{A}^T \end{matrix} \right)^T \\ &= A^T A \\ &= \textcolor{blue}{A}\end{aligned}$$

So  $A$  is symmetric.

Since  $A = A^T$

$$\begin{aligned}A A &= A^T A \quad \text{A}^T A = A \\ \textcolor{blue}{A}^2 &= \textcolor{blue}{A}\end{aligned}$$

### Exercise

A square matrix  $A$  is called **skew-symmetric** if  $A^T = -A$ . Prove

- a) If  $A$  is an invertible skew-symmetric matrix, then  $A^{-1}$  is skew-symmetric.
- b) If  $A$  and  $B$  are skew-symmetric matrices, then so are  $A^T$ ,  $A + B$ ,  $A - B$ , and  $kA$  for any scalar  $k$ .
- c) Every square matrix  $A$  can be expressed as the sum of a symmetric matrix and a skew-symmetric matrix.

$$\left[ \text{Hint: Note the identity } A = \frac{1}{2}(A + A^T) + \frac{1}{2}(A - A^T) \right]$$

### Solution

$$\begin{aligned} \text{a) } (A^{-1})^T &= (A^T)^{-1} \\ &= (-A)^{-1} \quad \text{skew-symmetric} \\ &= -A^{-1} \end{aligned}$$

$\therefore A^{-1}$  is also skew-symmetric

- b) Let  $A$  and  $B$  are skew-symmetric matrices

$$\begin{aligned} (A^T)^T &= (-A)^T \\ &= -A^T \\ (A+B)^T &= A^T + B^T \\ &= -A - B \\ &= -(A+B) \end{aligned}$$

$$\begin{aligned} (A-B)^T &= A^T - B^T \\ &= -A + B \\ &= -(A-B) \end{aligned}$$

$$\begin{aligned} (kA)^T &= k(A)^T \\ &= k(-A) \\ &= -kA \end{aligned}$$

- c) We need to prove from the hint that  $\frac{1}{2}(A + A^T)$  is symmetric and  $\frac{1}{2}(A - A^T)$  is skew-symmetric

$$\begin{aligned} \frac{1}{2}(A + A^T)^T &= \frac{1}{2}\left(A^T + (A^T)^T\right) \\ &= \frac{1}{2}(A + A^T) \end{aligned}$$

Thus  $\frac{1}{2}(A + A^T)$  is symmetric

$$\begin{aligned}\frac{1}{2}(A - A^T)^T &= \frac{1}{2}(A^T - (A^T)^T) \\ &= \frac{1}{2}(A^T - A) \\ &= -\frac{1}{2}(A - A^T)\end{aligned}$$

Thus  $\frac{1}{2}(A - A^T)$  is skew-symmetric

### Exercise

Suppose  $R$  is rectangular ( $m$  by  $n$ ) and  $A$  is symmetric ( $m$  by  $m$ )

- Transpose  $R^T A R$  to show its symmetric
- Show why  $R^T R$  has no negative numbers on its diagonal.

### Solution

$$\begin{aligned}a) \quad (R^T A R)^T &= ((R^T A) R)^T \\ &= R^T (R^T A)^T \\ &= R^T A^T (R^T)^T \\ &= R^T A R\end{aligned}$$

$$\begin{aligned}b) \quad (R^T R)_{jj} &= (\text{column } j \text{ of } R) \cdot (\text{column } j \text{ of } R) \\ &= \text{Product of the diagonal entry by itself.} \\ &= \text{length squared of column } j.\end{aligned}$$

### Exercise

If  $L$  is a lower-triangular matrix, then  $(L^{-1})^T$  is \_\_\_\_\_ Triangular

### Solution

$(L^{-1})^T$  is **upper** triangular.

$L^{-1}$  is a lower-triangular because  $L$  is.

The transpose carries the lower-triangular matrices to the upper-triangular (and vice versa).

## Exercise

True or False

- a) The block matrix  $\begin{bmatrix} 0 & A \\ A & 0 \end{bmatrix}$  is automatically symmetric
- b) If  $A$  and  $B$  are symmetric then their product is symmetric
- c) If  $A$  is not symmetric then  $A^{-1}$  is not symmetric
- d) When  $A, B, C$  are symmetric, the transpose of  $ABC$  is  $CBA$ .
- e) The transpose of a diagonal matrix is a diagonal.
- f) The transpose of an upper triangular matrix is an upper triangular matrix.
- g) The sum of an upper triangular matrix and a lower triangular matrix is a diagonal matrix.
- h) All entries of a symmetric matrix are determined by the entries occurring on and above the main diagonal.
- i) All entries of an upper triangular matrix are determined by the entries occurring on and above the main diagonal.
- j) The inverse of an invertible lower triangular matrix is an upper triangular matrix.
- k) A diagonal matrix is invertible if and only if all of its diagonal entries are positive.
- l) The sum of a diagonal matrix and a lower triangular matrix is a lower triangular matrix.
- m) A matrix that is both symmetric and upper triangular must be a diagonal matrix.
- n) If  $A$  and  $B$  are  $n \times n$  matrices such that  $A + B$  is symmetric, then  $A$  and  $B$  are symmetric.
- o) If  $A$  and  $B$  are  $n \times n$  matrices such that  $A + B$  is upper triangular, then  $A$  and  $B$  are upper triangular.
- p) If  $A^2$  is a symmetric matrix, then  $A$  is a symmetric matrix.
- q) If  $kA$  is a symmetric matrix for some  $k \neq 0$ , then  $A$  is a symmetric matrix.

## Solution

a) **False:**  $\left( \begin{array}{cc|cc} 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 \\ \hline 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \end{array} \right)$

b) **False**  $\begin{pmatrix} 1 & 0 \\ 0 & 2 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 2 & 2 \end{pmatrix}$   
 $A$   $B$

c) **True** by definition.

d) **True**  $(ABC)^T = C^T (AB)^T = C^T B^T A^T = CBA$  Since  $A^T = A, B^T = B, C^T = C$

e) **True** Since a diagonal matrix must be square and have zeros off the main diagonal, its transpose is also diagonal.

- f) **False** The transpose of an upper triangular matrix is lower triangular.
- g) **False**  $\begin{bmatrix} 1 & 2 \\ 0 & 3 \end{bmatrix} + \begin{bmatrix} 3 & 0 \\ 1 & 1 \end{bmatrix} = \begin{bmatrix} 4 & 2 \\ 1 & 4 \end{bmatrix}$
- h) **True** The entries above the main diagonal determine the entries below the main diagonal in a symmetric matrix.
- i) **True** in an upper triangular matrix, the series below the main diagonal are all zeros.
- j) **False** The inverse of an invertible lower triangular matrix is lower triangular.
- k) **False** The diagonal entries may be negative, as long as they are nonzero.
- l) **True** Adding a diagonal matrix to a lower triangular matrix will not create nonzero entries above the main diagonal.
- m) **True** Since the entries below the main diagonal must be zero, so also must be the entries above the main diagonal.
- n) **False**  $\begin{bmatrix} 1 & 2 \\ 1 & 3 \end{bmatrix} + \begin{bmatrix} 3 & 0 \\ 1 & 1 \end{bmatrix} = \begin{bmatrix} 4 & 2 \\ 2 & 4 \end{bmatrix}$  which is symmetric
- o) **False**  $\begin{bmatrix} 1 & 2 \\ 1 & 3 \end{bmatrix} + \begin{bmatrix} 3 & 0 \\ -1 & 1 \end{bmatrix} = \begin{bmatrix} 4 & 2 \\ 0 & 4 \end{bmatrix}$  which is upper triangular.
- p) **False**  $\begin{bmatrix} 1 & 0 \\ 1 & -1 \end{bmatrix}^2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$
- q) **True**  $(kA)^T = kA$  then  
 $(kA)^T - kA = 0$   
 $kA^T - kA = 0$   
 $k(A^T - A) = 0$  since  $k \neq 0$  then  $A^T = A$   
 Therefore,  $A$  is a symmetric matrix

### **Exercise**

Find 2 by 2 symmetric matrices  $A = A^T$  with these properties

- a)  $A$  is not invertible
- b)  $A$  is invertible but cannot be factored into  $LU$  (row exchanges needed)
- c)  $A$  can be factored into  $LDL^T$  but not into  $LL^T$  (because of negative  $D$ )

### **Solution**

a)  $A = \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$



b)  $A = \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix}$  only need a *zero* in the diagonal.

c)  $A = LDL^T$

$$A = \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} a & 0 \\ 0 & d \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$$

$$A = \begin{pmatrix} a & 0 \\ a & d \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} a & a \\ a & a+d \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 1 & 2 \end{pmatrix} \rightarrow \begin{cases} a=1 \\ d=1 \end{cases}$$

$LL^T$

$$A = \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} \rightarrow D = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

### Exercise

A group of matrices includes  $AB$  and  $A^{-1}$  if it includes  $A$  and  $B$ . “Products and inverses stay in the group.” Which of these sets are groups?

Lower triangular matrices  $L$  with 1's on the diagonal, symmetric matrices  $S$ , positive matrices  $M$ , diagonal invertible matrices  $D$ , permutation matrices  $P$ , matrices with  $Q^T = Q^{-1}$ . ***Invent two more matrix groups.***

### Solution

The lower triangular matrices  $L$  with 1's on the diagonal form a group.

Clearly the product of two is a third. The Gauss-Jordan method shows that the inverse of one is another.

The symmetric matrices don't form a group. An example of the 2 symmetric matrices  $A$  and  $B$  whose product is not symmetric

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad B = \begin{bmatrix} 1 & 2 & 3 \\ 2 & 4 & 5 \\ 3 & 5 & 6 \end{bmatrix} \quad AB = \begin{bmatrix} 2 & 4 & 5 \\ 1 & 2 & 3 \\ 3 & 5 & 6 \end{bmatrix}$$

The positive matrices do not form a group.

$$M = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \quad M^{-1} = \begin{bmatrix} 1 & -1 \\ 0 & 1 \end{bmatrix}, \text{ the inverse is not symmetric.}$$

The diagonal invertible matrices form a group.

The permutation matrices form a group.

The matrices with  $Q^T = Q^{-1}$  form a group. If  $A$  and  $B$  are two matrices, then so are  $AB$  and  $A^{-1}$ , as

$$(AB)^T = B^T A^T = B^{-1} A^{-1} = (AB)^{-1}$$

$$(A^{-1})^T = (A^T)^{-1} = A^{-1}$$

There are many more matrix groups. For example, given two, the block matrices  $\begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix}$  form a

third as  $A$  ranges over the first group and  $B$  ranges over the second.

Another example is the set of all products  $cP$  where  $c$  is a nonzero scalar and  $P$  is a permutation matrix of given size.

### ***Exercise***

Write  $A = \begin{bmatrix} 1 & 2 \\ 4 & 9 \end{bmatrix}$  as the product  $EH$  of an elementary row operation matrix  $E$  and a symmetric matrix  $H$ .

### **Solution**

$$A = EH$$

$$E^{-1}A = E^{-1}EH$$

$$E^{-1}A = H$$

An elementary row operation matrix has the form  $E = \begin{pmatrix} 1 & 0 \\ x & 1 \end{pmatrix}$

The inverse is:  $E^{-1} = \begin{pmatrix} 1 & 0 \\ -x & 1 \end{pmatrix}$

$$\begin{aligned} H &= \begin{pmatrix} 1 & 0 \\ -x & 1 \end{pmatrix} \begin{pmatrix} 1 & 2 \\ 4 & 9 \end{pmatrix} \\ &= \begin{pmatrix} 1 & 2 \\ -x+4 & -2x+9 \end{pmatrix} \end{aligned}$$

Since matrix  $H$  is symmetric, therefore:

$$-x+4=2$$

$$\underline{x=2}$$

$$\begin{pmatrix} 1 & 2 \\ 4 & 9 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 2 & 1 \end{pmatrix} \begin{pmatrix} 1 & 2 \\ 2 & 5 \end{pmatrix}$$

*Elementary    Symmetric*

### Exercise

When is the product of two symmetric matrices symmetric? Explain your answer.

#### Solution

$AB$  is symmetric iff  $AB = (AB)^T$

$$\begin{aligned} AB &= (AB)^T \\ &= B^T A^T \quad \text{A and B are symmetric} \\ &= BA \end{aligned}$$

$AB$  is symmetric iff  $A$  and  $B$  commute

### Exercise

Express  $((AB)^{-1})^T$  in terms of  $(A^{-1})^T$  and  $(B^{-1})^T$

#### Solution

$$\begin{aligned} ((AB)^{-1})^T &= (B^{-1}A^{-1})^T \\ &= (A^{-1})^T (B^{-1})^T \end{aligned}$$

### Exercise

Find the transpose of the given matrix:

$$\begin{bmatrix} 8 & -1 \\ 3 & 5 \\ -2 & 5 \\ 1 & 2 \\ -3 & -5 \end{bmatrix}$$

#### Solution

$$A^T = \begin{bmatrix} 8 & 3 & -2 & 1 & -3 \\ -1 & 5 & 5 & 2 & -5 \end{bmatrix}$$

### Exercise

Show that if  $A$  is symmetric and invertible, then  $A^{-1}$  is also symmetric.

#### Solution

$A$  is symmetric and invertible, then  $A = A^T$   $AA^{-1} = I$

$$\begin{aligned}\left(A^{-1}\right)^T &= \left(A^T\right)^{-1} \\ &= A^{-1}\end{aligned}$$

$\Rightarrow A^{-1}$  is symmetric.

### Exercise

Prove that  $(AB)^T = B^T A^T$

### Solution

Let  $A = \begin{bmatrix} a_{ik} \end{bmatrix}$  and  $B = \begin{bmatrix} b_{kj} \end{bmatrix}$

Then the  $ij$ -entry of  $AB$  is:

$$a_{i1}b_{1j} + a_{i2}b_{2j} + \dots + a_{im}b_{mj}$$

The reverse order,  $ji$ -entry of  $(AB)^T$

Column  $j$  of  $B$  becomes row  $j$  of  $B^T$ , and row  $i$  of  $A$  becomes column  $i$  of  $A^T$ .

Thus, the  $ij$ -entry of  $B^T A^T$  is:

$$\left(b_{1j}, b_{2j}, \dots, b_{mj}\right)\left(a_{i1}, a_{i2}, \dots, a_{im}\right)^T = b_{1j}a_{i1} + b_{2j}a_{i2} + \dots + b_{mj}a_{im}$$

Thus  $(AB)^T = B^T A^T$

### Exercise

For the given matrix, compute  $A^T$ ,  $(A^T)^{-1}$ ,  $A^{-1}$ , and  $(A^{-1})^T$ , then compare  $(A^T)^{-1}$  and  $(A^{-1})^T$

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

### Solution

$$A^T = \begin{bmatrix} 1 & 2 & 3 \\ 0 & 1 & 2 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\left[ \begin{array}{ccc|ccc} 1 & 2 & 3 & 1 & 0 & 0 \\ 0 & 1 & 2 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \end{array} \right] \quad R_1 - 2R_2$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & -1 & 1 & -2 & 0 \\ 0 & 1 & 2 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \end{array} \right] \begin{array}{l} R_1 + R_3 \\ R_1 - 2R_3 \end{array}$$

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

$$\left( A^T \right)^{-1} = \begin{bmatrix} 1 & -2 & 1 \\ 0 & 1 & -2 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 0 & 1 & 0 & 0 \\ 2 & 1 & 0 & 0 & 1 & 0 \\ 3 & 2 & 1 & 0 & 0 & 1 \end{array} \right] \begin{array}{l} \\ R_2 - 2R_1 \\ R_3 - 3R_1 \end{array}$$

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & -2 & 1 & 0 \\ 0 & 2 & 1 & -3 & 0 & 1 \end{array} \right] R_3 - 2R_2$$

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

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

$$\left( A^{-1} \right)^T = \begin{bmatrix} 1 & -2 & 1 \\ 0 & 1 & -2 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\left( A^T \right)^{-1} = \left( A^{-1} \right)^T$$

### ***Exercise***

Show that a  $2 \times 2$  lower triangular matrix is invertible if and only if  $a_{11}a_{22} \neq 0$  and in this case the inverse is also lower triangular.

### ***Solution***

Let  $A$  to be the lower triangular matrix

$$A = \begin{pmatrix} a_{11} & 0 \\ a_{21} & a_{22} \end{pmatrix}$$

$\det(A) = a_{11}a_{22} \neq 0$  is invertible iff  $a_{11}a_{22} \neq 0$  and then

$$A^{-1} = \frac{1}{a_{11}a_{22}} \begin{pmatrix} a_{22} & 0 \\ -a_{21} & a_{11} \end{pmatrix}$$

$$= \begin{pmatrix} \frac{1}{a_{11}} & 0 \\ -\frac{a_{21}}{a_{11}a_{22}} & \frac{1}{a_{22}} \end{pmatrix}$$

### ***Exercise***

Let  $A$  be any  $2 \times 2$  diagonal matrix. Give a necessary and sufficient condition on the diagonal entries so that  $A$  has an inverse. Compute the inverse of any such matrix.

### **Solution**

$$\text{Let } A = \begin{pmatrix} a_{11} & 0 \\ 0 & a_{22} \end{pmatrix}$$

$$A^{-1} = \begin{pmatrix} \frac{1}{a_{11}} & 0 \\ 0 & \frac{1}{a_{22}} \end{pmatrix}$$

So,  $A^{-1}$  exists when both entries on the main diagonal are nonzero.

## ***Solution***      **Section 1.6 – The Properties of Determinants**

### ***Exercise***

Verify that  $\det(AB) = \det(A)\det(B)$  when:  $A = \begin{pmatrix} 2 & 1 & 0 \\ 3 & 4 & 0 \\ 0 & 0 & 2 \end{pmatrix}$  and  $B = \begin{pmatrix} 1 & -1 & 3 \\ 7 & 1 & 2 \\ 5 & 0 & 1 \end{pmatrix}$

### **Solution**

$$AB = \begin{pmatrix} 2 & 1 & 0 \\ 3 & 4 & 0 \\ 0 & 0 & 2 \end{pmatrix} \begin{pmatrix} 1 & -1 & 3 \\ 7 & 1 & 2 \\ 5 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} 9 & -1 & 8 \\ 31 & 1 & 17 \\ 10 & 0 & 2 \end{pmatrix}$$

$$\det(AB) = \begin{vmatrix} 9 & -1 & 8 \\ 31 & 1 & 17 \\ 10 & 0 & 2 \end{vmatrix} \begin{matrix} 9 & -1 \\ 31 & 1 \\ 10 & 0 \end{matrix}$$
$$\underline{\underline{= -170}}$$

$$\det(A) = \begin{vmatrix} 2 & 1 & 0 \\ 3 & 4 & 0 \\ 0 & 0 & 2 \end{vmatrix}$$
$$\underline{\underline{= 10}}$$

$$\det(B) = \begin{vmatrix} 1 & -1 & 3 \\ 7 & 1 & 2 \\ 5 & 0 & 1 \end{vmatrix}$$
$$\underline{\underline{= -17}}$$

$$\det(AB) = \det(A)\det(B) = -170 \quad \checkmark$$

### ***Exercise***

For which value(s) of  $k$  does  $A$  fail to be invertible?  $A = \begin{bmatrix} k-3 & -2 \\ -2 & k-2 \end{bmatrix}$

### **Solution**

For  $A$  to have an invertible the determinant cannot be equal to zero. To **fail**  $\det(A) = 0$ .

$$|A| = \begin{vmatrix} k-3 & -2 \\ -2 & k-2 \end{vmatrix} = 0$$

$$(k-3)(k-2)-4=0$$

$$k^2-5k+6-4=0$$

$$k^2-5k+2=0$$

$$k = \frac{5 \pm \sqrt{17}}{2}$$

### Exercise

Without directly evaluating, show that 
$$\begin{vmatrix} b+c & c+a & b+a \\ a & b & c \\ 1 & 1 & 1 \end{vmatrix} = 0$$

### Solution

$$\begin{vmatrix} b+c & c+a & b+a \\ a & b & c \\ 1 & 1 & 1 \end{vmatrix} \xrightarrow{R_2 + R_1} \begin{vmatrix} a+b+c & b+c+a & c+b+a \\ a & b & c \\ 1 & 1 & 1 \end{vmatrix} = 0$$

It is equal to zero, since first row and third row are proportional.

$$\begin{vmatrix} a+b+c & b+c+a & c+b+a \\ a & b & c \\ 1 & 1 & 1 \end{vmatrix} \xrightarrow{R_3 - \frac{1}{a+b+c}R_1} \begin{vmatrix} a+b+c & b+c+a & c+b+a \\ a & b & c \\ 0 & 0 & 0 \end{vmatrix} = 0$$

### Exercise

If the entries in every row of  $A$  add to zero, solve  $A\mathbf{x} = 0$  to prove  $\det A = 0$ . If those entries add to one, show that  $\det(A - I) = 0$ . Does this mean  $\det A = I$ ?

### Solution

If  $\mathbf{x} = (1, 1, \dots, 1)$ , then  $A\mathbf{x}$  = the sums of the rows of  $A$ . Since every row of  $A$  add to zero, that implies  $A\mathbf{x} = 0$ . Since  $A$  has non-zero nullspace, it is not invertible and  $\det A = 0$ . If the entries in every row of  $A$  sum to one, then the entries in every row of  $A - I$  sum to zero.  $A - I$  has a non-zero nullspace and  $\det(A - I) = 0$ . This does not mean that  $\det A = I$ .

### Example:

$$A = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \text{ every row of } A \text{ adds up to zero}$$

$$\Rightarrow \det A = -1 \neq 1 = \det I$$



### Exercise

Does  $\det(AB) = \det(BA)$  in general?

- a) True or false if  $A$  and  $B$  are square  $n \times n$  matrices?
- b) True or false if  $A$  is  $m \times n$  and  $B$  is  $n \times m$  with  $m \neq n$ ?

### Solution

- a) Matrices  $A$  and  $B$  are square matrices, then by the property:

$$\begin{aligned}\det(AB) &= \det(A)\det(B) \\ &= \det(B)\det(A) \\ &= \det(BA)\end{aligned}$$

Therefore; it is true for any  $A$  and  $B$  square matrices.

- b) False, example if  $A = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$   $B = \begin{pmatrix} 1 & 1 \end{pmatrix}$

$$\begin{aligned}AB &= \begin{pmatrix} 1 \\ 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \end{pmatrix} \\ &= \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}\end{aligned}$$

$$\begin{aligned}\det(AB) &= \begin{vmatrix} 1 & 1 \\ 1 & 1 \end{vmatrix} \\ &= 0\end{aligned}$$

$$BA = \begin{pmatrix} 1 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 2 \end{pmatrix}$$

$$\det(BA) = 2$$

$$\det(AB) \neq \det(BA)$$

### Exercise

True or false, with a reason if true or a counterexample if false:

- a) The determinant of  $I + A$  is  $1 + \det A$ .
- b) The determinant of  $ABC$  is  $|A||B||C|$ .
- c) The determinant of  $4A$  is  $4|A|$
- d) The determinant of  $AB - BA$  is zero. (try an example)
- e) If  $A$  is not invertible then  $AB$  is not invertible.
- f) The determinant of  $A - B$  equals to  $\det A - \det B$ .

### Solution

a) **False**, if  $A = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$

$$\det(I + A) = \det \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \\ = 0$$

$$\det A = 1$$

$$1 + \det A = 1 + 1 \\ = 2$$

$$\neq \det(I + A)$$

b) **True**,  $\det(ABC) = \det(A)\det(BC) = \det(A)\det(B)\det(C)$ .

c) **False**, in general  $\det(4A) = 4^n \det(A)$  if  $A$  is  $n \times n$ .

d) **False**,  $A = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$ ,  $B = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$

$$AB - BA = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} - \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \\ = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} - \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \\ = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$\det(AB - BA) = \begin{vmatrix} 0 & 1 \\ -1 & 0 \end{vmatrix} \\ = 1 \neq 0$$

e) **False**, any matrix is invertible, iff its determinant is nonzero. So  $\det A = 0$  which  
 $\det(AB) = \det(A)\det(B) = 0$ . Therefore,  $AB$  can't be invertible.

f)  $A = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \Rightarrow |A| = 0$

$$B = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \Rightarrow |B| = -1$$

$$\det(A) - \det(B) = 0 - (-1) = 1$$

$$\det(A - B) = \det \begin{pmatrix} 1 & -1 \\ -1 & 0 \end{pmatrix} = -1$$

$$\Rightarrow \det(A - B) \neq \det(A) - \det(B)$$

### Exercise

Use row operations to show the 3 by 3 “Vandermonde determinant” is

$$\det \begin{bmatrix} 1 & a & a^2 \\ 1 & b & b^2 \\ 1 & c & c^2 \end{bmatrix} = (b-a)(c-a)(c-b)$$

### Solution

$$\begin{aligned} \det \begin{bmatrix} 1 & a & a^2 \\ 1 & b & b^2 \\ 1 & c & c^2 \end{bmatrix} &= \det \begin{bmatrix} 1 & a & a^2 \\ 1 & b & b^2 \\ 1 & c & c^2 \end{bmatrix} \begin{array}{l} R_2 - R_1 \\ R_3 - R_1 \end{array} \\ &= \det \begin{bmatrix} 1 & a & a^2 \\ 0 & b-a & b^2-a^2 \\ 0 & c-a & c^2-a^2 \end{bmatrix} \quad \text{factor } (b-a) \\ &= (b-a) \det \begin{bmatrix} 1 & a & a^2 \\ 0 & 1 & b+a \\ 0 & c-a & c^2-a^2 \end{bmatrix} \begin{array}{l} R_2 - (c-a)R_2 \\ (c-a)(c+a) - (b+a)(c-a) = (c-a)(c+a-b-a) \end{array} \\ &= (b-a) \det \begin{bmatrix} 1 & a & a^2 \\ 0 & 1 & b+a \\ 0 & 0 & (c-a)(c-b) \end{bmatrix} \quad \text{Multiply the main diagonal by } (b-a) \\ &= \underline{(b-a)(c-a)(c-b)} \end{aligned}$$

### Exercise

The inverse of a 2 by 2 matrix seems to have determinant = 1:

$$\det A^{-1} = \det \frac{1}{ad-bc} \begin{bmatrix} d & -b \\ -c & a \end{bmatrix} = \frac{ad-bc}{ad-bc} = 1$$

What is wrong with this calculation? What is the correct  $\det A^{-1}$

### Solution

The  $\det \frac{1}{ad-bc} \begin{bmatrix} d & -b \\ -c & a \end{bmatrix}$   $(ad-bc)$  it is part of the determinant and it is not the solution.

$$\begin{aligned}
\det \frac{1}{ad-bc} \begin{bmatrix} d & -b \\ -c & a \end{bmatrix} &= \frac{1}{ad-bc} \det \begin{bmatrix} d & -b \\ -c & a \end{bmatrix} \\
&= \frac{1}{ad-bc} \frac{1}{ad-bc} (ad-bc) \\
&= \frac{1}{ad-bc}
\end{aligned}$$

### Exercise

A *Hessenberg* matrix is a triangular matrix with one extra diagonal. Use cofactors of row 1 to show that the 4 by 4 determinant satisfies Fibonacci's rule  $|H_4| = |H_3| + |H_2|$ . The same rule will continue for all sizes  $|H_n| = |H_{n-1}| + |H_{n-2}|$ . Which Fibonacci number is  $|H_n|$ ?

$$H_2 = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \quad H_3 = \begin{bmatrix} 2 & 1 & \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{bmatrix} \quad H_4 = \begin{bmatrix} 2 & 1 & & \\ 1 & 2 & 1 & \\ 1 & 1 & 2 & 1 \\ 1 & 1 & 1 & 2 \end{bmatrix}$$

### Solution

$$|H_4| = 2C_{11} + 1C_{12}$$

The cofactor  $C_{11}$  for  $H_4$  is the determinant  $|H_3|$ .

$$C_{11} = (-1)^{1+1} \begin{vmatrix} 2 & 1 & 0 \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{vmatrix} = \begin{vmatrix} 2 & 1 & 0 \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{vmatrix}$$

$$\text{The cofactor } C_{12} = (-1)^{1+2} \begin{vmatrix} 1 & 1 & 0 \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{vmatrix}$$

$$= - \begin{vmatrix} 1 & 1 & 0 \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{vmatrix}$$

$$= - \begin{vmatrix} 2 & 1 & 0 \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{vmatrix} + \begin{vmatrix} 1 & 0 & 0 \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{vmatrix}$$

$$= -|H_3| + |H_2|$$

$$|H_2| = \begin{vmatrix} 2 & 1 \\ 1 & 2 \end{vmatrix} = \begin{vmatrix} 1 & 0 & 0 \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{vmatrix}$$

$$\begin{aligned}
 |H_4| &= 2C_{11} + 1C_{12} \\
 &= 2|H_3| - |H_3| + |H_2| \\
 &= |H_3| + |H_2|
 \end{aligned}$$

The actual number:  $|H_2| = 3$ ,  $|H_3| = 5$ ,  $H_4 = 8$ .

Since  $|H_n|$  follows Fibonacci's rule  $|H_{n-1}| + |H_{n-2}|$ , it must be  $|H_n| = F_{n+2}$ .

### ***Exercise***

Evaluate  $\begin{vmatrix} -1 & 3 \\ -2 & 9 \end{vmatrix}$

### **Solution**

$$\begin{aligned}
 \begin{vmatrix} -1 & 3 \\ -2 & 9 \end{vmatrix} &= -9 - (-6) \\
 &= \underline{-3}
 \end{aligned}$$

### ***Exercise***

Evaluate  $\begin{vmatrix} 6 & -4 \\ 0 & -1 \end{vmatrix}$

### **Solution**

$$\begin{aligned}
 \begin{vmatrix} 6 & -4 \\ 0 & -1 \end{vmatrix} &= -6 - (0) \\
 &= \underline{-6}
 \end{aligned}$$

### ***Exercise***

Evaluate  $\begin{vmatrix} x & 4x \\ 2x & 8x \end{vmatrix}$

### **Solution**

$$\begin{aligned}
 \begin{vmatrix} x & 4x \\ 2x & 8x \end{vmatrix} &= x(8x) - 4x(2x) \\
 &= 8x^2 - 8x^2 \\
 &= \underline{0}
 \end{aligned}$$

***Exercise***

Evaluate  $\begin{vmatrix} x & 2x \\ 4 & 3 \end{vmatrix}$

**Solution**

$$\begin{aligned} \begin{vmatrix} x & 2x \\ 4 & 3 \end{vmatrix} &= 3x - 2x(4) \\ &= 3x - 8x \\ &= \underline{-5x} \end{aligned}$$

***Exercise***

Evaluate  $\begin{vmatrix} x^4 & 2 \\ x & -3 \end{vmatrix}$

**Solution**

$$\begin{vmatrix} x^4 & 2 \\ x & -3 \end{vmatrix} = \underline{-3x^4 - 2x}$$

***Exercise***

Evaluate  $\begin{vmatrix} -8 & -5 \\ b & a \end{vmatrix}$

**Solution**

$$\begin{vmatrix} -8 & -5 \\ b & a \end{vmatrix} = \underline{-8a + 5b}$$

***Exercise***

Evaluate  $\begin{vmatrix} 5 & 7 \\ 2 & 3 \end{vmatrix}$

**Solution**

$$\begin{aligned} \begin{vmatrix} 5 & 7 \\ 2 & 3 \end{vmatrix} &= 15 - 14 \\ &= \underline{1} \end{aligned}$$

***Exercise***

Evaluate  $\begin{vmatrix} 1 & 4 \\ 5 & 5 \end{vmatrix}$

***Solution***

$$\begin{vmatrix} 1 & 4 \\ 5 & 5 \end{vmatrix} = 5 - 20 \\ = -16$$

***Exercise***

Evaluate  $\begin{vmatrix} 5 & 3 \\ -2 & 3 \end{vmatrix}$

***Solution***

$$\begin{vmatrix} 5 & 3 \\ -2 & 3 \end{vmatrix} = 15 + 6 \\ = 21$$

***Exercise***

Evaluate  $\begin{vmatrix} -4 & -1 \\ 5 & 6 \end{vmatrix}$

***Solution***

$$\begin{vmatrix} -4 & -1 \\ 5 & 6 \end{vmatrix} = -24 + 5 \\ = -19$$

***Exercise***

Evaluate  $\begin{vmatrix} \sqrt{3} & -2 \\ -3 & \sqrt{3} \end{vmatrix}$

***Solution***

$$\begin{vmatrix} \sqrt{3} & -2 \\ -3 & \sqrt{3} \end{vmatrix} = 3 - 6 \\ = -3$$

***Exercise***

Evaluate  $\begin{vmatrix} \sqrt{7} & 6 \\ -3 & \sqrt{7} \end{vmatrix}$

***Solution***

$$\begin{vmatrix} \sqrt{7} & 6 \\ -3 & \sqrt{7} \end{vmatrix} = 7 + 18$$
$$\underline{= 25}$$

***Exercise***

Evaluate  $\begin{vmatrix} \sqrt{5} & 3 \\ -2 & 2 \end{vmatrix}$

***Solution***

$$\begin{vmatrix} \sqrt{5} & 3 \\ -2 & 2 \end{vmatrix} = \underline{2\sqrt{5} + 6}$$

***Exercise***

Evaluate  $\begin{vmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{8} & -\frac{3}{4} \end{vmatrix}$

***Solution***

$$\begin{vmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{8} & -\frac{3}{4} \end{vmatrix} = -\frac{3}{8} - \frac{1}{16}$$
$$\underline{= -\frac{7}{16}}$$

***Exercise***

Evaluate  $\begin{vmatrix} \frac{1}{5} & \frac{1}{6} \\ -6 & -5 \end{vmatrix}$

***Solution***

$$\begin{vmatrix} \frac{1}{5} & \frac{1}{6} \\ -6 & -5 \end{vmatrix} = -1 + 1$$
$$\underline{= 0}$$



**Exercise**

Evaluate  $\begin{vmatrix} \frac{2}{3} & \frac{1}{3} \\ -\frac{1}{2} & \frac{3}{4} \end{vmatrix}$

**Solution**

$$\begin{vmatrix} \frac{2}{3} & \frac{1}{3} \\ -\frac{1}{2} & \frac{3}{4} \end{vmatrix} = \frac{1}{2} + \frac{1}{6}$$

$$= \frac{2}{3}$$

**Exercise**

Evaluate  $\begin{vmatrix} x & x^2 \\ 4 & x \end{vmatrix}$

**Solution**

$$\begin{vmatrix} x & x^2 \\ 4 & x \end{vmatrix} = x^2 - 4x^2$$

$$= -3x^2$$

**Exercise**

Evaluate  $\begin{vmatrix} x & x^2 \\ x & 9 \end{vmatrix}$

**Solution**

$$\begin{vmatrix} x & x^2 \\ x & 9 \end{vmatrix} = 9x - x^3$$

**Exercise**

Evaluate  $\begin{vmatrix} x^2 & x \\ -3 & 2 \end{vmatrix}$

**Solution**

$$\begin{vmatrix} x^2 & x \\ -3 & 2 \end{vmatrix} = 2x^2 + 3x$$

### ***Exercise***

Evaluate  $\begin{vmatrix} x+2 & 6 \\ x-2 & 4 \end{vmatrix}$

### **Solution**

$$\begin{aligned} \begin{vmatrix} x+2 & 6 \\ x-2 & 4 \end{vmatrix} &= 4(x+2) - 6(x-2) \\ &= 4x + 8 - 6x + 12 \\ &= \underline{-2x + 20} \end{aligned}$$

### ***Exercise***

Evaluate  $\begin{vmatrix} x+1 & -6 \\ x+3 & -3 \end{vmatrix}$

### **Solution**

$$\begin{aligned} \begin{vmatrix} x+1 & -6 \\ x+3 & -3 \end{vmatrix} &= -3x - 3 + 6x + 18 \\ &= \underline{-2x + 20} \end{aligned}$$

### ***Exercise***

Evaluate  $\begin{vmatrix} 3 & 0 & 0 \\ 2 & 1 & -5 \\ 2 & 5 & -1 \end{vmatrix}$

### **Solution**

$$\begin{aligned} \begin{vmatrix} 3 & 0 & 0 \\ 2 & 1 & -5 \\ 2 & 5 & -1 \end{vmatrix} &= \begin{vmatrix} 3 & 0 \\ 2 & 1 \end{vmatrix} - \begin{vmatrix} 3 & 0 \\ 2 & 5 \end{vmatrix} + \begin{vmatrix} 2 & 1 \\ 2 & 5 \end{vmatrix} \\ &= -3 + 0 + 0 - 0 + 75 - 0 \\ &= \underline{72} \end{aligned}$$

### ***Exercise***

Evaluate  $\begin{vmatrix} 4 & 0 & 0 \\ 3 & -1 & 4 \\ 2 & -3 & 6 \end{vmatrix}$

### **Solution**

$$\begin{vmatrix} 4 & 0 & 0 \\ 3 & -1 & 4 \\ 2 & -3 & 6 \end{vmatrix} \begin{matrix} 4 & 0 \\ 3 & -1 \\ 2 & -3 \end{matrix} \\
 = -24 + 48 \\
 = \underline{24}$$

$$\text{or} = 4 \begin{vmatrix} -1 & 4 \\ -3 & 6 \end{vmatrix}$$

### ***Exercise***

$$\text{Evaluate } \begin{vmatrix} 3 & 1 & 0 \\ -3 & -4 & 0 \\ -1 & 3 & 5 \end{vmatrix}$$

### **Solution**

$$\begin{vmatrix} 3 & 1 & 0 \\ -3 & -4 & 0 \\ -1 & 3 & 5 \end{vmatrix} \begin{matrix} 3 & 1 \\ -3 & -4 \\ -1 & 3 \end{matrix} \\
 = -60 + 15 \\
 = \underline{-45}$$

### ***Exercise***

$$\text{Evaluate } \begin{vmatrix} 1 & 1 & 1 \\ 2 & 2 & 2 \\ 3 & -4 & 5 \end{vmatrix}$$

### **Solution**

$$\begin{vmatrix} 1 & 1 & 1 \\ 2 & 2 & 2 \\ 3 & -4 & 5 \end{vmatrix} \begin{matrix} 1 & 1 \\ 2 & 2 \\ 3 & -4 \end{matrix} \\
 = 10 + 6 - 8 - 6 + 8 - 10 \\
 = \underline{0}$$

### ***Exercise***

Evaluate  $\begin{vmatrix} x & 0 & -1 \\ 2 & 1 & x^2 \\ -3 & x & 1 \end{vmatrix}$

### **Solution**

$$\begin{vmatrix} x & 0 & -1 \\ 2 & 1 & x^2 \\ -3 & x & 1 \end{vmatrix} \begin{matrix} x & 0 \\ 2 & 1 \\ -3 & x \end{matrix}$$
$$= x - 2x - 3 - x^4$$
$$= \underline{-x^4 - x - 3}$$

### ***Exercise***

Evaluate  $\begin{vmatrix} x & 1 & -1 \\ x^2 & x & x \\ 0 & x & 1 \end{vmatrix}$

### **Solution**

$$\begin{vmatrix} x & 1 & -1 \\ x^2 & x & x \\ 0 & x & 1 \end{vmatrix} \begin{matrix} x & 1 \\ x^2 & x \\ 0 & x \end{matrix}$$
$$= x^2 - x^3 - x^3 - x^2$$
$$= \underline{-2x^3}$$

### ***Exercise***

Evaluate  $\begin{vmatrix} 4 & -7 & 8 \\ 2 & 1 & 3 \\ -6 & 3 & 0 \end{vmatrix}$

### **Solution**

$$\begin{vmatrix} 4 & -7 & 8 \\ 2 & 1 & 3 \\ -6 & 3 & 0 \end{vmatrix} = 0 + 126 + 48 - (-48 + 36 + 0)$$
$$= \underline{90}$$

### ***Exercise***

Evaluate  $\begin{vmatrix} 2 & 1 & -1 \\ 4 & 7 & -2 \\ 2 & 4 & 0 \end{vmatrix}$

### **Solution**

$$\begin{vmatrix} 2 & 1 & -1 \\ 4 & 7 & -2 \\ 2 & 4 & 0 \end{vmatrix} = 0 - 4 - 16 - (-14 - 16 + 0) \\ = 10$$

### ***Exercise***

Evaluate  $\begin{vmatrix} 3 & 1 & 2 \\ -2 & 3 & 1 \\ 3 & 4 & -6 \end{vmatrix}$

### **Solution**

$$\begin{vmatrix} 3 & 1 & 2 \\ -2 & 3 & 1 \\ 3 & 4 & -6 \end{vmatrix} \begin{matrix} 3 & 1 \\ -2 & 3 \\ 3 & 4 \end{matrix} \\ = -54 + 3 - 16 - 18 - 12 - 12 \\ = -109$$

### ***Exercise***

Evaluate  $\begin{vmatrix} 2x & 1 & -1 \\ 0 & 4 & x \\ 3 & 0 & 2 \end{vmatrix}$

### **Solution**

$$\begin{vmatrix} 2x & 1 & -1 \\ 0 & 4 & x \\ 3 & 0 & 2 \end{vmatrix} \begin{matrix} 2x & 1 \\ 0 & 4 \\ 3 & 0 \end{matrix} \\ = 16x + 3x + 12 \\ = 19x + 12$$

### ***Exercise***

Evaluate  $\begin{vmatrix} 0 & x & x \\ x & x^2 & 5 \\ x & 7 & -5 \end{vmatrix}$

### **Solution**

$$\begin{vmatrix} 0 & x & x \\ x & x^2 & 5 \\ x & 7 & -5 \end{vmatrix} \begin{matrix} 0 & x \\ x & x^2 \\ x & 7 \end{matrix}$$
$$= 5x^2 + 7x^2 - x^4 + 5x^2$$
$$= \underline{17x^2 - x^4}$$

### ***Exercise***

Evaluate  $\begin{vmatrix} 2 & x & 1 \\ -3 & 1 & 0 \\ 2 & 1 & 4 \end{vmatrix}$

### **Solution**

$$\begin{vmatrix} 2 & x & 1 \\ -3 & 1 & 0 \\ 2 & 1 & 4 \end{vmatrix} \begin{matrix} 2 & x \\ -3 & 1 \\ 2 & 1 \end{matrix}$$
$$= 8 - 3 - 2 + 12x$$
$$= \underline{12x + 3}$$

### ***Exercise***

Evaluate  $\begin{vmatrix} 1 & x & -2 \\ 3 & 1 & 1 \\ 0 & -2 & 2 \end{vmatrix}$

### **Solution**

$$\begin{vmatrix} 1 & x & -2 \\ 3 & 1 & 1 \\ 0 & -2 & 2 \end{vmatrix} \begin{matrix} 1 & x \\ 3 & 1 \\ 0 & -2 \end{matrix}$$
$$= 2 + 12 + 2 - 6x$$
$$= \underline{-6x + 16}$$

### Exercise

Evaluate 
$$\begin{vmatrix} 1 & 1 & 0 & 0 & 0 \\ -1 & 1 & 1 & 0 & 0 \\ 0 & -1 & 1 & 1 & 0 \\ 0 & 0 & -1 & 1 & 1 \\ 0 & 0 & 0 & -1 & 1 \end{vmatrix}$$

### Solution

$$\begin{aligned} \begin{vmatrix} 1 & 1 & 0 & 0 & 0 \\ -1 & 1 & 1 & 0 & 0 \\ 0 & -1 & 1 & 1 & 0 \\ 0 & 0 & -1 & 1 & 1 \\ 0 & 0 & 0 & -1 & 1 \end{vmatrix} &= \begin{vmatrix} 1 & 1 & 0 & 0 & 0 \\ -1 & 1 & 1 & 0 & 0 \\ 0 & -1 & 1 & 1 & 0 \\ 0 & 0 & -1 & 1 & 1 \\ 0 & 0 & 0 & -1 & 1 \end{vmatrix} - \begin{vmatrix} -1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & -1 & 1 & 1 & 0 \\ 0 & 0 & -1 & 1 & 1 \\ 0 & 0 & 0 & -1 & 1 \end{vmatrix} \\ &= \begin{vmatrix} 1 & 1 & 0 \\ -1 & 1 & 1 \\ 0 & -1 & 1 \end{vmatrix} - \begin{vmatrix} -1 & 1 & 0 \\ 0 & 1 & 1 \\ 0 & -1 & 1 \end{vmatrix} - (-1) \begin{vmatrix} 1 & 1 & 0 \\ -1 & 1 & 1 \\ 0 & -1 & 1 \end{vmatrix} - (-) \begin{vmatrix} 0 & 1 & 0 \\ 0 & 1 & 1 \\ 0 & -1 & 1 \end{vmatrix} \\ &= 3 + 2 + 3 + 0 \\ &= 0 \end{aligned}$$

### Exercise

Find all the values of  $\lambda$  for which  $\det(\mathbf{A}) = 0$ :  $A = \begin{bmatrix} \lambda - 1 & -2 \\ 1 & \lambda - 4 \end{bmatrix}$

### Solution

$$\begin{aligned} \begin{vmatrix} \lambda - 1 & -2 \\ 1 & \lambda - 4 \end{vmatrix} &= (\lambda - 1)(\lambda - 4) + 2 \\ &= \lambda^2 - 5\lambda + 4 + 2 \\ &= \lambda^2 - 5\lambda + 6 = 0 \quad \text{Solve for } \lambda \\ \lambda_{1,2} &= -1, 6 \end{aligned}$$

### Exercise

Find all the values of  $\lambda$  for which  $\det(\mathbf{A}) = 0$ :  $A = \begin{bmatrix} \lambda - 6 & 0 & 0 \\ 0 & \lambda & -1 \\ 0 & 4 & \lambda - 4 \end{bmatrix}$

### Solution

$$\begin{aligned}
 \begin{vmatrix} \lambda - 6 & 0 & 0 \\ 0 & \lambda & -1 \\ 0 & 4 & \lambda - 4 \end{vmatrix} &= \lambda(\lambda - 6)(\lambda - 4) + 4(\lambda - 6) \\
 &= \lambda(\lambda^2 - 10\lambda + 24) + 4\lambda - 24 \\
 &= \lambda^3 - 10\lambda^2 + 24\lambda + 4\lambda - 24 \\
 &= \lambda^3 - 10\lambda^2 + 28\lambda - 24
 \end{aligned}$$

$$\lambda^3 - 10\lambda^2 + 28\lambda - 24 = 0$$

$$\lambda_{1,2,3} = 2, 2, 6$$

### Exercise

Prove that if a square matrix  $\mathbf{A}$  has a column of zeros, then  $\det(\mathbf{A}) = 0$

### Solution

Consider a 3 by 3 matrix with a zero column, however to find the determinant we can interchange any column of that matrix; therefore:

$$\mathbf{A} = [a_{ij}] = \begin{bmatrix} 0 & a_{12} & a_{13} \\ 0 & a_{22} & a_{23} \\ 0 & a_{32} & a_{33} \end{bmatrix}$$

By definition, the determinant of  $\mathbf{A}$  using the cofactor:

$$\begin{aligned}
 |A| &= a_{11} \begin{vmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{vmatrix} - a_{12} \begin{vmatrix} a_{21} & a_{23} \\ a_{31} & a_{33} \end{vmatrix} + a_{13} \begin{vmatrix} a_{21} & a_{22} \\ a_{31} & a_{32} \end{vmatrix} \\
 &= 0 \begin{vmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{vmatrix} - a_{12} \begin{vmatrix} 0 & a_{23} \\ 0 & a_{33} \end{vmatrix} + a_{13} \begin{vmatrix} 0 & a_{22} \\ 0 & a_{32} \end{vmatrix} \\
 &= 0
 \end{aligned}$$

### Exercise

With 2 by 2 blocks in 4 by 4 matrices, you cannot always use block determinants:

$$\begin{vmatrix} A & B \\ 0 & D \end{vmatrix} = |A||D| \quad \text{but} \quad \begin{vmatrix} A & B \\ C & D \end{vmatrix} \neq |A||D| - |C||B|$$

a) Why is the first statement true? Somehow  $B$  doesn't enter.



- b) Show by example that equality fails (as shown) when  $C$  enters.  
 c) Show by example that the answer  $\det(AD - CB)$  is also wrong.

### Solution

- a) If we don't pick any 0 entries, then the first two columns are picked from  $A$  and the last two rows are from  $D$ . We can't pick any columns or rows from  $B$ , because there aren't any left.

$$b) \begin{vmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{vmatrix} = - \begin{vmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{vmatrix} \\ = -1$$

$$\text{and } A = \begin{vmatrix} 0 & 1 \\ 0 & 0 \end{vmatrix} = 0, \quad B = \begin{vmatrix} 0 & 0 \\ 1 & 0 \end{vmatrix} = 0, \quad C = \begin{vmatrix} 0 & 0 \\ 1 & 0 \end{vmatrix} = 0, \quad D = \begin{vmatrix} 0 & 1 \\ 0 & 0 \end{vmatrix} = 0$$

- c) Use the example from part (b):  $1 \neq 0$

$$\begin{vmatrix} A & B \\ C & D \end{vmatrix} \neq |A||D| - |C||B|$$

### **Exercise**

Show that the value of the following determinant is independent of  $\theta$ .

$$\begin{vmatrix} \sin \theta & \cos \theta & 0 \\ -\cos \theta & \sin \theta & 0 \\ \sin \theta - \cos \theta & \sin \theta + \cos \theta & 1 \end{vmatrix}$$

### Solution

$$\begin{vmatrix} \sin \theta & \cos \theta & 0 \\ -\cos \theta & \sin \theta & 0 \\ \sin \theta - \cos \theta & \sin \theta + \cos \theta & 1 \end{vmatrix} = \begin{vmatrix} \sin \theta & \cos \theta \\ -\cos \theta & \sin \theta \end{vmatrix} \\ = \sin^2 \theta + \cos^2 \theta \\ = \sin^2 \theta - (-\cos^2 \theta) \\ = 1$$

Therefore, the determinant is independent of  $\theta$ .

### Exercise

Show that the matrices  $A = \begin{bmatrix} a & b \\ 0 & c \end{bmatrix}$  and  $B = \begin{bmatrix} d & e \\ 0 & f \end{bmatrix}$  commute if and only if  $\begin{vmatrix} b & a-c \\ e & d-f \end{vmatrix} = 0$

### Solution

$$AB = \begin{pmatrix} a & b \\ 0 & c \end{pmatrix} \begin{pmatrix} d & e \\ 0 & f \end{pmatrix} = \begin{pmatrix} ad & ae+bf \\ 0 & cf \end{pmatrix}$$

$$BA = \begin{pmatrix} d & e \\ 0 & f \end{pmatrix} \begin{pmatrix} a & b \\ 0 & c \end{pmatrix} = \begin{pmatrix} da & db+ec \\ 0 & fc \end{pmatrix}$$

$$AB = BA \Rightarrow \begin{pmatrix} ad & ae+bf \\ 0 & cf \end{pmatrix} = \begin{pmatrix} da & db+ec \\ 0 & fc \end{pmatrix}$$

Iff  $ae+bf = db+ec$

$$\begin{vmatrix} b & a-c \\ e & d-f \end{vmatrix} = b(d-f) - e(a-c) = bd - bf - ea + ec = 0$$

$$\underline{bd+ec = bf+ae} \quad \checkmark$$

### Exercise

Show that  $\det(A) = \frac{1}{2} \begin{vmatrix} \text{tr}(A) & 1 \\ \text{tr}(A^2) & \text{tr}(A) \end{vmatrix}$  for every  $2 \times 2$  matrix A.

### Solution

$$\text{Let } A = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \Rightarrow \text{tr}(A) = a+d$$

$$A^2 = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{pmatrix} a^2+bc & ab+bd \\ ac+cd & bc+d^2 \end{pmatrix} \Rightarrow \text{tr}(A^2) = a^2+bc+bc+d^2$$

$$\det(A) = \begin{vmatrix} a & b \\ c & d \end{vmatrix} = ad - bc$$

$$\begin{aligned} \frac{1}{2} \begin{vmatrix} \text{tr}(A) & 1 \\ \text{tr}(A^2) & \text{tr}(A) \end{vmatrix} &= \frac{1}{2} \begin{vmatrix} a+d & 1 \\ a^2+bc+bc+d^2 & a+d \end{vmatrix} \\ &= \frac{1}{2} \left[ (a+d)^2 - (a^2+bc+bc+d^2) \right] \\ &= \frac{1}{2} (a^2 + 2ad + d^2 - a^2 - bc - bc - d^2) \\ &= ad - bc \end{aligned}$$

$$\begin{aligned}
&= \frac{1}{2}(2ad - 2bc) \\
&= ad - bc \\
&= \det(A)
\end{aligned}$$

### Exercise

What is the maximum number of zeros that a  $4 \times 4$  matrix can have without a zero determinant? Explain your reasoning.

### Solution

The maximum number of zeros that a  $4 \times 4$  matrix can have without a zero determinant is 12 zeros. If the main diagonal has nonzero entries and the rest are zero, then the determinant of the matrix is equal to the product of the main diagonal entries.

### Exercise

Evaluate  $\det(A)$ ,  $\det(E)$ , and  $\det(AE)$ . Then verify that  $\det(A) \cdot \det(E) = \det(AE)$

$$A = \begin{bmatrix} 4 & 1 & 3 \\ 0 & -2 & 0 \\ 3 & 1 & 5 \end{bmatrix}, \quad E = \begin{bmatrix} 1 & & \\ & 3 & \\ & & 1 \end{bmatrix}$$

### Solution

$$\begin{aligned}
\det(A) &= \begin{vmatrix} 4 & 1 & 3 \\ 0 & -2 & 0 \\ 3 & 1 & 5 \end{vmatrix} \\
&= -40 + 18 \\
&= -22
\end{aligned}$$

$$\begin{aligned}
\det(E) &= \begin{vmatrix} 1 & & \\ & 3 & \\ & & 1 \end{vmatrix} \\
&= 3
\end{aligned}$$

$$\begin{aligned}
AE &= \begin{bmatrix} 4 & 1 & 3 \\ 0 & -2 & 0 \\ 3 & 1 & 5 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
&= \begin{bmatrix} 4 & 3 & 3 \\ 0 & -6 & 0 \\ 3 & 3 & 5 \end{bmatrix}
\end{aligned}$$

$$\det(AE) = \begin{vmatrix} 4 & 3 & 3 \\ 0 & -6 & 0 \\ 3 & 3 & 5 \end{vmatrix}$$

$$= -120 + 54$$

$$= -66$$

$$\det(A)\det(E) = (-22)(3)$$

$$= -66$$

$$\det(A)\det(E) = \det(AE) \quad \checkmark$$

### Exercise

Show that  $\begin{bmatrix} \sin^2 \alpha & \sin^2 \beta & \sin^2 \gamma \\ \cos^2 \alpha & \cos^2 \beta & \cos^2 \gamma \\ 1 & 1 & 1 \end{bmatrix}$  is not invertible for any values of  $\alpha, \beta, \gamma$

### Solution

$$\begin{vmatrix} \sin^2 \alpha & \sin^2 \beta & \sin^2 \gamma \\ \cos^2 \alpha & \cos^2 \beta & \cos^2 \gamma \\ 1 & 1 & 1 \end{vmatrix} = \sin^2 \alpha \cos^2 \beta + \sin^2 \beta \cos^2 \gamma + \sin^2 \gamma \cos^2 \alpha$$

$$- \sin^2 \gamma \cos^2 \beta - \sin^2 \alpha \cos^2 \gamma - \cos^2 \alpha \sin^2 \beta$$

$$= \sin^2 \alpha (\cos^2 \beta - \cos^2 \gamma) + \cos^2 \alpha (\sin^2 \gamma - \sin^2 \beta) + \sin^2 \beta \cos^2 \gamma - \sin^2 \gamma \cos^2 \beta$$

$$= \sin^2 \alpha (\cos^2 \beta - \cos^2 \gamma) + \cos^2 \alpha (1 - \cos^2 \gamma - 1 + \cos^2 \beta) + (1 - \cos^2 \beta) \cos^2 \gamma - (1 - \cos^2 \gamma) \cos^2 \beta$$

$$= \sin^2 \alpha (\cos^2 \beta - \cos^2 \gamma) + \cos^2 \alpha (\cos^2 \beta - \cos^2 \gamma) + \cos^2 \gamma - \cos^2 \gamma \cos^2 \beta - \cos^2 \beta + \cos^2 \gamma \cos^2 \beta$$

$$= (\sin^2 \alpha + \cos^2 \alpha) (\cos^2 \beta - \cos^2 \gamma) + \cos^2 \gamma - \cos^2 \beta$$

$$= \cos^2 \beta - \cos^2 \gamma + \cos^2 \gamma - \cos^2 \beta$$

$$= 0$$

Therefore, this matrix is not invertible.

### Exercise

The determinant of a  $2 \times 2$  matrix  $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$  is  $\det(A) = ad - bc$ .

Assuming no rows swaps are required, perform elimination on A and show explicitly that  $ad - bc$  is the product of the pivots.

### Solution

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} \xrightarrow{aR_2 - cR_1} \begin{pmatrix} a & b \\ 0 & ad - bc \end{pmatrix}$$

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} \xrightarrow{R_2 - \frac{c}{a}R_1} \begin{pmatrix} a & b \\ 0 & d - \frac{bc}{a} \end{pmatrix}$$

$$\begin{vmatrix} a & b \\ 0 & d - \frac{bc}{a} \end{vmatrix} = a \left( d - \frac{bc}{a} \right) \\ = ad - bc \\ = \det(A)$$

### Exercise

If A is a  $7 \times 7$  matrix and let  $\det(A) = 17$ . What is  $\det(3A^2)$ ?

### Solution

$$\det(A^2) = \det(A)\det(A) \\ = 17^2$$

Multiplying a single row by 3 multiplies the determinant by 3.

Multiplying the whole  $7 \times 7$  matrix by 3 multiplies all 7 rows by 3  $\Rightarrow 3^7$ .

$$\therefore \det(3A^2) = 3^7 \cdot 17^2 \\ = \underline{632043}$$

### Exercise

Explain without computations why the following determinant is equal to zero

$$\begin{vmatrix} a_1 & a_2 & a_3 & a_4 & a_5 \\ b_1 & b_2 & b_3 & b_4 & b_5 \\ c_1 & c_2 & 0 & 0 & 0 \\ d_1 & d_2 & 0 & 0 & 0 \\ e_1 & e_2 & 0 & 0 & 0 \end{vmatrix}$$

### Solution

The determinant is equal to zero because there are too many zeros (as block  $3 \times 3$ ).

*Or*

$$d_1 R_5 - e_1 R_4 \rightarrow R_5 \Rightarrow \begin{matrix} 0 & d_1 e_2 - e_1 d_2 & 0 & 0 & 0 \end{matrix}$$

Since row 5 has zero entries, therefore the determinant is zero.

### Exercise

Let  $A$  be an  $n \times n$  real matrix.

- a) Show that if  $A^t = -A$  and  $n$  is odd, then  $|A| = 0$ .
- b) Show that if  $A^2 + I = 0$ , then  $n$  must be even.
- c) Does part (b) remain true for complex matrices?

### Solution

- a) Given:  $A^t = -A$  and  $n$  is odd

$$\begin{aligned} |A| &= |A^t| \\ &= |-A| \\ &= (-1)^n |A| \quad \text{Since } n \text{ is odd} \\ &= -|A| \end{aligned}$$

$$|A| = -|A| \text{ only when } |A| = 0$$

- b)  $A^2 + I = 0$

$$\begin{aligned} A^2 &= -I \\ |A|^2 &= |A^2| \\ &= |-I| \\ &= (-1)^n \end{aligned}$$

If  $n$  is odd, then  ~~$|A|^2 = -1$~~  *impossible*

If  $n$  is even, then  $|A|^2 = 1$

c) It can't be true because  $|I| = -1 \in \mathbb{R}$

And  $A$  is real matrix, the determinant has to be a real number.

### Exercise

Let  $A$  and  $C$  be  $m \times m$  and  $n \times n$  matrices, respectively.

a) Show that  $\begin{vmatrix} A & B \\ 0 & C \end{vmatrix} = \begin{vmatrix} A & 0 \\ B & C \end{vmatrix} = |A||C|$

b) Evaluate

i.  $\begin{vmatrix} I_m & 0 \\ 0 & I_n \end{vmatrix}$

ii.  $\begin{vmatrix} 0 & I_m \\ I_n & 0 \end{vmatrix}$

iii.  $\begin{vmatrix} I_m & B \\ 0 & I_n \end{vmatrix}$

iv.  $\begin{vmatrix} 0 & 0 & \cdots & 0 & 1 \\ 0 & 0 & \cdots & 1 & 0 \\ \vdots & \vdots & & \vdots & \vdots \\ 0 & 1 & \cdots & 0 & 0 \\ 1 & 0 & \cdots & 0 & 0 \end{vmatrix}$

c) Find a formula for  $\begin{vmatrix} 0 & A \\ C & B \end{vmatrix}_{n \times n}$

### Solution

a) If we let matrices  $B$  be  $m \times n$  and  $0$  be  $n \times m$ , so the determinant of the matrix size will be  $(m+n) \times (m+n)$ , then

$$\begin{aligned} \begin{vmatrix} A & B \\ 0 & C \end{vmatrix} &= \begin{vmatrix} A_{m \times m} & B_{m \times n} \\ 0_{n \times m} & C_{n \times n} \end{vmatrix} \\ &= |A||C| - |B||0| \\ &= |A||C| - 0 \\ &= |A||C| \end{aligned}$$

If we let matrices  $B$  be  $n \times m$  and  $\mathbf{0}$  be  $m \times n$ , so the determinant of the matrix size will be  $(m+n) \times (m+n)$ , then

$$\begin{aligned} \begin{vmatrix} A & 0 \\ B & C \end{vmatrix} &= \begin{vmatrix} A & 0 \\ B & C \end{vmatrix} \\ &= |A||C| - |B||0| \\ &= |A||C| - 0 \\ &= |A||C| \end{aligned}$$

$$\begin{aligned} b) \quad i - \begin{vmatrix} I_m & 0 \\ 0 & I_n \end{vmatrix} &= \begin{vmatrix} I_m & 0_{m \times n} \\ 0_{n \times m} & I_n \end{vmatrix} \\ &= |I_m||I_n| - 0 \\ &= 1 \cdot 1 \\ &= 1 \end{aligned}$$

$$\begin{aligned} ii - \begin{vmatrix} 0 & I_m \\ I_n & 0 \end{vmatrix} &= \begin{vmatrix} 0_{m \times n} & I_m \\ I_n & 0_{n \times m} \end{vmatrix} \\ &= -|I_m| \cdot (-1)|I_n| \\ &= (-1)^{mn} \end{aligned}$$

$$\begin{aligned} iii - \begin{vmatrix} I_m & B \\ 0 & I_n \end{vmatrix} &= \begin{vmatrix} I_m & B_{m \times n} \\ 0_{n \times m} & I_n \end{vmatrix} \\ &= |I_m||I_n| - 0 \\ &= 1 \cdot 1 \\ &= 1 \end{aligned}$$

$$iv - \begin{vmatrix} 0 & 0 & \cdots & 0 & 1 \\ 0 & 0 & \cdots & 1 & 0 \\ \vdots & \vdots & & \vdots & \vdots \\ 0 & 1 & \cdots & 0 & 0 \\ 1 & 0 & \cdots & 0 & 0 \end{vmatrix}_{n \times n}$$

$$\begin{vmatrix} 0 & 1 \\ 1 & 0 \end{vmatrix} = -1$$

$$\begin{vmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{vmatrix} = -1$$



$$\begin{array}{cccc}
+ & - & + & - \\
\left| \begin{array}{cc|cc} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ \hline 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{array} \right| & = - \left| \begin{array}{ccc} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{array} \right| = -(-1) = 1
\end{array}$$

$4 \times 4$

$$\begin{array}{ccccc}
+ & - & + & - & + \\
\left| \begin{array}{ccccc} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{array} \right| & = + \left| \begin{array}{cccc} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{array} \right| = 1
\end{array}$$

$5 \times 5$        $4 \times 4$

From that we can see that the signs are:  $- \quad - \quad + \quad + \quad - \quad - \quad + \quad +$

$$\left| \begin{array}{cccc} 0 & 0 & \cdots & 0 & 1 \\ 0 & 0 & \cdots & 1 & 0 \\ \vdots & \vdots & & \vdots & \vdots \\ 0 & 1 & \cdots & 0 & 0 \\ 1 & 0 & \cdots & 0 & 0 \end{array} \right| = (-1)^{\frac{n^2+3n}{2}}$$

$n \times n$

$$\begin{aligned}
c) \quad \left| \begin{array}{cc} 0 & A \\ C & B \end{array} \right|_{n \times n} &= \left| \begin{array}{c|c} 0_{m \times n} & A_{m \times m} \\ \hline C_{n \times n} & B_{n \times m} \end{array} \right| \\
&= - \left| A_{m \times m} \right| \cdot (-1) \left| C_{n \times n} \right| \\
&= \underline{(-1)^{mn} |A| |C|}
\end{aligned}$$

### Exercise

Let  $f(x) = (p_1 - x)(p_2 - x) \dots (p_n - x)$  and let

$$\Delta_n = \begin{vmatrix} p_1 & a & a & \dots & a & a \\ b & p_2 & a & \dots & a & a \\ b & b & p_3 & \dots & a & a \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ b & b & b & \dots & p_{n-1} & a \\ b & b & b & \dots & b & p_n \end{vmatrix}$$

a) Show that, if  $a \neq b$ ,

$$\Delta_n = \frac{bf(a) - af(b)}{b - a}$$

b) Show that, if  $a = b$ ,

$$\Delta_n = a \sum_{i=1}^n f_i(a) + p_n f_n(a)$$

Where  $f_i(a)$  means  $f(a)$  with factor  $(p_i - a)$  missing.

c) Use part (b) to evaluate

$$\begin{vmatrix} a & b & b & \dots & b & b \\ b & a & b & \dots & b & b \\ b & b & a & \dots & b & b \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ b & b & b & \dots & a & b \\ b & b & b & \dots & b & a \end{vmatrix}_{n \times n}$$

### Solution

$$a) \Delta_n = \frac{bf(a) - af(b)}{b - a}; \text{ with } a \neq b$$

Using the mathematical Induction to prove the equality.

For  $n = 2$ :

$$\begin{aligned} \Delta_2 &= \begin{vmatrix} p_1 & a \\ b & p_2 \end{vmatrix} \\ &= p_1 p_2 - ab \\ \Delta_2 &= \frac{bf(a) - af(b)}{b - a} \end{aligned}$$

$$\begin{aligned}
&= \frac{b(p_1 - a)(p_2 - a) - a(p_1 - b)(p_2 - b)}{b - a} \\
&= \frac{bp_1p_2 - abp_1 - abp_2 + a^2b - ap_1p_2 + abp_1 + abp_2 - ab^2}{b - a} \\
&= \frac{bp_1p_2 + a^2b - ap_1p_2 - ab^2}{b - a} \\
&= \frac{(b - a)p_1p_2 + ab(a - b)}{b - a} \\
&= \frac{(b - a)(p_1p_2 - ab)}{b - a} \\
&= p_1p_2 - ab
\end{aligned}$$

For  $n = 2$ , the proof is true.

Assume that is true for  $\Delta_k$

$$\begin{aligned}
\Delta_k &= \frac{bf(a) - af(b)}{b - a} \\
&= \frac{b((p_1 - a) \dots (p_{k-1} - a)) - a((p_1 - b) \dots (p_{k-1} - b))}{b - a}
\end{aligned}$$

$$f(x) = (p_1 - x)(p_2 - x) \dots (p_k - x)$$

We need to prove it is also true for  $\Delta_{k+1} \Rightarrow \Delta_{k+1} = \frac{bF(a) - aF(b)}{b - a}$

$$\begin{aligned}
F(x) &= (p_1 - x)(p_2 - x) \dots (p_k - x)(p_{k+1} - x) \\
&= f(x)(p_{k+1} - x)
\end{aligned}$$

$$\begin{aligned}
\Delta_{k+1} &= \frac{b((p_1 - a) \dots (p_k - a)(p_{k+1} - a)) - a((p_1 - b) \dots (p_k - b)(p_{k+1} - b))}{b - a} \\
&= \frac{bf(a)(p_{k+1} - a) - af(b)(p_{k+1} - b)}{b - a} \\
&= \frac{bF(a) - aF(b)}{b - a} \quad \checkmark
\end{aligned}$$

$\Delta_{k+1}$  is also true.

$\therefore$  by the mathematical induction, the proof is completed.

$$b) \text{ If } a = b \rightarrow \Delta_n = a \sum_{i=1}^n f_i(a) + p_n f_n(a)$$

Where  $f_i(a)$  means  $f(a)$  with factor  $(p_i - a)$  missing.

$$\begin{aligned}
\Delta_n &= (p_1 - a)\Delta_{n-1} + a(p_2 - b) \cdots (p_n - b) & a=b \\
&= (p_1 - a)\Delta_{n-1} + a(p_2 - a) \cdots (p_n - a) & (p_1 - a) \text{ missing} \\
&= (p_1 - a) \left[ (p_2 - a)\Delta_{n-2} + aF_2(a) \right] + af_1(a) \\
&= (p_1 - a)(p_2 - a)\Delta_{n-2} + a(p_1 - a)F_2(a) + af_1(a) \\
&= (p_1 - a)(p_2 - a)\Delta_{n-2} + af_2(a) + af_1(a) \\
&= (p_1 - a)(p_2 - a)(p_3 - a)\Delta_{n-3} + af_3(a) + af_2(a) + af_1(a) \\
&= (p_1 - a)(p_2 - a)(p_3 - a)\Delta_{n-3} + a(f_3(a) + f_2(a) + f_1(a)) \\
&\quad \vdots \quad \quad \quad \vdots \quad \quad \quad \vdots \quad \quad \quad \vdots \\
&= (p_1 - a) \cdots (p_{n-2} - a)\Delta_2 + a(f_{n-2}(a) + \cdots + f_1(a))
\end{aligned}$$

$$\begin{aligned}
\Delta_2 &= \begin{vmatrix} p_{n-1} & a \\ a & p_n \end{vmatrix} \\
&= p_{n-1}p_n - a^2 \\
&= p_{n-1}p_n - \textcolor{red}{ap_n} + \textcolor{red}{ap_n} - a^2 \\
&= p_n(p_{n-1} - a) + a(p_n - a)
\end{aligned}$$

$$\begin{aligned}
\Delta_n &= \left[ (p_1 - a) \cdots (p_{n-2} - a) \right] \left( p_n(p_{n-1} - a) + a(p_n - a) \right) + a(f_{n-2}(a) + \cdots + f_1(a)) \\
&= p_n(p_1 - a) \cdots (p_{n-2} - a)(p_{n-1} - a) + a(p_1 - a) \cdots (p_{n-2} - a)(p_n - a) + a \sum_{i=1}^{n-1} f_i(a) \\
&= p_n f_n(a) + af_{n-1}(a) + a \sum_{i=1}^{n-1} f_i(a) \\
&= p_n f_n(a) + a \sum_{i=1}^n f_i(a)
\end{aligned}$$

$$\begin{aligned}
\text{c) } f_n(x) &= (p_1 - x)(p_2 - x) \cdots (p_{n-1} - x) \\
f_n(b) &= (a - b)(a - b) \cdots (a - b) \\
p_n &= a
\end{aligned}$$

$$\begin{vmatrix} a & b & b & \dots & b & b \\ b & a & b & \dots & b & b \\ b & b & a & \dots & b & b \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ b & b & b & \dots & a & b \\ b & b & b & \dots & b & a \end{vmatrix}_{n \times n} = p_n f_n(b) + b \sum_{i=1}^n f_i(b)$$

$$= a(a-b)^{n-1} + b \underbrace{\left( (a-b)^{n-1} + \dots + (a-b)^{n-1} \right)}_{n-1}$$

$$= a(a-b)^{n-1} + b(n-1)(a-b)^{n-1}$$

$$= \underline{\left[ a + (n-1)b \right] (a-b)^{n-1}}$$

### Exercise

Let  $A, B, C, D \in M_n(\mathbb{C})$

- a) Show that when  $A$  is invertible:  $\begin{vmatrix} A & B \\ C & D \end{vmatrix} = |A| |D - CA^{-1}B|$
- b) Show that when  $AC = CA$ :  $\begin{vmatrix} A & B \\ C & D \end{vmatrix} = |AD - CB|$
- c) Can  $B$  and  $C$  on the right-hand side of the identity be switched?
- d) Does part (b) remain true if the condition  $AC = CA$  is dropped?

### Solution

- a) Since  $A$  is invertible, then  $A^{-1}$  exists and  $AA^{-1} = A^{-1}A = I$

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} \xrightarrow{A^{-1}R_1}$$

$$\begin{pmatrix} I & A^{-1}B \\ C & D \end{pmatrix} \xrightarrow{R_2 - CR_1}$$

$$\begin{pmatrix} I & A^{-1}B \\ 0 & D - CA^{-1}B \end{pmatrix} \xrightarrow{AR_1}$$

$$\begin{pmatrix} A & B \\ 0 & D - CA^{-1}B \end{pmatrix}$$

$$\begin{vmatrix} A & B \\ C & D \end{vmatrix} = \begin{vmatrix} A & B \\ 0 & D - CA^{-1}B \end{vmatrix}$$

$$= |A| |D - CA^{-1}B|$$

**b)** When  $AC = CA$

$$\begin{aligned} \begin{vmatrix} A & B \\ C & D \end{vmatrix} &= |A| |D - CA^{-1}B| \\ &= |AD - ACA^{-1}B| && AC = CA \\ &= |AD - C(AA^{-1})B| \\ &= |AD - CIB| \\ &= \underline{|AD - CB|} \end{aligned}$$

**c)** To switch  $B$  and  $C$  it is not necessary that  $BC = CB$

$$\text{Let } A = \begin{pmatrix} 1 & -1 \\ 0 & 0 \end{pmatrix}, \quad B = \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}, \quad C = \begin{pmatrix} 1 & -1 \\ 0 & 0 \end{pmatrix}, \quad D = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

$$\begin{aligned} AD &= \begin{pmatrix} 1 & -1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \end{aligned}$$

$$\begin{aligned} CB &= \begin{pmatrix} 1 & -1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \\ &= \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \end{aligned}$$

$$\begin{aligned} BC &= \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & -1 \\ 0 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 1 & -1 \\ 1 & -1 \end{pmatrix} \end{aligned}$$

$$\begin{aligned} |AD - CB| &= \left| \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} - \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \right| \\ &= \begin{vmatrix} 1 & 0 \\ 0 & 0 \end{vmatrix} \\ &= \underline{0} \end{aligned}$$

$$\begin{aligned} |AD - BC| &= \left| \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} - \begin{pmatrix} 1 & -1 \\ 1 & -1 \end{pmatrix} \right| \\ &= \begin{vmatrix} 0 & 1 \\ -1 & 1 \end{vmatrix} \end{aligned}$$

$$\equiv 1$$

$$|AD - CB| \neq |AD - BC|$$

No,  $B$  and  $C$  on the right-hand side of the identity cannot be switched since

$$|AD - CB| \neq |AD - BC|$$

*d)* No, since from previous part (c)  $D$  doesn't commute necessarily.

## Solution

### Section 1.7 – Properties of Determinants: Cramer’s Rule

#### Exercise

Use Cramer’s Rule with ratios  $\frac{\det B_j}{\det A}$  to solve  $A\mathbf{x} = b$ . Also find the inverse matrix  $A^{-1} = \frac{C^T}{\det A}$ . Why

is the solution  $\mathbf{x}$  is the first part the same as column 3 of  $A^{-1}$ ? Which cofactors are involved in computing that column  $\mathbf{x}$ ?

$$Ax = b \quad \text{is} \quad \begin{bmatrix} 2 & 6 & 2 \\ 1 & 4 & 2 \\ 5 & 9 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

Find the volumes of the boxes whose edges are columns of  $A$  and then rows of  $A^{-1}$ .

#### Solution

$$|A| = \begin{vmatrix} 2 & 6 & 2 \\ 1 & 4 & 2 \\ 5 & 9 & 0 \end{vmatrix} = 2$$

$$|B_1| = \begin{vmatrix} 0 & 6 & 2 \\ 0 & 4 & 2 \\ 1 & 9 & 0 \end{vmatrix} = 4$$

$$|B_2| = \begin{vmatrix} 2 & 0 & 2 \\ 1 & 0 & 2 \\ 5 & 1 & 0 \end{vmatrix} = -2$$

$$|B_3| = \begin{vmatrix} 2 & 6 & 0 \\ 1 & 4 & 0 \\ 5 & 9 & 1 \end{vmatrix} = 2$$

$$x = \frac{4}{2} = 2; \quad y = \frac{-2}{2} = -1; \quad z = \frac{2}{2} = 1$$

The solution is:  $(2, -1, 1)$

$$C_{11} = \begin{vmatrix} 4 & 2 \\ 9 & 0 \end{vmatrix} = -18$$

$$C_{12} = -\begin{vmatrix} 1 & 2 \\ 5 & 0 \end{vmatrix} = 10$$

$$C_{13} = \begin{vmatrix} 1 & 4 \\ 5 & 9 \end{vmatrix} = -11$$

$$C_{21} = -\begin{vmatrix} 6 & 2 \\ 9 & 0 \end{vmatrix} = 18$$

$$C_{22} = \begin{vmatrix} 2 & 2 \\ 5 & 0 \end{vmatrix} = -10$$

$$C_{23} = -\begin{vmatrix} 2 & 6 \\ 5 & 9 \end{vmatrix} = 12$$

$$C_{31} = \begin{vmatrix} 6 & 2 \\ 4 & 2 \end{vmatrix} = 4$$

$$C_{32} = -\begin{vmatrix} 2 & 2 \\ 1 & 2 \end{vmatrix} = -2$$

$$C_{33} = \begin{vmatrix} 2 & 6 \\ 1 & 4 \end{vmatrix} = 2$$

$$C = \begin{pmatrix} -18 & 10 & -11 \\ 18 & -10 & 12 \\ 4 & -2 & 2 \end{pmatrix}$$

$$C^T = \begin{pmatrix} -18 & 18 & 4 \\ 10 & -10 & -2 \\ -11 & 12 & 2 \end{pmatrix}$$



$$A^{-1} = \frac{1}{2} \begin{pmatrix} -18 & 18 & 4 \\ 10 & -10 & -2 \\ -11 & 12 & 2 \end{pmatrix} \quad A^{-1} = \frac{C^T}{\det A}$$

$$= \begin{pmatrix} -9 & 9 & 2 \\ 5 & -5 & -1 \\ -\frac{11}{2} & 6 & 1 \end{pmatrix}$$

The solution  $\mathbf{x}$  is the third column of  $A^{-1}$  because  $\mathbf{b} = (0, 0, 1)$  is the third column of  $I$ .

The volume of the boxes whose edges are columns of  $\mathbf{A} = \det(\mathbf{A}) = 2$ .

Since  $|A^T| = |A|$ . The box from rows of  $A^{-1}$  has volume  $|A^{-1}| = \frac{1}{|A|} = \frac{1}{2}$

### Exercise

Verify that  $\det(AB) = \det(BA)$  and determine whether the equality  $\det(A+B) = \det(A) + \det(B)$  holds

$$A = \begin{bmatrix} 2 & 1 & 0 \\ 3 & 4 & 0 \\ 0 & 0 & 2 \end{bmatrix} \quad \text{and} \quad B = \begin{bmatrix} 1 & -1 & 3 \\ 7 & 1 & 2 \\ 5 & 0 & 1 \end{bmatrix}$$

### Solution

$$AB = \begin{bmatrix} 2 & 1 & 0 \\ 3 & 4 & 0 \\ 0 & 0 & 2 \end{bmatrix} \begin{bmatrix} 1 & -1 & 3 \\ 7 & 1 & 2 \\ 5 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 9 & -1 & 8 \\ 31 & 1 & 17 \\ 10 & 0 & 2 \end{bmatrix}$$

$$\det(AB) = \begin{vmatrix} 9 & -1 & 8 \\ 31 & 1 & 17 \\ 10 & 0 & 2 \end{vmatrix}$$

$$= -170$$

$$BA = \begin{bmatrix} 1 & -1 & 3 \\ 7 & 1 & 2 \\ 5 & 0 & 1 \end{bmatrix} \begin{bmatrix} 2 & 1 & 0 \\ 3 & 4 & 0 \\ 0 & 0 & 2 \end{bmatrix}$$

$$= \begin{bmatrix} -1 & -3 & 6 \\ 17 & 11 & 4 \\ 10 & 5 & 2 \end{bmatrix}$$

$$\det(BA) = \begin{vmatrix} -1 & -3 & 6 \\ 17 & 11 & 4 \\ 10 & 5 & 2 \end{vmatrix}$$

$$\underline{= -170}$$

$$\text{Thus, } \underline{\det(AB) = \det(BA)}$$

$$\det(A) = \begin{vmatrix} 2 & 1 & 0 \\ 3 & 4 & 0 \\ 0 & 0 & 2 \end{vmatrix}$$

$$\underline{= 10}$$

$$\det(B) = \begin{vmatrix} 1 & -1 & 3 \\ 7 & 1 & 2 \\ 5 & 0 & 1 \end{vmatrix}$$

$$\underline{= -17}$$

$$A + B = \begin{bmatrix} 2 & 1 & 0 \\ 3 & 4 & 0 \\ 0 & 0 & 2 \end{bmatrix} + \begin{bmatrix} 1 & -1 & 3 \\ 7 & 1 & 2 \\ 5 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 3 & 0 & 3 \\ 10 & 5 & 2 \\ 5 & 0 & 3 \end{bmatrix}$$

$$\det(A + B) = \begin{vmatrix} 3 & 0 & 3 \\ 10 & 5 & 2 \\ 5 & 0 & 3 \end{vmatrix}$$

$$\underline{= -30}$$

$$\det(A) + \det(B) = 10 - 17$$

$$= -7 \neq -30$$

$$\underline{\neq \det(A + B)}$$

### ***Exercise***

Verify that  $\det(kA) = k^n \det(A)$   $A = \begin{bmatrix} -1 & 2 \\ 3 & 4 \end{bmatrix}$ ,  $k = 2$

### **Solution**

$$\begin{aligned} \det(A) &= \begin{vmatrix} -1 & 2 \\ 3 & 4 \end{vmatrix} \\ &= -10 \end{aligned}$$

$$\begin{aligned} \det(2A) &= \begin{vmatrix} -2 & 4 \\ 6 & 8 \end{vmatrix} \\ &= -40 \\ &= 4(-10) \\ &= 2^2(-10) \\ &= k^2 \det(A) \end{aligned}$$

### ***Exercise***

Verify that  $\det(kA) = k^n \det(A)$   $A = \begin{bmatrix} 2 & -1 & 3 \\ 3 & 2 & 1 \\ 1 & 4 & 5 \end{bmatrix}$ ,  $k = -2$

### **Solution**

$$\begin{aligned} \det(A) &= \begin{vmatrix} 2 & -1 & 3 \\ 3 & 2 & 1 \\ 1 & 4 & 5 \end{vmatrix} \\ &= 56 \end{aligned}$$

$$\begin{aligned} \det(-2A) &= \begin{vmatrix} -4 & 2 & -6 \\ -6 & -4 & -2 \\ -2 & -8 & -10 \end{vmatrix} \\ &= -448 \\ &= (-2)^3(56) \\ &= k^3 \det(A) \end{aligned}$$

### Exercise

Verify that  $\det(kA) = k^n \det(A)$   $A = \begin{bmatrix} 1 & 1 & 1 \\ 0 & 2 & 3 \\ 0 & 1 & -2 \end{bmatrix}$ ,  $k = 3$

### Solution

$$\det(A) = \begin{vmatrix} 1 & 1 & 1 \\ 0 & 2 & 3 \\ 0 & 1 & -2 \end{vmatrix} \\ = -7$$

$$\det(3A) = \begin{vmatrix} 3 & 3 & 3 \\ 0 & 6 & 9 \\ 0 & 3 & -6 \end{vmatrix} \\ = -189 \\ = 3^3(-7) \\ = k^3 \det(A)$$

### Exercise

Use Cramer's rule to solve the system  $\begin{cases} 3x + 2y = -4 \\ 2x - y = -5 \end{cases}$

### Solution

$$D = \begin{vmatrix} 3 & 2 \\ 2 & -1 \end{vmatrix} = -3 - 4 = -7$$

$$D_x = \begin{vmatrix} -4 & 2 \\ -5 & -1 \end{vmatrix} = 4 - (-10) = 14$$

$$D_y = \begin{vmatrix} 3 & -4 \\ 2 & -5 \end{vmatrix} = -15 - (-8) = -7$$

$$x = \frac{D_x}{D} = \frac{14}{-7} = -2$$

$$y = \frac{D_y}{D} = \frac{-7}{-7} = 1$$

$$\therefore \text{Solution: } \underline{(-2, 1)}$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 2x + 5y = 7 \\ 5x - 2y = -3 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 2 & 5 \\ 5 & -2 \end{vmatrix} = -29 \quad D_x = \begin{vmatrix} 7 & 5 \\ -3 & -2 \end{vmatrix} = 1 \quad D_y = \begin{vmatrix} 2 & 7 \\ 5 & -3 \end{vmatrix} = -41$$

$$x = \frac{1}{-29} = -\frac{1}{29} \quad x = \frac{D_x}{D}$$

$$y = \frac{41}{29} \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \left( -\frac{1}{29}, \frac{41}{29} \right)$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 3x + 2y = -4 \\ 2x - y = -5 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 3 & 2 \\ 2 & -1 \end{vmatrix} = -7 \quad D_x = \begin{vmatrix} -4 & -5 \\ 2 & -1 \end{vmatrix} = 14 \quad D_y = \begin{vmatrix} 3 & -4 \\ 2 & -5 \end{vmatrix} = -7$$

$$x = -\frac{14}{7} = -2 \quad x = \frac{D_x}{D}$$

$$y = \frac{7}{7} = 1 \quad y = \frac{D_y}{D}$$

$$\text{Solution: } (-2, 1)$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 2x + 5y = 7 \\ 5x - 2y = -3 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 2 & 5 \\ 5 & -2 \end{vmatrix} = -29 \quad D_x = \begin{vmatrix} 7 & 5 \\ -3 & -2 \end{vmatrix} = 1 \quad D_y = \begin{vmatrix} 2 & 7 \\ 5 & -3 \end{vmatrix} = -41$$

$$x = -\frac{1}{29} \quad x = \frac{D_x}{D}$$

$$y = \frac{41}{29} \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \left( -\frac{1}{29}, \frac{41}{29} \right)$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 4x - 7y = -16 \\ 2x + 5y = 9 \end{cases}$$

#### Solution

$$D = \begin{vmatrix} 4 & -7 \\ 2 & 5 \end{vmatrix} = 34 \quad D_x = \begin{vmatrix} -16 & -7 \\ 9 & 5 \end{vmatrix} = -17 \quad D_y = \begin{vmatrix} 4 & -16 \\ 2 & 9 \end{vmatrix} = 68$$

$$x = -\frac{17}{34} = -\frac{1}{2} \quad x = \frac{D_x}{D}$$

$$y = \frac{68}{34} = 2 \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \left( -\frac{1}{2}, 2 \right)$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 3x + 2y = 4 \\ 2x + y = 1 \end{cases}$$

#### Solution

$$D = \begin{vmatrix} 3 & 2 \\ 2 & 1 \end{vmatrix} = -1 \quad D_x = \begin{vmatrix} 4 & 2 \\ 1 & 1 \end{vmatrix} = 2 \quad D_y = \begin{vmatrix} 3 & 4 \\ 2 & 1 \end{vmatrix} = -5$$

$$x = -2 \quad x = \frac{D_x}{D}$$

$$y = 5 \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \left( -2, 5 \right)$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 3x + 4y = 2 \\ 2x + 5y = -1 \end{cases}$$

#### Solution

$$D = \begin{vmatrix} 3 & 4 \\ 2 & 5 \end{vmatrix} = 7$$

$$D_x = \begin{vmatrix} 2 & 4 \\ -1 & 5 \end{vmatrix} = 14$$

$$D_y = \begin{vmatrix} 3 & 2 \\ 2 & -1 \end{vmatrix} = -7$$

$$x = \frac{14}{7} = 2$$

$$x = \frac{D_x}{D}$$

$$y = -\frac{7}{7} = -1$$

$$y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{(2, -1)}$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 5x - 2y = 4 \\ -10x + 4y = 7 \end{cases}$$

#### Solution

$$D = \begin{vmatrix} 5 & -2 \\ -10 & 4 \end{vmatrix} = 0$$

$$D_y = \begin{vmatrix} 5 & 4 \\ -10 & 7 \end{vmatrix} = 75 \neq 0$$

$\therefore$  **No Solution**

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} x - 4y = -8 \\ 5x - 20y = -40 \end{cases}$$

#### Solution

$$D = \begin{vmatrix} 1 & -4 \\ 5 & -20 \end{vmatrix} = 0$$

$$D_y = \begin{vmatrix} 1 & -8 \\ 5 & -40 \end{vmatrix} = 0$$

$$\frac{1}{5} \times \begin{cases} x - 4y = -8 \\ 5x - 20y = -40 \end{cases}$$

$$\begin{cases} x - 4y = -8 \\ x - 4y = -8 \end{cases}$$

$$\therefore \text{Solution: } \underline{(4y - 8, y)}$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 2x + y = 3 \\ x - y = 3 \end{cases}$$

#### Solution

$$D = \begin{vmatrix} 2 & 1 \\ 1 & -1 \end{vmatrix} = -3$$

$$D_x = \begin{vmatrix} 3 & 1 \\ 3 & -1 \end{vmatrix} = -6$$

$$D_y = \begin{vmatrix} 2 & 3 \\ 1 & 3 \end{vmatrix} = 3$$

$$x = \frac{6}{-3} = -2$$

$$x = \frac{D_x}{D}$$

$$y = -\frac{3}{-3} = 1$$

$$y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{(2, -1)}$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 2x + 10y = -14 \\ 7x - 2y = -16 \end{cases}$$

#### Solution

$$D = \begin{vmatrix} 2 & 10 \\ 7 & -2 \end{vmatrix} = -74$$

$$D_x = \begin{vmatrix} -14 & 10 \\ -16 & -2 \end{vmatrix} = 188$$

$$D_y = \begin{vmatrix} 2 & -14 \\ 7 & -16 \end{vmatrix} = 66$$

$$x = -\frac{188}{-74} = \frac{94}{37}$$

$$x = \frac{D_x}{D}$$

$$y = -\frac{66}{-74} = \frac{33}{37}$$

$$y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{\left(\frac{94}{37}, \frac{33}{37}\right)}$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 4x - 3y = 24 \\ -3x + 9y = -1 \end{cases}$$

#### Solution

$$D = \begin{vmatrix} 4 & -3 \\ -3 & 9 \end{vmatrix} = 27$$

$$D_x = \begin{vmatrix} 24 & -3 \\ -1 & 9 \end{vmatrix} = 213$$

$$D_y = \begin{vmatrix} 4 & 24 \\ -3 & -1 \end{vmatrix} = 68$$

$$x = \frac{213}{27} = \frac{71}{9}$$

$$x = \frac{D_x}{D}$$

$$y = \frac{68}{27}$$

$$y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{\left(\frac{71}{9}, \frac{68}{27}\right)}$$



### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 4x + 2y = 12 \\ 3x - 2y = 16 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 4 & 2 \\ 3 & -2 \end{vmatrix} = -14 \quad D_x = \begin{vmatrix} 12 & 2 \\ 16 & -2 \end{vmatrix} = -56 \quad D_y = \begin{vmatrix} 4 & 12 \\ 3 & 16 \end{vmatrix} = 28$$

$$x = \frac{56}{14} = 4 \quad x = \frac{D_x}{D}$$

$$y = -\frac{28}{14} = -2 \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{(4, -2)}$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} x + 2y = -1 \\ 4x - 2y = 6 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 1 & 2 \\ 4 & -2 \end{vmatrix} = -10 \quad D_x = \begin{vmatrix} -1 & 2 \\ 6 & -2 \end{vmatrix} = -10 \quad D_y = \begin{vmatrix} 1 & -1 \\ 4 & 6 \end{vmatrix} = 10$$

$$x = 1 \quad x = \frac{D_x}{D}$$

$$y = -1 \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{(1, -1)}$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} x - 2y = 5 \\ -10x + 2y = 4 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 1 & -2 \\ -10 & 2 \end{vmatrix} = -18 \quad D_x = \begin{vmatrix} 5 & -2 \\ 4 & 2 \end{vmatrix} = 18 \quad D_y = \begin{vmatrix} 1 & 5 \\ -10 & 4 \end{vmatrix} = 54$$

$$x = -1 \quad x = \frac{D_x}{D}$$

$$y = -\frac{54}{18} = -3 \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{(-1, -3)}$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 12x + 15y = -27 \\ 30x - 15y = -15 \end{cases}$$

### Solution

$$\begin{array}{l} \frac{1}{3} \times \begin{cases} 12x + 15y = -27 \\ 30x - 15y = -15 \end{cases} \\ \frac{1}{15} \times \end{array}$$

$$\begin{cases} 4x + 5y = -9 \\ 2x - y = -1 \end{cases}$$

$$D = \begin{vmatrix} 4 & 5 \\ 2 & -1 \end{vmatrix} = -14 \quad D_x = \begin{vmatrix} -9 & 5 \\ -1 & -1 \end{vmatrix} = 14 \quad D_y = \begin{vmatrix} 4 & -9 \\ 2 & -1 \end{vmatrix} = 14$$

$$\underline{x = -1} \quad x = \frac{D_x}{D}$$

$$\underline{y = -1} \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{(-1, -1)}$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 4x - 4y = -12 \\ 4x + 4y = -20 \end{cases}$$

### Solution

$$\begin{array}{l} \frac{1}{4} \times \begin{cases} 4x - 4y = -12 \\ 4x + 4y = -20 \end{cases} \\ \frac{1}{4} \times \end{array}$$

$$\begin{cases} x - y = -3 \\ x + y = -5 \end{cases}$$

$$D = \begin{vmatrix} 1 & -1 \\ 1 & 1 \end{vmatrix} = 2 \quad D_x = \begin{vmatrix} -3 & -1 \\ -5 & 1 \end{vmatrix} = -8 \quad D_y = \begin{vmatrix} 1 & -3 \\ 1 & -5 \end{vmatrix} = -2$$

$$\underline{x = -4} \quad x = \frac{D_x}{D}$$

$$\underline{y = -1} \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{(-4, -1)}$$

### Exercise

Use Cramer's rule to solve the system  $\begin{cases} x + y = 7 \\ x - y = 3 \end{cases}$

### Solution

$$D = \begin{vmatrix} 1 & 1 \\ 1 & -1 \end{vmatrix} = -2$$

$$D_x = \begin{vmatrix} 7 & 1 \\ 3 & -1 \end{vmatrix} = -10 \quad D_y = \begin{vmatrix} 1 & 7 \\ 1 & 3 \end{vmatrix} = -4$$

$$\underline{x = 5} \quad x = \frac{D_x}{D}$$

$$\underline{y = 2} \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{(5, 2)}$$

### Exercise

Use Cramer's rule to solve the system  $\begin{cases} 2x + y = 3 \\ x - y = 3 \end{cases}$

### Solution

$$D = \begin{vmatrix} 2 & 1 \\ 1 & -1 \end{vmatrix} = -3$$

$$D_x = \begin{vmatrix} 3 & 1 \\ 3 & -1 \end{vmatrix} = -6 \quad D_y = \begin{vmatrix} 2 & 3 \\ 1 & 3 \end{vmatrix} = 3$$

$$\underline{x = 2} \quad x = \frac{D_x}{D}$$

$$\underline{y = -1} \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{(2, -1)}$$

### Exercise

Use Cramer's rule to solve the system  $\begin{cases} 12x + 3y = 15 \\ 2x - 3y = 13 \end{cases}$

### Solution

$$D = \begin{vmatrix} 12 & 3 \\ 2 & -3 \end{vmatrix} = -42$$

$$D_x = \begin{vmatrix} 15 & 3 \\ 13 & -3 \end{vmatrix} = -84 \quad D_y = \begin{vmatrix} 12 & 15 \\ 2 & 13 \end{vmatrix} = 126$$

$$\underline{x = 2} \quad x = \frac{D_x}{D}$$

$$\underline{y = -3} \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{(2, -3)}$$

### Exercise

Use Cramer's rule to solve the system  $\begin{cases} x - 2y = 5 \\ 5x - y = -2 \end{cases}$

#### Solution

$$D = \begin{vmatrix} 1 & -2 \\ 5 & -1 \end{vmatrix} = 9$$

$$D_x = \begin{vmatrix} 5 & -2 \\ -2 & -1 \end{vmatrix} = -9 \quad D_y = \begin{vmatrix} 1 & 5 \\ 5 & -2 \end{vmatrix} = -27$$

$$\underline{x = -1} \quad x = \frac{D_x}{D}$$

$$\underline{y = -3} \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{(-1, -3)}$$

### Exercise

Use Cramer's rule to solve the system  $\begin{cases} 4x - 5y = 17 \\ 2x + 3y = 3 \end{cases}$

#### Solution

$$D = \begin{vmatrix} 4 & -5 \\ 2 & 3 \end{vmatrix} = 22$$

$$D_x = \begin{vmatrix} 17 & -5 \\ 3 & 3 \end{vmatrix} = 66 \quad D_y = \begin{vmatrix} 4 & 17 \\ 2 & 3 \end{vmatrix} = -22$$

$$\underline{x = 3} \quad x = \frac{D_x}{D}$$

$$\underline{y = -1} \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{(3, -1)}$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 3x + 2y = 2 \\ 2x + 2y = 3 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 3 & 2 \\ 2 & 2 \end{vmatrix} = 2$$

$$D_x = \begin{vmatrix} 2 & 2 \\ 3 & 2 \end{vmatrix} = -2 \quad D_y = \begin{vmatrix} 3 & 2 \\ 2 & 3 \end{vmatrix} = 5$$

$$\underline{x = -1} \quad x = \frac{D_x}{D}$$

$$\underline{y = \frac{5}{2}} \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{\left(-1, \frac{5}{2}\right)}$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} x - 3y = 4 \\ 3x - 4y = 12 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 1 & -3 \\ 3 & -4 \end{vmatrix} = 5 \quad D_x = \begin{vmatrix} 4 & -3 \\ 12 & -4 \end{vmatrix} = 20 \quad D_y = \begin{vmatrix} 1 & 4 \\ 3 & 12 \end{vmatrix} = 0$$

$$\underline{x = 4} \quad x = \frac{D_x}{D}$$

$$\underline{y = 0} \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{(4, 0)}$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 2x - 9y = 5 \\ 3x - 3y = 11 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 2 & -9 \\ 3 & -3 \end{vmatrix} = 21 \quad D_x = \begin{vmatrix} 5 & -9 \\ 11 & -3 \end{vmatrix} = 84 \quad D_y = \begin{vmatrix} 2 & 5 \\ 3 & 11 \end{vmatrix} = 7$$

$$\underline{x = 4} \quad x = \frac{D_x}{D}$$

$$\underline{y = \frac{1}{3}} \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{\left(4, \frac{1}{3}\right)}$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 3x - 4y = 4 \\ x + y = 6 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 3 & -4 \\ 1 & 1 \end{vmatrix} = 7$$

$$D_x = \begin{vmatrix} 4 & -4 \\ 6 & 1 \end{vmatrix} = 28 \quad D_y = \begin{vmatrix} 3 & 4 \\ 1 & 6 \end{vmatrix} = 14$$

$$\underline{x = 4} \quad x = \frac{D_x}{D}$$

$$\underline{y = 2} \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{(4, 2)}$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 3x = 7y + 1 \\ 2x = 3y - 1 \end{cases}$$

### Solution

$$\begin{cases} 3x - 7y = 1 \\ 2x - 3y = -1 \end{cases}$$

$$D = \begin{vmatrix} 3 & -7 \\ 2 & -3 \end{vmatrix} = 5$$

$$D_x = \begin{vmatrix} 1 & -7 \\ -1 & -3 \end{vmatrix} = -10 \quad D_y = \begin{vmatrix} 3 & 1 \\ 2 & -1 \end{vmatrix} = -5$$

$$\underline{x = -2} \quad x = \frac{D_x}{D}$$

$$\underline{y = -1} \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{(-2, -1)}$$

### Exercise

Use Cramer's rule to solve the system  $\begin{cases} 2x = 3y + 2 \\ 5x = 51 - 4y \end{cases}$

### Solution

$$\begin{cases} 2x - 3y = 2 \\ 5x + 4y = 51 \end{cases}$$

$$D = \begin{vmatrix} 2 & -3 \\ 5 & 4 \end{vmatrix} = 23$$

$$D_x = \begin{vmatrix} 2 & -3 \\ 51 & 4 \end{vmatrix} = 161 \quad D_y = \begin{vmatrix} 2 & 2 \\ 5 & 51 \end{vmatrix} = 92$$

$$\underline{x = 7} \quad x = \frac{D_x}{D}$$

$$\underline{y = 4} \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{(7, 4)}$$

### Exercise

Use Cramer's rule to solve the system  $\begin{cases} y = -4x + 2 \\ 2x = 3y - 1 \end{cases}$

### Solution

$$\begin{cases} 4x + y = 2 \\ 2x - 3y = -1 \end{cases}$$

$$D = \begin{vmatrix} 4 & 1 \\ 2 & -3 \end{vmatrix} = -14$$

$$D_x = \begin{vmatrix} 2 & 1 \\ -1 & -3 \end{vmatrix} = -5 \quad D_y = \begin{vmatrix} 4 & 2 \\ 2 & -1 \end{vmatrix} = -8$$

$$\underline{x = \frac{5}{14}} \quad x = \frac{D_x}{D}$$

$$\underline{y = \frac{4}{7}} \quad y = \frac{D_y}{D}$$

$$\therefore \text{Solution: } \underline{\left(\frac{5}{14}, \frac{4}{7}\right)}$$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 3x = 2 - 3y \\ 2y = 3 - 2x \end{cases}$$

#### Solution

$$\begin{cases} 3x + 3y = 2 \\ 2x + 2y = 3 \end{cases}$$

$$D = \begin{vmatrix} 3 & 3 \\ 2 & 2 \end{vmatrix} = 0 \qquad D_y = \begin{vmatrix} 3 & 2 \\ 2 & 3 \end{vmatrix} = 5 \neq 0$$

$\therefore$  **No Solution**

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} x + 2y - 3 = 0 \\ 12 = 8y + 4x \end{cases}$$

#### Solution

$$\begin{cases} x + 2y = 3 \\ 4x + 8y = 12 \end{cases}$$

$$\begin{cases} x + 2y = 3 \\ x + 2y = 3 \end{cases}$$

$\therefore$  **Solution:**  $\underline{(3 - 2y, y)}$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 7x - 2y = 3 \\ 3x + y = 5 \end{cases}$$

#### Solution

$$D = \begin{vmatrix} 7 & -2 \\ 3 & 1 \end{vmatrix} = 13$$

$$D_x = \begin{vmatrix} 3 & -2 \\ 5 & 1 \end{vmatrix} = 13 \qquad D_y = \begin{vmatrix} 7 & 3 \\ 3 & 5 \end{vmatrix} = 26$$

$$\underline{x = 1} \qquad x = \frac{D_x}{D}$$

$$\underline{y = 2} \qquad y = \frac{D_y}{D}$$

$\therefore$  **Solution:**  $\underline{(1, 2)}$



### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} 3x + 2y - z = 4 \\ 3x - 2y + z = 5 \\ 4x - 5y - z = -1 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 3 & 2 & -1 \\ 3 & -2 & 1 \\ 4 & -5 & -1 \end{vmatrix} = 42$$

$$D_x = \begin{vmatrix} 4 & 2 & -1 \\ 5 & -2 & 1 \\ -1 & -5 & -1 \end{vmatrix} = 63$$

$$D_y = \begin{vmatrix} 3 & 4 & -1 \\ 3 & 5 & 1 \\ 4 & -1 & -1 \end{vmatrix} = 39$$

$$D_z = \begin{vmatrix} 3 & 2 & 4 \\ 3 & -2 & 5 \\ 4 & -5 & -1 \end{vmatrix} = 99$$

$$x = \frac{63}{42} = \frac{3}{2} \quad x = \frac{D_x}{D}$$

$$y = \frac{39}{42} = \frac{13}{14} \quad y = \frac{D_y}{D}$$

$$z = \frac{99}{42} = \frac{33}{14} \quad z = \frac{D_z}{D}$$

**Solution:**  $\left( \frac{3}{2}, \frac{13}{14}, \frac{33}{14} \right)$

### Exercise

Use Cramer's rule to solve the system 
$$\begin{cases} x + y + z = 2 \\ 2x + y - z = 5 \\ x - y + z = -2 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 1 & 1 & 1 \\ 2 & 1 & -1 \\ 1 & -1 & 1 \end{vmatrix} = -6$$

$$D_x = \begin{vmatrix} 2 & 1 & 1 \\ 5 & 1 & -1 \\ -2 & -1 & 1 \end{vmatrix} = -6$$

$$D_y = \begin{vmatrix} 1 & 2 & 1 \\ 2 & 5 & -1 \\ 1 & -2 & 1 \end{vmatrix} = -12$$

$$D_z = \begin{vmatrix} 1 & 1 & 2 \\ 2 & 1 & 5 \\ 1 & -2 & 2 \end{vmatrix} = 6$$

$$x = \frac{-6}{-6} = 1 \quad x = \frac{D_x}{D}$$

$$y = \frac{-12}{-6} = 2 \quad y = \frac{D_y}{D}$$

$$z = \frac{6}{-6} = -1 \quad z = \frac{D_z}{D}$$

$$z = \underline{\underline{-1}} \qquad z = \frac{D_z}{D}$$

$$\therefore \text{Solution: } \underline{(1, 2, -1)}$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} 2x + y + z = 9 \\ -x - y + z = 1 \\ 3x - y + z = 9 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 2 & 1 & 1 \\ -1 & -1 & 1 \\ 3 & -1 & 1 \end{vmatrix} \begin{vmatrix} 2 & 1 \\ -1 & -1 \\ 3 & -1 \end{vmatrix} = -2 + 3 + 1 + 3 + 2 + 1$$

$$= \underline{\underline{8}}$$

$$D_x = \begin{vmatrix} 9 & 1 & 1 \\ 1 & -1 & 1 \\ 9 & -1 & 1 \end{vmatrix} \begin{vmatrix} 9 & 1 \\ 1 & -1 \\ 9 & -1 \end{vmatrix} = -9 + 9 - 1 + 9 + 9 - 1$$

$$= \underline{\underline{16}}$$

$$D_y = \begin{vmatrix} 2 & 9 & 1 \\ -1 & 1 & 1 \\ 3 & 9 & 1 \end{vmatrix} \begin{vmatrix} 2 & 9 \\ -1 & 1 \\ 3 & 9 \end{vmatrix} = 2 + 27 - 9 - 3 - 18 + 9$$

$$= \underline{\underline{8}}$$

$$D_z = \begin{vmatrix} 2 & 1 & 9 \\ -1 & -1 & 1 \\ 3 & -1 & 9 \end{vmatrix} \begin{vmatrix} 2 & 1 \\ -1 & -1 \\ 3 & -1 \end{vmatrix} = -18 + 3 + 9 + 27 + 2 + 9$$

$$= \underline{\underline{32}}$$

$$x = \underline{\underline{2}} \qquad x = \frac{D_x}{D}$$

$$y = \underline{\underline{1}} \qquad y = \frac{D_y}{D}$$

$$z = \frac{32}{8} = \underline{\underline{4}} \qquad z = \frac{D_z}{D}$$

$$\therefore \text{Solution: } \underline{(2, 1, 4)}$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} 3y - z = -1 \\ x + 5y - z = -4 \\ -3x + 6y + 2z = 11 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 0 & 3 & -1 \\ 1 & 5 & -1 \\ -3 & 6 & 2 \end{vmatrix} \begin{matrix} 0 & 3 \\ 1 & 5 \\ -3 & 6 \end{matrix}$$
$$= 9 - 6 - 15 - 6$$
$$= \underline{-18}$$

$$D_x = \begin{vmatrix} -1 & 3 & -1 \\ -4 & 5 & -1 \\ 11 & 6 & 2 \end{vmatrix} \begin{matrix} -1 & 3 \\ -4 & 5 \\ 11 & 6 \end{matrix}$$
$$= -10 - 33 + 24 + 55 - 6 + 24$$
$$= \underline{54}$$

$$D_y = \begin{vmatrix} 0 & -1 & -1 \\ 1 & -4 & -1 \\ -3 & 11 & 2 \end{vmatrix} \begin{matrix} 0 & -1 \\ 1 & -4 \\ -3 & 11 \end{matrix}$$
$$= -3 - 11 + 12 + 2$$
$$= \underline{0}$$

$$D_z = \begin{vmatrix} 0 & 3 & -1 \\ 1 & 5 & -4 \\ -3 & 6 & 11 \end{vmatrix} \begin{matrix} 0 & 3 \\ 1 & 5 \\ -3 & 6 \end{matrix}$$
$$= 36 - 6 - 15 - 33$$
$$= \underline{-18}$$

$$x = \underline{-3} \quad x = \frac{D_x}{D}$$

$$y = \underline{0} \quad y = \frac{D_y}{D}$$

$$z = \underline{1} \quad z = \frac{D_z}{D}$$

$$\therefore \text{Solution: } \underline{(-3, 0, 1)}$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} x + 3y + 4z = 14 \\ 2x - 3y + 2z = 10 \\ 3x - y + z = 9 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 1 & 3 & 4 \\ 2 & -3 & 2 \\ 3 & -1 & 1 \end{vmatrix} \begin{vmatrix} 1 & 3 \\ 2 & -3 \\ 3 & -1 \end{vmatrix}$$
$$= -3 + 18 - 8 + 36 + 2 - 6$$
$$= \underline{39}$$

$$D_x = \begin{vmatrix} 14 & 3 & 4 \\ 10 & -3 & 2 \\ 9 & -1 & 1 \end{vmatrix} \begin{vmatrix} 14 & 3 \\ 10 & -3 \\ 9 & -1 \end{vmatrix}$$
$$= -42 + 54 - 40 + 108 + 28 - 30$$
$$= \underline{78}$$

$$D_y = \begin{vmatrix} 1 & 14 & 4 \\ 2 & 10 & 2 \\ 3 & 9 & 1 \end{vmatrix} \begin{vmatrix} 1 & 14 \\ 2 & 10 \\ 3 & 9 \end{vmatrix}$$
$$= 10 + 84 + 72 - 120 - 18 - 28$$
$$= \underline{0}$$

$$D_z = \begin{vmatrix} 1 & 3 & 14 \\ 2 & -3 & 10 \\ 3 & -1 & 9 \end{vmatrix} \begin{vmatrix} 1 & 3 \\ 2 & -3 \\ 3 & -1 \end{vmatrix}$$
$$= -27 + 90 - 28 + 126 + 10 - 54$$
$$= \underline{117}$$

$$x = \frac{78}{39} = \underline{2} \quad x = \frac{D_x}{D}$$

$$y = \underline{0} \quad y = \frac{D_y}{D}$$

$$z = \frac{117}{39} = \underline{3} \quad z = \frac{D_z}{D}$$

$$\therefore \text{Solution: } \underline{(2, 0, 3)}$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} x + 4y - z = 20 \\ 3x + 2y + z = 8 \\ 2x - 3y + 2z = -16 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 1 & 4 & -1 \\ 3 & 2 & 1 \\ 2 & -3 & 2 \end{vmatrix} \begin{vmatrix} 1 & 4 \\ 3 & 2 \\ 2 & -3 \end{vmatrix}$$
$$= 4 + 8 + 9 + 4 + 3 - 24$$
$$= \underline{4}$$

$$D_x = \begin{vmatrix} 20 & 4 & -1 \\ 8 & 2 & 1 \\ -16 & -3 & 2 \end{vmatrix} \begin{vmatrix} 20 & 4 \\ 8 & 2 \\ -16 & -3 \end{vmatrix}$$
$$= 80 - 64 + 24 - 32 + 60 - 64$$
$$= \underline{4}$$

$$D_y = \begin{vmatrix} 1 & 20 & -1 \\ 3 & 8 & 1 \\ 2 & -16 & 2 \end{vmatrix} \begin{vmatrix} 1 & 20 \\ 3 & 8 \\ 2 & -16 \end{vmatrix}$$
$$= 16 + 40 + 48 + 16 + 16 - 120$$
$$= \underline{16}$$

$$D_z = \begin{vmatrix} 1 & 4 & 20 \\ 3 & 2 & 8 \\ 2 & -3 & -16 \end{vmatrix} \begin{vmatrix} 1 & 4 \\ 3 & 2 \\ 2 & -3 \end{vmatrix}$$
$$= -32 + 64 - 180 - 80 + 24 + 192$$
$$= \underline{-12}$$

$$x = \frac{4}{4} = \underline{1} \quad x = \frac{D_x}{D}$$

$$y = \frac{16}{4} = \underline{4} \quad y = \frac{D_y}{D}$$

$$z = -\frac{12}{4} = \underline{-3} \quad z = \frac{D_z}{D}$$

$\therefore$  **Solution:** (1, 4, -3)

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} -2x + 6y + 7z = 3 \\ -4x + 5y + 3z = 7 \\ -6x + 3y + 5z = -4 \end{cases}$$

### Solution

$$D = \begin{vmatrix} -2 & 6 & 7 \\ -4 & 5 & 3 \\ -6 & 3 & 5 \end{vmatrix} \begin{matrix} -2 & 6 \\ -4 & 5 \\ -6 & 3 \end{matrix}$$
$$= -50 - 108 - 84 + 210 + 18 + 120$$
$$= \underline{106}$$

$$D_x = \begin{vmatrix} 3 & 6 & 7 \\ 7 & 5 & 3 \\ -4 & 3 & 5 \end{vmatrix} \begin{matrix} 3 & 6 \\ 7 & 5 \\ -4 & 3 \end{matrix}$$
$$= 75 - 72 + 147 + 140 - 27 - 210$$
$$= \underline{53}$$

$$D_y = \begin{vmatrix} -2 & 3 & 7 \\ -4 & 7 & 3 \\ -6 & -4 & 5 \end{vmatrix} \begin{matrix} -2 & 3 \\ -4 & 7 \\ -6 & -4 \end{matrix}$$
$$= -70 - 54 + 112 + 294 - 24 + 60$$
$$= \underline{318}$$

$$D_z = \begin{vmatrix} -2 & 6 & 3 \\ -4 & 5 & 7 \\ -6 & 3 & -4 \end{vmatrix} \begin{matrix} -2 & 6 \\ -4 & 5 \\ -6 & 3 \end{matrix}$$
$$= 40 - 252 - 36 + 90 + 42 - 96$$
$$= \underline{-212}$$

$$x = \frac{53}{106} = \underline{\frac{1}{2}} \quad x = \frac{D_x}{D}$$

$$y = \frac{318}{106} = \underline{3} \quad y = \frac{D_y}{D}$$

$$z = -\frac{212}{106} = \underline{-2} \quad z = \frac{D_z}{D}$$

$$\therefore \text{Solution: } \underline{\left(\frac{1}{2}, 3, -2\right)}$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} 2x - y + z = 1 \\ 3x - 3y + 4z = 5 \\ 4x - 2y + 3z = 4 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 2 & -1 & 1 \\ 3 & -3 & 4 \\ 4 & -2 & 3 \end{vmatrix} \begin{vmatrix} 2 & -1 \\ 3 & -3 \\ 4 & -2 \end{vmatrix}$$
$$= -18 - 16 - 6 + 12 + 16 + 9$$
$$= -3$$

$$D_x = \begin{vmatrix} 1 & -1 & 1 \\ 5 & -3 & 4 \\ 4 & -2 & 3 \end{vmatrix} \begin{vmatrix} 1 & -1 \\ 5 & -3 \\ 4 & -2 \end{vmatrix}$$
$$= -9 - 16 - 10 + 12 + 8 + 15$$
$$= 0$$

$$D_y = \begin{vmatrix} 2 & 1 & 1 \\ 3 & 5 & 4 \\ 4 & 4 & 3 \end{vmatrix} \begin{vmatrix} 2 & 1 \\ 3 & 5 \\ 4 & 4 \end{vmatrix}$$
$$= 30 + 16 + 12 - 20 - 32 - 9$$
$$= -3$$

$$D_z = \begin{vmatrix} 2 & -1 & 1 \\ 3 & -3 & 5 \\ 4 & -2 & 4 \end{vmatrix} \begin{vmatrix} 2 & -1 \\ 3 & -3 \\ 4 & -2 \end{vmatrix}$$
$$= -24 - 20 - 6 + 12 + 20 + 12$$
$$= -6$$

$$x = -\frac{0}{-3} = 0 \quad x = \frac{D_x}{D}$$

$$y = \frac{-3}{-3} = 1 \quad y = \frac{D_y}{D}$$

$$z = \frac{-6}{-3} = 2 \quad z = \frac{D_z}{D}$$

$\therefore$  **Solution:**  $(0, 1, 2)$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} 3x - 4y + 4z = 7 \\ x - y - 2z = 2 \\ 2x - 3y + 6z = 5 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 3 & -4 & 4 \\ 1 & -1 & -2 \\ 2 & -3 & 6 \end{vmatrix} \begin{vmatrix} 3 & -4 \\ 1 & -1 \\ 2 & -3 \end{vmatrix}$$
$$= -18 + 16 - 12 + 8 - 18 + 24$$
$$= 0$$

$$D_z = \begin{vmatrix} 3 & -4 & 7 \\ 1 & -1 & 2 \\ 2 & -3 & 5 \end{vmatrix} \begin{vmatrix} 3 & -4 \\ 1 & -1 \\ 2 & -3 \end{vmatrix}$$
$$= -15 - 16 - 21 + 14 + 18 + 20$$
$$= 0$$

$$\begin{array}{l} -3 \times (2) \quad \begin{cases} -3x + 3y + 6z = -6 \\ 2x - 3y + 6z = 5 \end{cases} \\ \hline -x + 12z = -1 \end{array}$$

$$x = 12z + 1$$

$$(2) \rightarrow y = 12z + 1 - 2z - 2$$
$$= 10z - 1$$

$$\therefore \text{Solution: } (12z + 1, 10z - 1, z)$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} x - 2y - z = 2 \\ 2x - y + z = 4 \\ -x + y + z = 4 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 1 & -2 & -1 \\ 2 & -1 & 1 \\ -1 & 1 & 1 \end{vmatrix} \begin{vmatrix} 1 & -2 \\ 2 & -1 \\ -1 & 1 \end{vmatrix}$$
$$= -1 + 2 - 2 + 1 - 1 + 4$$
$$= 3$$



$$D_x = \begin{vmatrix} 2 & -2 & -1 \\ 4 & -1 & 1 \\ 4 & 1 & 1 \end{vmatrix} \begin{vmatrix} 2 & -2 \\ 4 & -1 \\ 4 & 1 \end{vmatrix}$$

$$= -2 - 8 - 4 - 4 - 2 + 8$$

$$= -12$$

$$D_y = \begin{vmatrix} 1 & 2 & -1 \\ 2 & 4 & 1 \\ -1 & 4 & 1 \end{vmatrix} \begin{vmatrix} 1 & 2 \\ 2 & 4 \\ -1 & 4 \end{vmatrix}$$

$$= 4 - 2 - 8 - 4 - 4 - 4$$

$$= -18$$

$$D_z = \begin{vmatrix} 1 & -2 & 2 \\ 2 & -1 & 4 \\ -1 & 1 & 4 \end{vmatrix} \begin{vmatrix} 1 & -2 \\ 2 & -1 \\ -1 & 1 \end{vmatrix}$$

$$= -4 + 8 + 4 - 2 - 4 + 16$$

$$= 18$$

$$x = -\frac{12}{3} = -4 \quad x = \frac{D_x}{D}$$

$$y = -\frac{18}{3} = -6 \quad y = \frac{D_y}{D}$$

$$z = \frac{18}{3} = 6 \quad z = \frac{D_z}{D}$$

**∴ Solution:**  $(-4, -6, 6)$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} x + y + z = 3 \\ -y + 2z = 1 \\ -x + z = 0 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 1 & 1 & 1 \\ 0 & -1 & 2 \\ -1 & 0 & 1 \end{vmatrix} \begin{vmatrix} 1 & 1 \\ 0 & -1 \\ -1 & 0 \end{vmatrix}$$

$$= -4$$

$$D_x = \begin{vmatrix} 3 & 1 & 1 \\ 1 & -1 & 2 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} 3 & 1 \\ 1 & -1 \\ 0 & 0 \end{vmatrix}$$

$$\underline{\underline{=-4}}$$

$$D_y = \begin{vmatrix} 1 & 3 & 1 \\ 0 & 1 & 2 \\ -1 & 0 & 1 \end{vmatrix} \begin{vmatrix} 1 & 1 \\ 0 & -1 \\ -1 & 0 \end{vmatrix}$$

$$\underline{\underline{=-4}}$$

$$D_z = \begin{vmatrix} 1 & 1 & 3 \\ 0 & -1 & 1 \\ -1 & 0 & 0 \end{vmatrix} \begin{vmatrix} 1 & 1 \\ 0 & -1 \\ -1 & 0 \end{vmatrix}$$

$$\underline{\underline{=-4}}$$

$$x = \frac{4}{4} \underline{\underline{=1}} \quad x = \frac{D_x}{D}$$

$$y = \frac{4}{4} \underline{\underline{=1}} \quad y = \frac{D_y}{D}$$

$$z = \frac{4}{4} \underline{\underline{=1}} \quad z = \frac{D_z}{D}$$

$$\therefore \text{Solution: } \underline{(1, 1, 1)}$$

## Exercise

Use Cramer's rule to solve the system

$$\begin{cases} 3x + y + 3z = 14 \\ 7x + 5y + 8z = 37 \\ x + 3y + 2z = 9 \end{cases}$$

## Solution

$$D = \begin{vmatrix} 3 & 1 & 3 \\ 7 & 5 & 8 \\ 1 & 3 & 2 \end{vmatrix} \begin{vmatrix} 3 & 1 \\ 7 & 5 \\ 1 & 3 \end{vmatrix}$$

$$= 30 + 8 + 62 - 15 - 72 - 14$$

$$\underline{\underline{=0}}$$

$$D_z = \begin{vmatrix} 3 & 1 & 14 \\ 7 & 5 & 37 \\ 1 & 3 & 9 \end{vmatrix} \begin{vmatrix} 3 & 1 \\ 7 & 5 \\ 1 & 3 \end{vmatrix}$$

$$= 135 + 37 + 294 - 70 - 333 - 63$$

$$\underline{\underline{=0}}$$

$$\begin{array}{l} -3 \times (1) \\ (3) \end{array} \begin{cases} -9x - 3y - 9z = -42 \\ x + 3y + 2z = 9 \end{cases}$$


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$$-8x - 7z = -33$$

$$\underline{x = -\frac{7}{8}z + \frac{33}{8}}$$

$$\begin{aligned} (1) \rightarrow y &= 14 - 3z - 3\left(-\frac{7}{8}z + \frac{33}{8}\right) \\ &= \frac{13}{8} - \frac{3}{8}z \end{aligned}$$

$$\therefore \text{Solution: } \underline{\left(\frac{33}{8} - \frac{7}{8}z, \frac{13}{8} - \frac{3}{8}z, z\right)}$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} 4x - 2y + z = 7 \\ x + y + z = -2 \\ 4x + 2y + z = 3 \end{cases}$$

### Solution

$$\begin{aligned} D &= \begin{vmatrix} 4 & -2 & 1 \\ 1 & 1 & 1 \\ 4 & 2 & 1 \end{vmatrix} \begin{vmatrix} 4 & -2 \\ 1 & 1 \\ 4 & 2 \end{vmatrix} \\ &= -12 \end{aligned}$$

$$\begin{aligned} D_x &= \begin{vmatrix} 7 & -2 & 1 \\ -2 & 1 & 1 \\ 3 & 2 & 1 \end{vmatrix} \begin{vmatrix} 7 & -2 \\ -2 & 1 \\ 3 & 2 \end{vmatrix} \\ &= -24 \end{aligned}$$

$$\begin{aligned} D_y &= \begin{vmatrix} 4 & 7 & 1 \\ 1 & -2 & 1 \\ 4 & 3 & 1 \end{vmatrix} \begin{vmatrix} 4 & 7 \\ 1 & -2 \\ 4 & 3 \end{vmatrix} \\ &= 12 \end{aligned}$$

$$\begin{aligned} D_z &= \begin{vmatrix} 4 & -2 & 7 \\ 1 & 1 & -2 \\ 4 & 2 & 3 \end{vmatrix} \begin{vmatrix} 4 & -2 \\ 1 & 1 \\ 4 & 2 \end{vmatrix} \\ &= 36 \end{aligned}$$

$$x = \frac{24}{-12} = -2 \qquad x = \frac{D_x}{D}$$

$$y = -\frac{12}{12} = -1 \qquad y = \frac{D_y}{D}$$

$$z = -\frac{36}{12} = -3 \qquad z = \frac{D_z}{D}$$

$$\therefore \text{Solution: } \underline{(2, -1, -3)}$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} 2y - z = 7 \\ x + 2y + z = 17 \\ 2x - 3y + 2z = -1 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 0 & 2 & -1 \\ 1 & 2 & 1 \\ 2 & 3 & 2 \end{vmatrix} \begin{vmatrix} 0 & 2 \\ 1 & 2 \\ 2 & 3 \end{vmatrix} \\ = 1$$

$$D_x = \begin{vmatrix} 7 & 2 & -1 \\ 17 & 2 & 1 \\ -1 & 3 & 2 \end{vmatrix} \begin{vmatrix} 7 & 2 \\ 17 & 2 \\ -1 & 3 \end{vmatrix} \\ = -116$$

$$D_y = \begin{vmatrix} 0 & 7 & -1 \\ 1 & 17 & 1 \\ 2 & -1 & 2 \end{vmatrix} \begin{vmatrix} 0 & 7 \\ 1 & 17 \\ 2 & -1 \end{vmatrix} \\ = 35$$

$$D_z = \begin{vmatrix} 0 & 2 & 7 \\ 1 & 2 & 17 \\ 2 & 3 & -1 \end{vmatrix} \begin{vmatrix} 0 & 2 \\ 1 & 2 \\ 2 & 3 \end{vmatrix} \\ = 63$$

$$x = \frac{-116}{D} \quad x = \frac{D_x}{D}$$

$$y = \frac{35}{D} \quad y = \frac{D_y}{D}$$

$$z = \frac{63}{D} \quad z = \frac{D_z}{D}$$

$$\therefore \text{Solution: } \underline{(-116, 35, 63)}$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} 2x - 2y + z = -4 \\ 6x + 4y - 3z = -24 \\ x - 2y + 2z = 1 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 2 & -2 & 1 \\ 6 & 4 & -3 \\ 1 & -2 & 2 \end{vmatrix} \begin{vmatrix} 2 & -2 \\ 6 & 4 \\ 1 & -2 \end{vmatrix}$$

$$\underline{= 18}$$

$$D_x = \begin{vmatrix} -4 & -2 & 1 \\ -24 & 4 & -3 \\ 1 & -2 & 2 \end{vmatrix} \begin{vmatrix} -4 & -2 \\ -24 & 4 \\ 1 & -2 \end{vmatrix}$$

$$\underline{= -54}$$

$$D_y = \begin{vmatrix} 2 & -4 & 1 \\ 6 & -24 & -3 \\ 1 & 1 & 2 \end{vmatrix} \begin{vmatrix} 2 & -4 \\ 6 & -24 \\ 1 & 1 \end{vmatrix}$$

$$\underline{= 0}$$

$$D_z = \begin{vmatrix} 2 & -2 & -4 \\ 6 & 4 & -24 \\ 1 & -2 & 1 \end{vmatrix} \begin{vmatrix} 2 & -2 \\ 6 & 4 \\ 1 & -2 \end{vmatrix}$$

$$\underline{= 36}$$

$$x = -\frac{54}{18}$$

$$\underline{= -3}$$

$$x = \frac{D_x}{D}$$

$$y = \underline{0}$$

$$y = \frac{D_y}{D}$$

$$z = \underline{2}$$

$$z = \frac{D_z}{D}$$

$$\therefore \text{Solution: } \underline{(-3, 0, 2)}$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} 9x + 3y + z = 4 \\ 16x + 4y + z = 2 \\ 25x + 5y + z = 2 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 9 & 3 & 1 \\ 16 & 4 & 1 \\ 25 & 5 & 1 \end{vmatrix} \begin{matrix} 9 & 3 \\ 16 & 4 \\ 25 & 5 \end{matrix}$$
$$= -2$$

$$D_x = \begin{vmatrix} 4 & 3 & 1 \\ 2 & 4 & 1 \\ 2 & 5 & 1 \end{vmatrix} \begin{matrix} 4 & 3 \\ 2 & 4 \\ 2 & 5 \end{matrix}$$
$$= -2$$

$$D_y = \begin{vmatrix} 9 & 4 & 1 \\ 16 & 2 & 1 \\ 25 & 2 & 1 \end{vmatrix} \begin{matrix} 9 & 4 \\ 16 & 2 \\ 25 & 2 \end{matrix}$$
$$= 18$$

$$D_z = \begin{vmatrix} 9 & 3 & 4 \\ 16 & 4 & 2 \\ 25 & 5 & 2 \end{vmatrix} \begin{matrix} 9 & 3 \\ 16 & 4 \\ 25 & 5 \end{matrix}$$
$$= -44$$

$$x = \frac{-2}{-2} \qquad x = \frac{D_x}{D}$$
$$= 1$$

$$y = \frac{18}{-2} \qquad y = \frac{D_y}{D}$$
$$= -9$$

$$z = \frac{-44}{-2} \qquad z = \frac{D_z}{D}$$
$$= 22$$

$$\therefore \text{Solution: } \underline{(1, -9, 22)}$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} 2x - y + 2z = -8 \\ x + 2y - 3z = 9 \\ 3x - y - 4z = 3 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 2 & -1 & 2 \\ 1 & 2 & -3 \\ 3 & -1 & -4 \end{vmatrix} \begin{vmatrix} 2 & -1 \\ 1 & 2 \\ 3 & -1 \end{vmatrix} \\ = -31$$

$$D_x = \begin{vmatrix} -8 & -1 & 2 \\ 9 & 2 & -3 \\ 3 & -1 & -4 \end{vmatrix} \begin{vmatrix} -8 & -1 \\ 9 & 2 \\ 3 & -1 \end{vmatrix} \\ = 31$$

$$D_y = \begin{vmatrix} 2 & -8 & 2 \\ 1 & 9 & -3 \\ 3 & 3 & -4 \end{vmatrix} \begin{vmatrix} 2 & -8 \\ 1 & 9 \\ 3 & 3 \end{vmatrix} \\ = -62$$

$$D_z = \begin{vmatrix} 2 & -1 & -8 \\ 1 & 2 & 9 \\ 3 & -1 & 3 \end{vmatrix} \begin{vmatrix} 2 & -1 \\ 1 & 2 \\ 3 & -1 \end{vmatrix} \\ = 62$$

$$x = -\frac{31}{31} \qquad x = \frac{D_x}{D} \\ = -1$$

$$y = \frac{62}{31} \qquad y = \frac{D_y}{D} \\ = 2$$

$$z = -\frac{62}{31} \qquad z = \frac{D_z}{D} \\ = -2$$

$$\therefore \text{Solution: } \underline{(-1, 2, -2)}$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} x - 3z = -5 \\ 2x - y + 2z = 16 \\ 7x - 3y - 5z = 19 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 1 & 0 & -3 \\ 2 & -1 & 2 \\ 7 & -3 & -5 \end{vmatrix} \begin{vmatrix} 1 & 0 \\ 2 & -1 \\ 7 & -3 \end{vmatrix} \\ = 8$$

$$D_x = \begin{vmatrix} -5 & 0 & -3 \\ 16 & -1 & 2 \\ 19 & -3 & -5 \end{vmatrix} \begin{vmatrix} -5 & 0 \\ 16 & -1 \\ 19 & -3 \end{vmatrix} \\ = 32$$

$$D_y = \begin{vmatrix} 1 & -5 & -3 \\ 2 & 16 & 2 \\ 7 & 19 & -5 \end{vmatrix} \begin{vmatrix} 1 & -5 \\ 2 & 16 \\ 7 & 19 \end{vmatrix} \\ = -16$$

$$D_z = \begin{vmatrix} 1 & 0 & -5 \\ 2 & -1 & 16 \\ 7 & -3 & 19 \end{vmatrix} \begin{vmatrix} 1 & 0 \\ 2 & -1 \\ 7 & -3 \end{vmatrix} \\ = 24$$

$$x = \frac{32}{8} \qquad x = \frac{D_x}{D} \\ = 4$$

$$y = -\frac{16}{8} \qquad y = \frac{D_y}{D} \\ = -2$$

$$z = \frac{24}{8} \qquad z = \frac{D_z}{D} \\ = 3$$

$$\therefore \text{Solution: } \underline{(4, -2, 3)}$$



### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} x + 2y - z = 5 \\ 2x - y + 3z = 0 \\ 2y + z = 1 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 1 & 2 & -1 \\ 2 & -1 & 3 \\ 0 & 2 & 1 \end{vmatrix} \begin{vmatrix} 1 & 2 \\ 2 & -1 \\ 0 & 2 \end{vmatrix}$$
$$= -15$$

$$D_x = \begin{vmatrix} 5 & 2 & -1 \\ 0 & -1 & 3 \\ 1 & 2 & 1 \end{vmatrix} \begin{vmatrix} 5 & 2 \\ 0 & -1 \\ 1 & 2 \end{vmatrix}$$
$$= -30$$

$$D_y = \begin{vmatrix} 1 & 5 & -1 \\ 2 & 0 & 3 \\ 0 & 1 & 1 \end{vmatrix} \begin{vmatrix} 1 & 5 \\ 2 & 0 \\ 0 & 1 \end{vmatrix}$$
$$= -15$$

$$D_z = \begin{vmatrix} 1 & 2 & 5 \\ 2 & -1 & 0 \\ 0 & 2 & 1 \end{vmatrix} \begin{vmatrix} 1 & 2 \\ 2 & -1 \\ 0 & 2 \end{vmatrix}$$
$$= 15$$

$$x = \frac{30}{-15}$$
$$= -2$$
$$x = \frac{D_x}{D}$$

$$y = \frac{-15}{-15}$$
$$= 1$$
$$y = \frac{D_y}{D}$$

$$z = \frac{15}{-15}$$
$$= -1$$
$$z = \frac{D_z}{D}$$

$$\therefore \text{Solution: } \underline{(2, 1, -1)}$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} x + y + z = 6 \\ 3x + 4y - 7z = 1 \\ 2x - y + 3z = 5 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 1 & 1 & 1 \\ 3 & 4 & -7 \\ 2 & -1 & 3 \end{vmatrix} \begin{vmatrix} 1 & 1 \\ 3 & 4 \\ 2 & -1 \end{vmatrix} \\ = -29$$

$$D_x = \begin{vmatrix} 6 & 1 & 1 \\ 1 & 4 & -7 \\ 5 & -1 & 3 \end{vmatrix} \begin{vmatrix} 6 & 1 \\ 1 & 4 \\ 5 & -1 \end{vmatrix} \\ = -29$$

$$D_y = \begin{vmatrix} 1 & 6 & 1 \\ 3 & 1 & -7 \\ 2 & 5 & 3 \end{vmatrix} \begin{vmatrix} 1 & 6 \\ 3 & 1 \\ 2 & 5 \end{vmatrix} \\ = -87$$

$$D_z = \begin{vmatrix} 1 & 2 & 6 \\ 2 & -1 & 1 \\ 0 & 2 & 5 \end{vmatrix} \begin{vmatrix} 1 & 2 \\ 2 & -1 \\ 0 & 2 \end{vmatrix} \\ = -58$$

$$x = \frac{29}{29} \qquad x = \frac{D_x}{D} \\ = 1$$

$$y = \frac{87}{29} \qquad y = \frac{D_y}{D} \\ = 3$$

$$z = \frac{58}{29} \qquad z = \frac{D_z}{D} \\ = 2$$

$$\therefore \text{Solution: } \underline{(1, 3, 2)}$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} 3x + 2y + 3z = 3 \\ 4x - 5y + 7z = 1 \\ 2x + 3y - 2z = 6 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 3 & 2 & 3 \\ 4 & -5 & 7 \\ 2 & 3 & -2 \end{vmatrix} \begin{vmatrix} 3 & 2 \\ 4 & -5 \\ 2 & 3 \end{vmatrix} \\ = 77$$

$$D_x = \begin{vmatrix} 3 & 2 & 3 \\ 1 & -5 & 7 \\ 6 & 3 & -2 \end{vmatrix} \begin{vmatrix} 3 & 2 \\ 1 & -5 \\ 6 & 3 \end{vmatrix} \\ = 154$$

$$D_y = \begin{vmatrix} 3 & 3 & 3 \\ 4 & 1 & 7 \\ 2 & 6 & -2 \end{vmatrix} \begin{vmatrix} 3 & 3 \\ 4 & 1 \\ 2 & 6 \end{vmatrix} \\ = 0$$

$$D_z = \begin{vmatrix} 3 & 2 & 3 \\ 4 & -5 & 1 \\ 2 & 3 & 6 \end{vmatrix} \begin{vmatrix} 3 & 2 \\ 4 & -5 \\ 2 & 3 \end{vmatrix} \\ = -77$$

$$x = \frac{154}{77} = 2$$

$$x = \frac{D_x}{D}$$

$$y = 0$$

$$y = \frac{D_y}{D}$$

$$z = -\frac{77}{77} = -1$$

$$z = \frac{D_z}{D}$$

$$\therefore \text{Solution: } (2, 0, -1)$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} 4x + 5y = 2 \\ 11x + y + 2z = 3 \\ x + 5y + 2z = 1 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 4 & 5 & 0 \\ 11 & 1 & 2 \\ 1 & 5 & 2 \end{vmatrix} \begin{matrix} 4 & 5 \\ 11 & 1 \\ 1 & 5 \end{matrix}$$
$$= -132$$

$$D_x = \begin{vmatrix} 2 & 5 & 0 \\ 3 & 1 & 2 \\ 1 & 5 & 2 \end{vmatrix} \begin{matrix} 2 & 5 \\ 3 & 1 \\ 1 & 5 \end{matrix}$$
$$= -36$$

$$D_y = \begin{vmatrix} 4 & 2 & 0 \\ 11 & 3 & 2 \\ 1 & 1 & 2 \end{vmatrix} \begin{matrix} 4 & 2 \\ 11 & 3 \\ 1 & 1 \end{matrix}$$
$$= -24$$

$$D_z = \begin{vmatrix} 4 & 5 & 2 \\ 11 & 1 & 3 \\ 1 & 5 & 1 \end{vmatrix} \begin{matrix} 4 & 5 \\ 11 & 1 \\ 1 & 5 \end{matrix}$$
$$= 12$$

$$x = \frac{36}{132}$$
$$= \frac{3}{11}$$
$$x = \frac{D_x}{D}$$

$$y = \frac{24}{132}$$
$$= \frac{2}{11}$$
$$y = \frac{D_y}{D}$$

$$z = -\frac{12}{132}$$
$$= -\frac{1}{11}$$
$$z = \frac{D_z}{D}$$

$$\therefore \text{Solution: } \left( \frac{3}{11}, \frac{2}{11}, -\frac{1}{11} \right)$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} x - 4y + z = 6 \\ 4x - y + 2z = -1 \\ 2x + 2y - 3z = -20 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 1 & -4 & 1 \\ 4 & -1 & 2 \\ 2 & 2 & -3 \end{vmatrix} \begin{vmatrix} 1 & -4 \\ 4 & -1 \\ 2 & 2 \end{vmatrix} \\ = -55$$

$$D_x = \begin{vmatrix} 6 & -4 & 1 \\ -1 & -1 & 2 \\ -20 & 2 & -3 \end{vmatrix} \begin{vmatrix} 6 & -4 \\ -1 & -1 \\ -20 & 2 \end{vmatrix} \\ = 144$$

$$D_y = \begin{vmatrix} 1 & 6 & 1 \\ 4 & -1 & 2 \\ 2 & -20 & -3 \end{vmatrix} \begin{vmatrix} 1 & 6 \\ 4 & -1 \\ 2 & -20 \end{vmatrix} \\ = 61$$

$$D_z = \begin{vmatrix} 1 & -4 & 6 \\ 4 & -1 & -1 \\ 2 & 2 & -20 \end{vmatrix} \begin{vmatrix} 1 & -4 \\ 4 & -1 \\ 2 & 2 \end{vmatrix} \\ = -230$$

$$x = -\frac{144}{55} \quad x = \frac{D_x}{D}$$

$$y = -\frac{61}{55} \quad y = \frac{D_y}{D}$$

$$z = \frac{230}{55} \quad z = \frac{D_z}{D}$$

$$= \frac{46}{11}$$

$$\therefore \text{Solution: } \left( -\frac{144}{55}, -\frac{61}{55}, \frac{46}{11} \right)$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} 2x - y + z = -1 \\ 3x + 4y - z = -1 \\ 4x - y + 2z = -1 \end{cases}$$

### Solution

$$D = \begin{vmatrix} 2 & -1 & 1 \\ 3 & 4 & -1 \\ 4 & -1 & 2 \end{vmatrix} \begin{vmatrix} 2 & -1 \\ 3 & 4 \\ 4 & -1 \end{vmatrix} \\ = 5$$

$$D_x = \begin{vmatrix} -1 & -1 & 1 \\ -1 & 4 & -1 \\ -1 & -1 & 2 \end{vmatrix} \begin{vmatrix} -1 & -1 \\ -1 & 4 \\ -1 & -1 \end{vmatrix} \\ = -5$$

$$D_y = \begin{vmatrix} 2 & -1 & 1 \\ 3 & -1 & -1 \\ 4 & -1 & 2 \end{vmatrix} \begin{vmatrix} 2 & -1 \\ 3 & -1 \\ 4 & -1 \end{vmatrix} \\ = 5$$

$$D_z = \begin{vmatrix} 2 & -1 & -1 \\ 3 & 4 & -1 \\ 4 & -1 & -1 \end{vmatrix} \begin{vmatrix} 2 & -1 \\ 3 & 4 \\ 4 & -1 \end{vmatrix} \\ = 10$$

$$x = \frac{-5}{5} \qquad x = \frac{D_x}{D} \\ = -1$$

$$y = \frac{5}{5} \qquad y = \frac{D_y}{D} \\ = 1$$

$$z = \frac{10}{5} \qquad z = \frac{D_z}{D} \\ = 2$$

$$\therefore \text{Solution: } \underline{(-1, 1, 2)}$$

### Exercise

Use Cramer's rule to solve the system

$$\begin{cases} -x_1 - 4x_2 + 2x_3 + x_4 = -32 \\ 2x_1 - x_2 + 7x_3 + 9x_4 = 14 \\ -x_1 + x_2 + 3x_3 + x_4 = 11 \\ -x_1 - 2x_2 + x_3 - 4x_4 = -4 \end{cases}$$

### Solution

$$D = \begin{vmatrix} -1 & -4 & 2 & 1 \\ 2 & -1 & 7 & 9 \\ -1 & 1 & 3 & 1 \\ -1 & -2 & 1 & -4 \end{vmatrix} \\ = -243$$

$$D_1 = \begin{vmatrix} -32 & -4 & 2 & 1 \\ 14 & -1 & 7 & 9 \\ 11 & 1 & 3 & 1 \\ -4 & -2 & 1 & -4 \end{vmatrix} \\ = -2115$$

$$D_2 = \begin{vmatrix} -1 & -32 & 2 & 1 \\ 2 & 14 & 7 & 9 \\ -1 & 11 & 3 & 1 \\ -1 & -4 & 1 & -4 \end{vmatrix} \\ = -1834$$

$$D_3 = \begin{vmatrix} -1 & -4 & -32 & 1 \\ 2 & -1 & 14 & 9 \\ -1 & 1 & 11 & 1 \\ -1 & -2 & -4 & -4 \end{vmatrix} \\ = -1279$$

$$D_4 = \begin{vmatrix} -1 & -4 & 2 & -32 \\ 2 & -1 & 7 & 14 \\ -1 & 1 & 3 & 11 \\ -1 & -2 & 1 & -4 \end{vmatrix} \\ = 883$$

$$x_1 = \frac{-2115}{-243} \\ = \frac{235}{27}$$

$$x_2 = \frac{-1834}{-243}$$

$$= \frac{1834}{243} \Big|$$

$$x_3 = \frac{-1279}{-243}$$

$$= \frac{1279}{243} \Big|$$

$$x_4 = -\frac{883}{243} \Big|$$

$$\therefore \text{Solution: } \left( \frac{235}{27}, \frac{1834}{243}, \frac{1279}{243}, -\frac{883}{243} \right) \Big|$$

### Exercise

Show that the matrix  $A$  is invertible for all values of  $\theta$ , then find  $A^{-1}$  using  $A^{-1} = \frac{1}{\det(A)} \text{adj}(A)$

$$A = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

### Solution

$$\begin{aligned} \det(A) &= \begin{vmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{vmatrix} \\ &= \cos^2 \theta + \sin^2 \theta \\ &= 1 \Big| \end{aligned}$$

$\Rightarrow A$  is invertible

$$\begin{aligned} C_{11} &= \begin{vmatrix} \cos \theta & 0 \\ 0 & 1 \end{vmatrix} \\ &= \cos \theta \Big| \end{aligned}$$

$$\begin{aligned} C_{12} &= -\begin{vmatrix} -\sin \theta & 0 \\ 0 & 1 \end{vmatrix} \\ &= \sin \theta \Big| \end{aligned}$$

$$\begin{aligned} C_{13} &= \begin{vmatrix} -\sin \theta & \cos \theta \\ 0 & 0 \end{vmatrix} \\ &= 0 \Big| \end{aligned}$$

$$\begin{aligned} C_{21} &= -\begin{vmatrix} \sin \theta & 0 \\ 0 & 1 \end{vmatrix} \\ &= -\sin \theta \Big| \end{aligned}$$

$$\begin{aligned} C_{22} &= \begin{vmatrix} \cos \theta & 0 \\ 0 & 1 \end{vmatrix} \\ &= \cos \theta \Big| \end{aligned}$$

$$\begin{aligned} C_{23} &= -\begin{vmatrix} \cos \theta & \sin \theta \\ 0 & 0 \end{vmatrix} \\ &= 0 \Big| \end{aligned}$$

$$\begin{aligned} C_{31} &= \begin{vmatrix} \sin \theta & 0 \\ \cos \theta & 0 \end{vmatrix} \\ &= 0 \Big| \end{aligned}$$

$$\begin{aligned} C_{32} &= -\begin{vmatrix} \cos \theta & 0 \\ -\sin \theta & 0 \end{vmatrix} \\ &= 0 \Big| \end{aligned}$$

$$\begin{aligned} C_{33} &= \begin{vmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{vmatrix} \\ &= 1 \Big| \end{aligned}$$



$$\text{adj}(A) = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

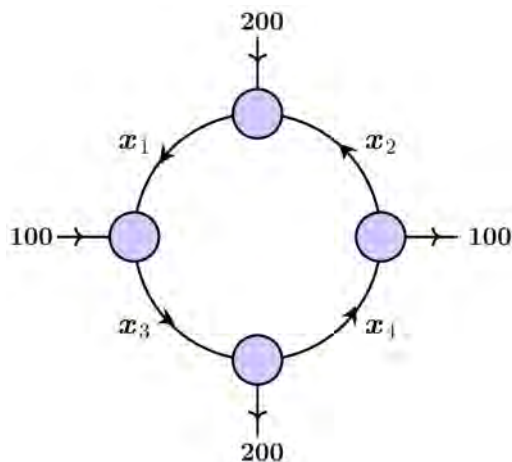
$$\begin{aligned} A^{-1} &= \frac{1}{\det(A)} \text{adj}(A) \\ &= \frac{1}{1} \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{aligned}$$

## Solution

### Section 1.8 – Applications

#### Exercise

The flow of traffic, in vehicles per hour, through a network of streets as is shown below



- Solve this system for  $x_i$ ,  $i = 1, 2, 3, 4$ .
- Find the traffic flow when  $x_4 = 0$ .
- Find the traffic flow when  $x_4 = 100$ .
- Find the traffic flow when  $x_1 = 2x_2$ .

#### Solution

$$a) \begin{cases} x_1 + 100 = x_3 \\ x_2 + 200 = x_1 \\ x_2 + 100 = x_4 \\ x_4 + 200 = x_3 \end{cases}$$

$$\begin{cases} -x_1 + x_3 = 100 \\ x_1 - x_2 = 200 \\ -x_2 + x_4 = 100 \\ x_3 - x_4 = 200 \end{cases}$$

$$\left( \begin{array}{cccc|c} -1 & 0 & 1 & 0 & 100 \\ 1 & -1 & 0 & 0 & 200 \\ 0 & -1 & 0 & 1 & 100 \\ 0 & 0 & 1 & -1 & 200 \end{array} \right)$$

$R_2 + R_1$

$$\left( \begin{array}{cccc|c} -1 & 0 & 1 & 0 & 100 \\ 1 & -1 & 0 & 0 & 200 \\ 0 & -1 & 0 & 1 & 100 \\ 0 & 0 & 1 & -1 & 200 \end{array} \right) = -1 \left( \begin{array}{ccc|c} -1 & 0 & 0 & 100 \\ -1 & 0 & 1 & 100 \\ 0 & 1 & -1 & 200 \end{array} \right) -1 \left( \begin{array}{ccc|c} 0 & 1 & 0 & 100 \\ -1 & 0 & 1 & 100 \\ 0 & 1 & -1 & 200 \end{array} \right)$$

$$\begin{pmatrix} -1 & 0 & 1 & 0 & | & 100 \\ 0 & -1 & 1 & 0 & | & 300 \\ 0 & -1 & 0 & 1 & | & 100 \\ 0 & 0 & 1 & -1 & | & 200 \end{pmatrix} \quad R_3 - R_2$$

$$\begin{pmatrix} -1 & 0 & 1 & 0 & | & 100 \\ 0 & -1 & 1 & 0 & | & 300 \\ 0 & 0 & -1 & 1 & | & -200 \\ 0 & 0 & 1 & -1 & | & 200 \end{pmatrix} \quad R_4 + R_3$$

$$\begin{pmatrix} -1 & 0 & 1 & 0 & | & 100 \\ 0 & -1 & 1 & 0 & | & 300 \\ 0 & 0 & -1 & 1 & | & -200 \\ 0 & 0 & 0 & 0 & | & 0 \end{pmatrix} \quad \begin{array}{l} \rightarrow -x_1 + x_3 = 100 \\ \rightarrow -x_2 + x_3 = 100 \\ \rightarrow -x_3 + x_4 = 100 \end{array}$$

Let  $x_4$  be the free variable

$$\begin{cases} \underline{x_3 = x_4 + 200} \\ \underline{x_2 = x_4 - 100} \\ \underline{x_1 = 200 + x_2 = x_4 + 100} \end{cases}$$

**Solution:**  $(x_4 + 100, x_4 - 100, x_4 + 200, x_4)$

**OR**

$$\begin{vmatrix} -1 & 0 & 1 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & -1 & 0 & 1 \\ 0 & 0 & 1 & -1 \end{vmatrix} = -1 \begin{vmatrix} -1 & 0 & 0 \\ -1 & 0 & 1 \\ 0 & 1 & -1 \end{vmatrix} - 1 \begin{vmatrix} 0 & 1 & 0 \\ -1 & 0 & 1 \\ 0 & 1 & -1 \end{vmatrix}$$

$$= -1(1) - 1(-1)$$

$$= -1 + 1$$

$$= 0$$

$$\begin{cases} -x_1 + x_3 = 100 & \rightarrow x_1 = x_3 - 100 = \underline{x_4 + 100} \\ x_1 - x_2 = 200 \\ -x_2 + x_4 = 100 & \rightarrow \underline{x_2 = x_4 - 100} \\ x_3 - x_4 = 200 & \rightarrow \underline{x_3 = x_4 + 200} \end{cases}$$

b) The traffic flow when  $x_4 = 0$  is:

$\therefore (100, -100, 200, 0)$

c) The traffic flow when  $x_4 = 100$  is:

$$\therefore (200, 0, 300, 100)$$

d) The traffic flow when  $x_1 = 2x_2$ :

$$x_4 + 100 = 2(x_4 - 100)$$

$$x_4 + 100 = 2x_4 - 200$$

$$x_4 = 300$$

$$\therefore (400, 200, 500, 300)$$

### Exercise

Through a network, Express  $x_n$ 's in terms of the parameters  $s$  and  $t$ .

### Solution

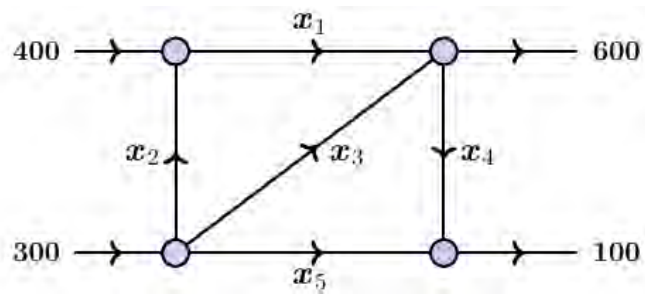
$$\begin{cases} x_1 = x_2 + 400 \\ x_1 + x_3 = x_4 + 600 \\ x_4 + x_5 = 100 \\ x_2 + x_3 + x_5 = 300 \end{cases}$$

$$\begin{cases} x_1 - x_2 = 400 \\ x_2 + x_3 - x_4 = 600 \\ x_4 + x_5 = 100 \\ x_2 + x_3 + x_5 = 300 \end{cases}$$

$$\left( \begin{array}{ccccc|c} 1 & -1 & 0 & 0 & 0 & 400 \\ 1 & 0 & 1 & -1 & 0 & 600 \\ 0 & 0 & 0 & 1 & 1 & 100 \\ 0 & 1 & 1 & 0 & 1 & 300 \end{array} \right) \quad \begin{array}{l} R_2 - R_1 \\ R_3 \leftrightarrow R_4 \end{array}$$

$$\left( \begin{array}{ccccc|c} 1 & -1 & 0 & 0 & 0 & 400 \\ 0 & 1 & 1 & -1 & 0 & 200 \\ 0 & 1 & 1 & 0 & 1 & 300 \\ 0 & 0 & 0 & 1 & 1 & 100 \end{array} \right) \quad R_3 - R_2$$

$$\left( \begin{array}{ccccc|c} 1 & -1 & 0 & 0 & 0 & 400 \\ 0 & 1 & 1 & -1 & 0 & 200 \\ 0 & 0 & 0 & 1 & 1 & 100 \\ 0 & 0 & 0 & 1 & 1 & 100 \end{array} \right) \quad R_4 - R_3$$



$$\left( \begin{array}{cccccc|c} 1 & -1 & 0 & 0 & 0 & 400 \\ 0 & 1 & 1 & -1 & 0 & 200 \\ 0 & 0 & 0 & 1 & 1 & 100 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{array} \right) \quad \begin{array}{l} x_1 - x_2 = 400 \quad \rightarrow x_1 = 400 + x_2 \\ x_2 + x_3 - x_4 = 200 \quad \rightarrow x_2 = 200 - x_3 + x_4 \\ x_4 + x_5 = 100 \quad \rightarrow \underline{x_4 = 100 - t} \end{array}$$

Let  $x_5 = t$  &  $x_3 = s$

$$x_2 = 200 - s + 100 - t = \underline{300 - s - t}$$

$$x_1 = 400 + 300 - s - t = \underline{700 - s - t}$$

### Exercise

Water is flowing through a network of pipes. Express  $x_n$ 's in terms of the parameters  $s$  and  $t$ .

### Solution

$$x_1 + x_3 = 900$$

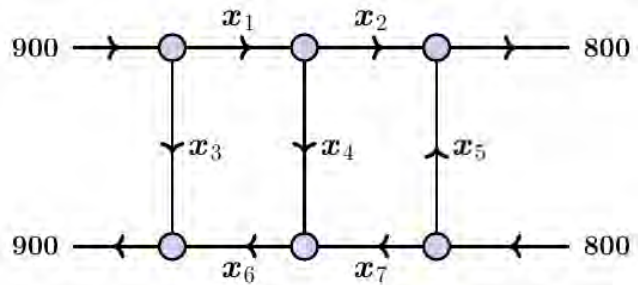
$$x_1 = x_2 + x_4 \quad \rightarrow \quad x_1 - x_2 - x_4 = 0$$

$$x_2 + x_5 = 800$$

$$x_5 + x_7 = 800$$

$$x_6 = x_4 + x_7 \quad \rightarrow \quad x_4 - x_6 + x_7 = 0$$

$$x_3 + x_6 = 900$$



$$\left[ \begin{array}{cccccc|c} 1 & 0 & 1 & 0 & 0 & 0 & 900 \\ 1 & -1 & 0 & -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 800 \\ 0 & 0 & 0 & 0 & 1 & 0 & 800 \\ 0 & 0 & 0 & 1 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 900 \end{array} \right] \quad \begin{array}{l} \\ R_2 - R_1 \\ \\ \\ \end{array}$$

$$\left[ \begin{array}{cccccc|c} 1 & 0 & 1 & 0 & 0 & 0 & 900 \\ 0 & -1 & -1 & -1 & 0 & 0 & -900 \\ 0 & 1 & 0 & 0 & 1 & 0 & 800 \\ 0 & 0 & 0 & 0 & 1 & 0 & 800 \\ 0 & 0 & 0 & 1 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 900 \end{array} \right] \quad \begin{array}{l} \\ R_3 + R_2 \\ R_6 \\ R_4 \end{array}$$

$$\left[ \begin{array}{cccccc|c} 1 & 0 & 1 & 0 & 0 & 0 & 900 \\ 0 & -1 & -1 & -1 & 0 & 0 & -900 \\ 0 & 0 & -1 & -1 & 1 & 0 & -100 \\ 0 & 0 & 1 & 0 & 0 & 1 & 900 \\ 0 & 0 & 0 & 1 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 800 \end{array} \right] \quad \begin{array}{l} -R_2 \\ R_4 + R_3 \end{array}$$

$$\left[ \begin{array}{cccccc|c} 1 & 0 & 1 & 0 & 0 & 0 & 900 \\ 0 & 1 & 1 & 1 & 0 & 0 & 900 \\ 0 & 0 & -1 & -1 & 1 & 0 & -100 \\ 0 & 0 & 0 & -1 & 1 & 1 & 800 \\ 0 & 0 & 0 & 1 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 800 \end{array} \right] \quad R_5 + R_4$$

$$\left[ \begin{array}{cccccc|c} 1 & 0 & 1 & 0 & 0 & 0 & 900 \\ 0 & 1 & 1 & 1 & 0 & 0 & 900 \\ 0 & 0 & -1 & -1 & 1 & 0 & -100 \\ 0 & 0 & 0 & -1 & 1 & 1 & 800 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 800 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 800 \end{array} \right] \quad R_6 - R_5$$

$$\left[ \begin{array}{cccccc|c} 1 & 0 & 1 & 0 & 0 & 0 & 900 \\ 0 & 1 & 1 & 1 & 0 & 0 & 900 \\ 0 & 0 & -1 & -1 & 1 & 0 & -100 \\ 0 & 0 & 0 & -1 & 1 & 1 & 800 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 800 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array} \right] \quad \begin{array}{l} x_2 = 900 - x_3 \quad (5) \\ x_2 = 900 - x_3 - x_4 \quad (4) \\ x_3 = 100 - x_4 + x_5 \quad (3) \\ -x_4 = 800 - x_5 - x_6 \quad (2) \\ x_5 = 800 - x_7 \quad (1) \end{array}$$

Let  $x_6 = s$  &  $x_7 = t$

$$(1) \rightarrow x_5 = 800 - t$$

$$(2) \rightarrow x_4 = s - t$$

$$(3) \rightarrow x_3 = 900 - s$$

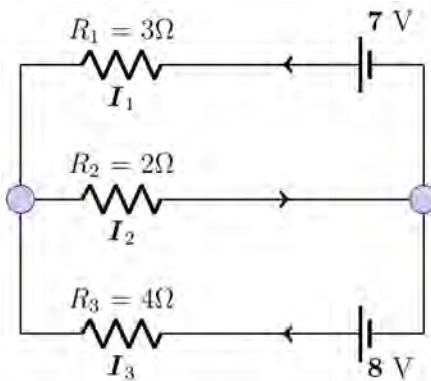
$$(2) \rightarrow x_2 = t$$

$$(1) \rightarrow x_2 = s$$

**Solution:**  $\underline{(s, t, 900-s, s-t, 800-t, s, t)}$

### Exercise

Determine the currents  $I_1$ ,  $I_2$ , and  $I_3$  for the electrical network shown below



### Solution

$$I_2 = I_1 + I_3$$

$$3I_1 + 2I_2 = 7$$

$$2I_2 + 4I_3 = 8$$

$$\begin{cases} I_1 - I_2 + I_3 = 0 \\ 3I_1 + 2I_2 = 7 \\ I_2 + 2I_3 = 4 \end{cases}$$

$$D = \begin{vmatrix} 1 & -1 & 1 \\ 3 & 2 & 0 \\ 0 & 1 & 2 \end{vmatrix} = 13 \quad D_1 = \begin{vmatrix} 0 & -1 & 1 \\ 7 & 2 & 0 \\ 4 & 1 & 2 \end{vmatrix} = 13 \quad D_2 = \begin{vmatrix} 1 & 0 & 1 \\ 3 & 7 & 0 \\ 0 & 4 & 2 \end{vmatrix} = 26 \quad D_3 = \begin{vmatrix} 1 & -1 & 0 \\ 3 & 2 & 7 \\ 0 & 1 & 4 \end{vmatrix} = 13$$

$$\underline{I_1 = 1 \text{ A}} \quad \underline{I_2 = 2 \text{ A}} \quad \underline{I_3 = 1 \text{ A}}$$

**OR**

$$\left( \begin{array}{ccc|c} 1 & -1 & 1 & 0 \\ 3 & 2 & 0 & 7 \\ 0 & 1 & 2 & 4 \end{array} \right) \quad R_2 - 3R_1$$

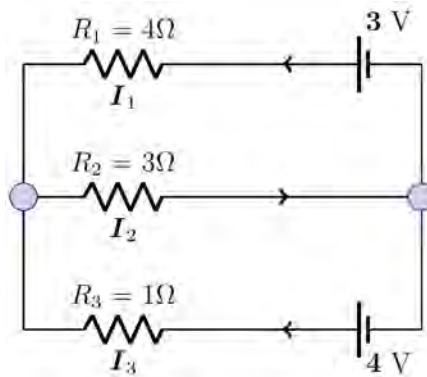
$$\left( \begin{array}{ccc|c} 1 & -1 & 1 & 0 \\ 0 & 5 & -3 & 7 \\ 0 & 1 & 2 & 4 \end{array} \right) \quad -5R_3 + R_2$$

$$\left( \begin{array}{ccc|c} 1 & -1 & 1 & 0 \\ 0 & 5 & -3 & 7 \\ 0 & 0 & -13 & -13 \end{array} \right) \quad \begin{array}{l} I_1 = I_2 - I_3 \\ 5I_2 = 3I_3 + 7 \\ \underline{I_3 = 1} \end{array}$$

$$\underline{I_2 = 2} \quad \underline{I_1 = 1}$$

### Exercise

Determine the currents  $I_1$ ,  $I_2$ , and  $I_3$  for the electrical network shown below



### Solution

$$I_2 = I_1 + I_3$$

$$4I_1 + 3I_2 = 3$$

$$3I_2 + I_3 = 4$$

$$\begin{cases} I_1 - I_2 + I_3 = 0 \\ 4I_1 + 3I_2 = 3 \\ 3I_2 + I_3 = 4 \end{cases}$$

$$D = \begin{vmatrix} 1 & -1 & 1 \\ 4 & 3 & 0 \\ 0 & 3 & 1 \end{vmatrix} = 19$$

$$D_1 = \begin{vmatrix} 0 & -1 & 1 \\ 3 & 3 & 0 \\ 4 & 3 & 1 \end{vmatrix} = 0$$

$$D_2 = \begin{vmatrix} 1 & 0 & 1 \\ 4 & 3 & 0 \\ 0 & 4 & 1 \end{vmatrix} = 19$$

$$D_3 = \begin{vmatrix} 1 & -1 & 0 \\ 4 & 3 & 3 \\ 0 & 3 & 4 \end{vmatrix} = 19$$

$$\underline{I_1 = 0 \text{ A}} \quad \underline{I_2 = 1 \text{ A}} \quad \underline{I_3 = 1 \text{ A}}$$

**OR**

$$\left( \begin{array}{ccc|c} 1 & -1 & 1 & 0 \\ 4 & 3 & 0 & 3 \\ 0 & 3 & 1 & 4 \end{array} \right) \quad R_2 - 4R_1$$

$$\left( \begin{array}{ccc|c} 1 & -1 & 1 & 0 \\ 0 & 7 & -4 & 3 \\ 0 & 3 & 1 & 4 \end{array} \right) \quad 7R_3 - 3R_2$$

$$\left( \begin{array}{ccc|c} 1 & -1 & 1 & 0 \\ 0 & 7 & -4 & 3 \\ 0 & 0 & 19 & 19 \end{array} \right) \quad \begin{array}{l} \rightarrow I_1 = I_2 - I_3 \quad (2) \\ \rightarrow 7I_2 = 4I_3 + 3 \quad (1) \end{array}$$

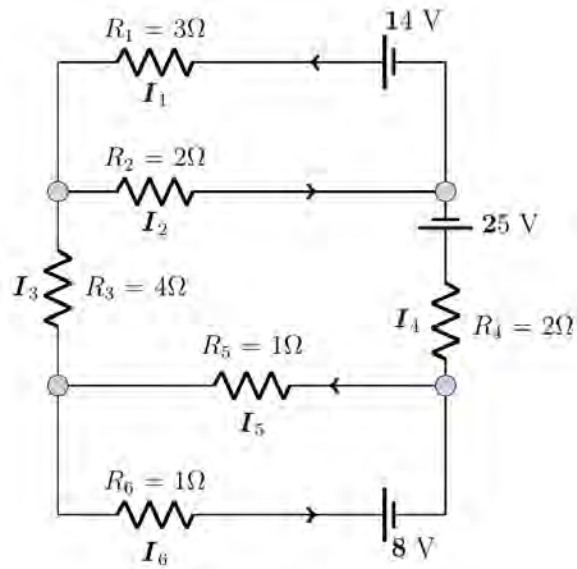
$$\underline{I_3 = 1}$$

$$\underline{I_2 = 1} \quad \underline{I_1 = 0}$$



### Exercise

Determine the currents  $I_1$ ,  $I_2$ ,  $I_3$ ,  $I_4$ ,  $I_5$ , and  $I_6$  for the electrical network shown below



### Solution

$$I_1 + I_3 = I_2 \rightarrow I_1 - I_2 + I_3 = 0$$

$$I_1 + I_4 = I_2 \rightarrow I_1 - I_2 + I_4 = 0$$

$$I_3 + I_6 = I_5 \rightarrow I_3 - I_5 + I_6 = 0$$

$$\begin{cases} 3I_1 + 2I_2 = 14 \\ 2I_2 + 4I_3 + I_5 + 2I_4 = 25 \\ I_5 + I_6 = 8 \end{cases}$$

$$\left[ \begin{array}{cccccc|c} 1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1 & 1 & 0 \\ 3 & 2 & 0 & 0 & 0 & 0 & 14 \\ 0 & 2 & 4 & 2 & 1 & 0 & 25 \\ 0 & 0 & 0 & 0 & 1 & 1 & 8 \end{array} \right] \quad \begin{array}{l} R_2 - R_1 \\ R_4 - 3R_1 \end{array}$$

$$\left[ \begin{array}{cccccc|c} 1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1 & 1 & 0 \\ 0 & 5 & -3 & 0 & 0 & 0 & 14 \\ 0 & 2 & 4 & 2 & 1 & 0 & 25 \\ 0 & 0 & 0 & 0 & 1 & 1 & 8 \end{array} \right] \quad \begin{array}{l} R_4 \\ R_2 \\ R_3 \end{array}$$

$$\left[ \begin{array}{cccccc|c} 1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 5 & -3 & 0 & 0 & 0 & 14 \\ 0 & 2 & 4 & 2 & 1 & 0 & 25 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 8 \end{array} \right] \quad \begin{array}{l} 5R_3 - 2R_2 \\ \\ R_5 + R_4 \end{array}$$

$$\left[ \begin{array}{cccccc|c} 1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 5 & -3 & 0 & 0 & 0 & 14 \\ 0 & 0 & 26 & 10 & 5 & 0 & 97 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 8 \end{array} \right] \quad 26R_4 + R_3$$

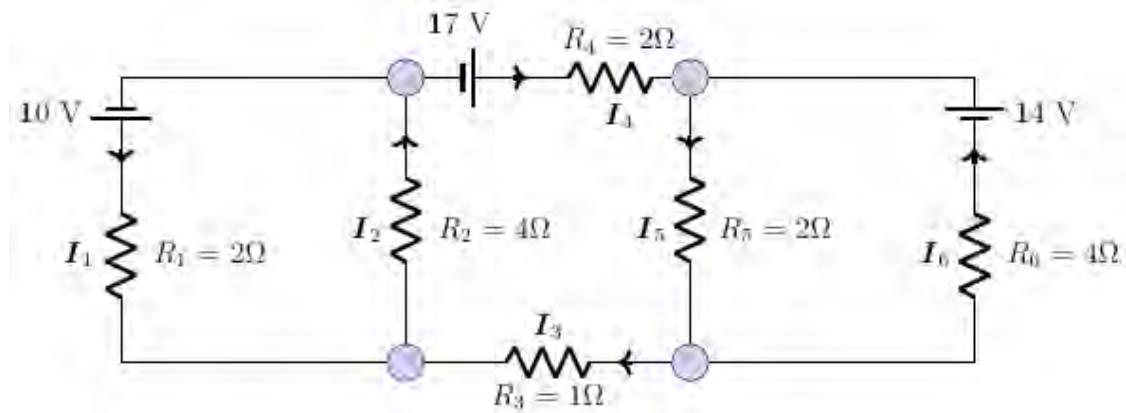
$$\left[ \begin{array}{cccccc|c} 1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 5 & -3 & 0 & 0 & 0 & 14 \\ 0 & 0 & 26 & 10 & 5 & 0 & 97 \\ 0 & 0 & 0 & 36 & 5 & 0 & 97 \\ 0 & 0 & 0 & 1 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 8 \end{array} \right] \quad 36R_5 - R_4$$

$$\left[ \begin{array}{cccccc|c} 1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 5 & -3 & 0 & 0 & 0 & 14 \\ 0 & 0 & 26 & 10 & 5 & 0 & 97 \\ 0 & 0 & 0 & 36 & 5 & 0 & 97 \\ 0 & 0 & 0 & 0 & -41 & 36 & -97 \\ 0 & 0 & 0 & 0 & 1 & 1 & 8 \end{array} \right] \quad 41R_6 + R_5$$

$$\left[ \begin{array}{cccccc|c} 1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 5 & -3 & 0 & 0 & 0 & 14 \\ 0 & 0 & 26 & 10 & 5 & 0 & 97 \\ 0 & 0 & 0 & 36 & 5 & 0 & 97 \\ 0 & 0 & 0 & 0 & -41 & 36 & -97 \\ 0 & 0 & 0 & 0 & 0 & 77 & 231 \end{array} \right] \quad \begin{array}{ll} I_1 = 4 - 2 & \rightarrow \underline{I_1 = 2} \\ 5I_2 = 14 + 3(2) & \rightarrow \underline{I_2 = 4} \\ 26I_3 = 97 - 10(2) - 5(5) & \rightarrow \underline{I_3 = 2} \\ 36I_4 = 97 - 5(5) & \rightarrow \underline{I_4 = 2} \\ -41I_5 = -97 - 36(3) & \rightarrow \underline{I_5 = 5} \\ 77I_6 = 231 & \rightarrow \underline{I_6 = 3} \end{array}$$

### Exercise

Determine the currents  $I_1$ ,  $I_2$ ,  $I_3$ ,  $I_4$ ,  $I_5$ , and  $I_6$  for the electrical network shown below



### Solution

$$1 \rightarrow I_1 + I_3 = I_2$$

$$2 \rightarrow I_1 + I_4 = I_2$$

$$3 \rightarrow I_3 + I_6 = I_5$$

$$4 \rightarrow I_4 + I_6 = I_5$$

$$\left\{ \begin{array}{l} I_1 - I_2 + I_3 = 0 \\ I_1 - I_2 + I_4 = 0 \\ I_3 - I_5 + I_6 = 0 \\ I_4 - I_5 + I_6 = 0 \\ 2I_1 + 4I_2 = 10 \\ 4I_2 + I_3 + 2I_4 + 2I_5 = 17 \\ 2I_5 + 4I_6 = 14 \end{array} \right.$$

$$\left( \begin{array}{cccccc|c} 1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 1 & -1 & 1 & 0 \\ 1 & 2 & 0 & 0 & 0 & 0 & 5 \\ 0 & 4 & 1 & 2 & 2 & 0 & 17 \\ 0 & 0 & 0 & 0 & 1 & 2 & 7 \end{array} \right) \quad \begin{array}{l} R_2 - R_1 \\ \\ \\ R_5 - R_1 \end{array}$$

$$\begin{pmatrix} 1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 1 & -1 & 1 & 0 \\ 0 & 3 & -1 & 0 & 0 & 0 & 5 \\ 0 & 4 & 1 & 2 & 2 & 0 & 17 \\ 0 & 0 & 0 & 0 & 1 & 2 & 7 \end{pmatrix} \begin{array}{l} R_3 + R_2 \\ \\ \\ 3R_6 - 4R_5 \end{array}$$

$$\begin{pmatrix} 1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 1 & 0 \\ 0 & 0 & 0 & 1 & -1 & 1 & 0 \\ 0 & 3 & -1 & 0 & 0 & 0 & 5 \\ 0 & 0 & 7 & 6 & 6 & 0 & 31 \\ 0 & 0 & 0 & 0 & 1 & 2 & 7 \end{pmatrix} R_4 - R_3$$

$$\begin{pmatrix} 1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3 & -1 & 0 & 0 & 0 & 5 \\ 0 & 0 & 7 & 6 & 6 & 0 & 31 \\ 0 & 0 & 0 & 0 & 1 & 2 & 7 \end{pmatrix} R_6 + 7R_2$$

$$\begin{pmatrix} 1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 3 & -1 & 0 & 0 & 0 & 5 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 1 & 0 \\ 0 & 0 & 0 & 13 & 6 & 0 & 31 \\ 0 & 0 & 0 & 0 & 1 & 2 & 7 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} R_5 - 13R_4$$

$$\begin{pmatrix} 1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 3 & -1 & 0 & 0 & 0 & 5 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 19 & -13 & 31 \\ 0 & 0 & 0 & 0 & 1 & 2 & 7 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} 19R_6 - R_5$$

$$\left( \begin{array}{cccccc|c} 1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 3 & -1 & 0 & 0 & 0 & 5 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 19 & -13 & 31 \\ 0 & 0 & 0 & 0 & 0 & 51 & 102 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array} \right) \begin{array}{l} (4) \\ (3) \\ (2) \\ (1) \\ I_5 = \frac{1}{19}(31 + 13I_6) \\ \underline{I_6 = 2} \end{array}$$

$$\underline{I_5 = 3}$$

$$(1) \rightarrow \underline{I_4 = I_5 - I_6 = 1}$$

$$(2) \rightarrow \underline{I_3 = I_4 = 1}$$

$$(3) \rightarrow \underline{I_2 = \frac{1}{3}(I_3 + 5) = 2}$$

$$(4) \rightarrow \underline{I_1 = I_2 - I_3 = 1}$$

### Exercise

Consider the invertible matrix:  $A = \begin{pmatrix} 1 & 2 & 2 \\ 3 & 7 & 9 \\ -3 & -2 & 7 \end{pmatrix}$

The message: **ICEBERG DEAD AHEAD**

- Write the uncoded row matrices  $1 \times 3$  for the message.
- Use the matrix  $A$  to encode the message.
- Decode a message from part  $b)$  given the matrix  $A$ .

### Solution

$a)$

0 = _	4 = D	8 = H	12 = L	16 = P	20 = T	24 = X
1 = A	5 = E	9 = I	13 = M	17 = Q	21 = U	25 = Y
2 = B	6 = F	10 = J	14 = N	18 = R	22 = V	26 = Z
3 = C	7 = G	11 = K	15 = O	19 = S	23 = W	

$$\begin{array}{cccccc} I & C & E & B & E & R & G & _ & D & E & A & D & _ & A & H & E & A & D \\ [9 & 3 & 5] & [2 & 5 & 18] & [7 & 0 & 4] & [5 & 1 & 4] & [0 & 1 & 8] & [5 & 1 & 4] \end{array}$$

- Let encode the message **ICEBERG DEAD AHEAD**

$$\begin{bmatrix} 9 & 3 & 5 \end{bmatrix} \begin{bmatrix} 1 & 2 & 2 \\ 3 & 7 & 9 \\ -3 & -2 & 7 \end{bmatrix} = \begin{bmatrix} 3 & 29 & 80 \end{bmatrix}$$

$$\begin{bmatrix} 2 & 5 & 18 \end{bmatrix} \begin{bmatrix} 1 & 2 & 2 \\ 3 & 7 & 9 \\ -3 & -2 & 7 \end{bmatrix} = \begin{bmatrix} -37 & 3 & 175 \end{bmatrix}$$

$$\begin{bmatrix} 7 & 0 & 4 \end{bmatrix} \begin{bmatrix} 1 & 2 & 2 \\ 3 & 7 & 9 \\ -3 & -2 & 7 \end{bmatrix} = \begin{bmatrix} -5 & 6 & 42 \end{bmatrix}$$

$$\begin{bmatrix} 5 & 1 & 4 \end{bmatrix} \begin{bmatrix} 1 & 2 & 2 \\ 3 & 7 & 9 \\ -3 & -2 & 7 \end{bmatrix} = \begin{bmatrix} -4 & 9 & 47 \end{bmatrix}$$

$$\begin{bmatrix} 0 & 1 & 8 \end{bmatrix} \begin{bmatrix} 1 & 2 & 2 \\ 3 & 7 & 9 \\ -3 & -2 & 7 \end{bmatrix} = \begin{bmatrix} -21 & -5 & 65 \end{bmatrix}$$

$$\begin{bmatrix} 5 & 1 & 4 \end{bmatrix} \begin{bmatrix} 1 & 2 & 2 \\ 3 & 7 & 9 \\ -3 & -2 & 7 \end{bmatrix} = \begin{bmatrix} -4 & 9 & 47 \end{bmatrix}$$

The sequence of coded row matrices is

$$\begin{bmatrix} 3 & 29 & 80 \end{bmatrix} \begin{bmatrix} -37 & 3 & 175 \end{bmatrix} \begin{bmatrix} -5 & 6 & 42 \end{bmatrix} \begin{bmatrix} -4 & 9 & 47 \end{bmatrix} \begin{bmatrix} -21 & -5 & 65 \end{bmatrix} \begin{bmatrix} -4 & 9 & 47 \end{bmatrix}$$

The cryptogram:

$$3 \ 29 \ 80 \ -37 \ 3 \ 175 \ -5 \ 6 \ 42 \ -4 \ 9 \ 47 \ -21 \ -5 \ 65 \ -4 \ 9 \ 47$$

c) To decode a message given the matrix  $A$ .

$$|A| = \begin{vmatrix} 1 & 2 & 2 \\ 3 & 7 & 9 \\ -3 & -2 & 7 \end{vmatrix} = 1$$

$$A^{-1} = \begin{bmatrix} 67 & -18 & 4 \\ -48 & 13 & -3 \\ 15 & -4 & 1 \end{bmatrix}$$

With the cryptogram:

$$\begin{bmatrix} 3 & 29 & 80 \end{bmatrix} \begin{bmatrix} -37 & 3 & 175 \end{bmatrix} \begin{bmatrix} -5 & 6 & 42 \end{bmatrix} \begin{bmatrix} -4 & 9 & 47 \end{bmatrix} \begin{bmatrix} -21 & -5 & 65 \end{bmatrix} \begin{bmatrix} -4 & 9 & 47 \end{bmatrix}$$

$$\begin{bmatrix} 3 & 29 & 80 \end{bmatrix} \begin{bmatrix} 67 & -18 & 4 \\ -48 & 13 & -3 \\ 15 & -4 & 1 \end{bmatrix} = \begin{bmatrix} 9 & 3 & 5 \end{bmatrix}$$

$$\begin{bmatrix} -37 & 3 & 175 \end{bmatrix} \begin{bmatrix} 67 & -18 & 4 \\ -48 & 13 & -3 \\ 15 & -4 & 1 \end{bmatrix} = \begin{bmatrix} 2 & 5 & 18 \end{bmatrix}$$

$$\begin{bmatrix} -5 & 6 & 42 \end{bmatrix} \begin{bmatrix} 67 & -18 & 4 \\ -48 & 13 & -3 \\ 15 & -4 & 1 \end{bmatrix} = \begin{bmatrix} 7 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} -4 & 9 & 47 \end{bmatrix} \begin{bmatrix} 67 & -18 & 4 \\ -48 & 13 & -3 \\ 15 & -4 & 1 \end{bmatrix} = \begin{bmatrix} 5 & 1 & 4 \end{bmatrix}$$

$$\begin{bmatrix} -21 & -9 & 65 \end{bmatrix} \begin{bmatrix} 67 & -18 & 4 \\ -48 & 13 & -3 \\ 15 & -4 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 8 \end{bmatrix}$$

$$\begin{bmatrix} -4 & 9 & 47 \end{bmatrix} \begin{bmatrix} 67 & -18 & 4 \\ -48 & 13 & -3 \\ 15 & -4 & 1 \end{bmatrix} = \begin{bmatrix} 5 & 1 & 4 \end{bmatrix}$$

The message is:

9 3 5 2 5 18 7 0 1 5 1 4 0 1 8 5 1 4  
*I C E B E R G \_ D E A D \_ A H E A D*

### Exercise

You want to send the message: **LINEAR ALGEBRA** with a key word **MATH**

- Write the matrix  $A$ .
- Write the uncoded row matrices  $1 \times 2$  for the message.
- Use the matrix  $A$  to encode the message.
- Decode a message from part  $b$ ) given the matrix  $A$ .

### Solution

$a)$

$0 = \_$	$4 = D$	$8 = H$	$12 = L$	$16 = P$	$20 = T$	$24 = X$
$1 = A$	$5 = E$	$9 = I$	$13 = M$	$17 = Q$	$21 = U$	$25 = Y$
$2 = B$	$6 = F$	$10 = J$	$14 = N$	$18 = R$	$22 = V$	$26 = Z$
$3 = C$	$7 = G$	$11 = K$	$15 = O$	$19 = S$	$23 = W$	

*M A T H*

13 1 20 8

$$A = \begin{pmatrix} 13 & 1 \\ 20 & 8 \end{pmatrix}$$

**b)**

*L I N E A R \_ A L G E B R A*

12 9 14 5 1 18 0 1 12 7 5 2 18 1

[12 9] [14 5] [1 18] [0 1] [12 7] [5 2] [18 1]

**c)** Encoding the message

$$[12 \ 9] \begin{bmatrix} 13 & 1 \\ 20 & 8 \end{bmatrix} = [336 \ 84]$$

$$[14 \ 5] \begin{bmatrix} 13 & 1 \\ 20 & 8 \end{bmatrix} = [282 \ 54]$$

$$[1 \ 18] \begin{bmatrix} 13 & 1 \\ 20 & 8 \end{bmatrix} = [373 \ 145]$$

$$[0 \ 1] \begin{bmatrix} 13 & 1 \\ 20 & 8 \end{bmatrix} = [20 \ 8]$$

$$[12 \ 7] \begin{bmatrix} 13 & 1 \\ 20 & 8 \end{bmatrix} = [296 \ 68]$$

$$[5 \ 2] \begin{bmatrix} 13 & 1 \\ 20 & 8 \end{bmatrix} = [105 \ 21]$$

$$[18 \ 1] \begin{bmatrix} 13 & 1 \\ 20 & 8 \end{bmatrix} = [254 \ 26]$$

The cryptogram:

336 84 282 54 373 145 20 8 296 68 105 21 254 26

**d)** To decode a message given the matrix A.

$$A = \begin{pmatrix} 13 & 1 \\ 20 & 8 \end{pmatrix}$$

$$A^{-1} = \frac{1}{84} \begin{pmatrix} 8 & -1 \\ -20 & 13 \end{pmatrix}$$



$$= \begin{pmatrix} \frac{2}{21} & -\frac{1}{84} \\ -\frac{5}{21} & \frac{13}{84} \end{pmatrix}$$

With the cryptogram:

$$\begin{bmatrix} 336 & 84 \end{bmatrix} \begin{bmatrix} 282 & 54 \end{bmatrix} \begin{bmatrix} 373 & 145 \end{bmatrix} \begin{bmatrix} 20 & 8 \end{bmatrix} \begin{bmatrix} 296 & 68 \end{bmatrix} \begin{bmatrix} 105 & 21 \end{bmatrix} \begin{bmatrix} 254 & 26 \end{bmatrix}$$

$$\begin{bmatrix} 336 & 84 \end{bmatrix} \begin{bmatrix} \frac{2}{21} & -\frac{1}{84} \\ -\frac{5}{21} & \frac{13}{84} \end{bmatrix} = \begin{bmatrix} 12 & 9 \end{bmatrix}$$

$$\begin{bmatrix} 282 & 54 \end{bmatrix} \begin{bmatrix} \frac{2}{21} & -\frac{1}{84} \\ -\frac{5}{21} & \frac{13}{84} \end{bmatrix} = \begin{bmatrix} 14 & 5 \end{bmatrix}$$

$$\begin{bmatrix} 373 & 145 \end{bmatrix} \begin{bmatrix} \frac{2}{21} & -\frac{1}{84} \\ -\frac{5}{21} & \frac{13}{84} \end{bmatrix} = \begin{bmatrix} 1 & 18 \end{bmatrix}$$

$$\begin{bmatrix} 20 & 8 \end{bmatrix} \begin{bmatrix} \frac{2}{21} & -\frac{1}{84} \\ -\frac{5}{21} & \frac{13}{84} \end{bmatrix} = \begin{bmatrix} 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 296 & 68 \end{bmatrix} \begin{bmatrix} \frac{2}{21} & -\frac{1}{84} \\ -\frac{5}{21} & \frac{13}{84} \end{bmatrix} = \begin{bmatrix} 12 & 7 \end{bmatrix}$$

$$\begin{bmatrix} 105 & 21 \end{bmatrix} \begin{bmatrix} \frac{2}{21} & -\frac{1}{84} \\ -\frac{5}{21} & \frac{13}{84} \end{bmatrix} = \begin{bmatrix} 5 & 2 \end{bmatrix}$$

$$\begin{bmatrix} 254 & 26 \end{bmatrix} \begin{bmatrix} \frac{2}{21} & -\frac{1}{84} \\ -\frac{5}{21} & \frac{13}{84} \end{bmatrix} = \begin{bmatrix} 18 & 1 \end{bmatrix}$$

12 9 14 5 1 18 0 1 12 7 5 2 18 1  
*L I N E A R \_ A L G E B R A*

The message is: *Linear Algebra*

## Exercise

You want to send the message: **CRYPTOGRAPHY IS A METHOD OF PROTECTING INFORMATION** with a key word **CODE**

- Write the matrix  $A$ .
- Write the uncoded row matrices  $1 \times 2$  for the message.
- Use the matrix  $A$  to encode the message.
- Decode a message from part  $b$ ) given the matrix  $A$ .

## Solution

a)

0 = _	4 = D	8 = H	12 = L	16 = P	20 = T	24 = X
1 = A	5 = E	9 = I	13 = M	17 = Q	21 = U	25 = Y
2 = B	6 = F	10 = J	14 = N	18 = R	22 = V	26 = Z
3 = C	7 = G	11 = K	15 = O	19 = S	23 = W	

C O D E

3 15 4 5

$$A = \begin{pmatrix} 3 & 15 \\ 4 & 5 \end{pmatrix}$$

b)

C R Y P T O G R A P H Y \_ I S \_ A \_  
3 18 25 16 20 15 7 18 1 16 8 25 0 9 19 0 1 0

M E T H O D \_ O F \_ P R O T E C T I N G  
13 5 20 8 15 4 0 15 6 0 16 18 15 20 5 3 20 9 14 7

\_ I N F O R M A T I O N S \_  
0 9 14 6 15 18 13 1 20 9 15 14 19 0

[3 18] [25 16] [20 15] [7 18] [1 16] [8 25] [0 9] [19 0]

[1 0] [13 5] [20 8] [15 4] [0 15] [6 0] [16 18] [15 20]

[5 3] [20 9] [14 7] [0 9] [14 6] [15 18] [13 1] [20 9]

[15 14] [19 0]

c) Encoding the message

$$\begin{bmatrix} 3 & 18 \\ 4 & 5 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 81 & 135 \end{bmatrix}$$

$$\begin{bmatrix} 25 & 16 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 139 & 455 \end{bmatrix}$$

$$\begin{bmatrix} 20 & 15 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 120 & 375 \end{bmatrix}$$

$$\begin{bmatrix} 7 & 18 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 93 & 195 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 16 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 67 & 95 \end{bmatrix}$$

$$\begin{bmatrix} 8 & 25 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 124 & 245 \end{bmatrix}$$

$$\begin{bmatrix} 0 & 9 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 36 & 45 \end{bmatrix}$$

$$\begin{bmatrix} 19 & 0 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 57 & 285 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 3 & 15 \end{bmatrix}$$

$$\begin{bmatrix} 13 & 5 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 59 & 220 \end{bmatrix}$$

$$\begin{bmatrix} 20 & 8 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 92 & 340 \end{bmatrix}$$

$$\begin{bmatrix} 15 & 4 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 61 & 245 \end{bmatrix}$$

$$\begin{bmatrix} 0 & 15 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 60 & 75 \end{bmatrix}$$

$$\begin{bmatrix} 6 & 0 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 18 & 90 \end{bmatrix}$$

$$\begin{bmatrix} 16 & 18 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 120 & 330 \end{bmatrix}$$

$$\begin{bmatrix} 15 & 20 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 125 & 325 \end{bmatrix}$$

$$\begin{bmatrix} 5 & 3 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 27 & 90 \end{bmatrix}$$

$$\begin{bmatrix} 20 & 9 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 96 & 345 \end{bmatrix}$$

$$\begin{bmatrix} 14 & 7 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 70 & 245 \end{bmatrix}$$

$$\begin{bmatrix} 0 & 9 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 36 & 45 \end{bmatrix}$$

$$\begin{bmatrix} 14 & 6 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 66 & 240 \end{bmatrix}$$

$$\begin{bmatrix} 15 & 18 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 117 & 315 \end{bmatrix}$$

$$\begin{bmatrix} 13 & 1 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 43 & 200 \end{bmatrix}$$

$$\begin{bmatrix} 20 & 9 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 96 & 345 \end{bmatrix}$$

$$\begin{bmatrix} 15 & 14 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 101 & 295 \end{bmatrix}$$

$$\begin{bmatrix} 19 & 0 \end{bmatrix} \begin{bmatrix} 3 & 15 \\ 4 & 5 \end{bmatrix} = \begin{bmatrix} 57 & 285 \end{bmatrix}$$

The cryptogram:

81 135 139 455 120 375 93 195 67 95 124 245 36 45 57 285  
 3 15 59 220 92 340 61 245 60 75 18 90 120 330 125 325  
 27 90 96 345 70 245 36 45 66 240 117 315 43 200 96 345  
 101 295 57 285

**d)** To decode a message given the matrix A.

$$A = \begin{pmatrix} 3 & 15 \\ 4 & 5 \end{pmatrix}$$

$$A^{-1} = -\frac{1}{45} \begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix}$$

$$-\frac{1}{45} \begin{bmatrix} 81 & 135 \end{bmatrix} \begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45} \begin{bmatrix} -135 & -810 \end{bmatrix} \\ = \begin{bmatrix} 3 & 18 \end{bmatrix}$$

$$-\frac{1}{45}[139 \ 455]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-1,125 \ -720] \\ = [25 \ 16]$$

$$-\frac{1}{45}[120 \ 375]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-900 \ -675] \\ = [20 \ 15]$$

$$-\frac{1}{45}[93 \ 195]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-315 \ -810] \\ = [7 \ 18]$$

$$-\frac{1}{45}[67 \ 95]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-45 \ -720] \\ = [1 \ 16]$$

$$-\frac{1}{45}[124 \ 245]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-360 \ -1,125] \\ = [8 \ 25]$$

$$-\frac{1}{45}[36 \ 45]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[0 \ -405] \\ = [0 \ 9]$$

$$-\frac{1}{45}[57 \ 285]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-855 \ 0] \\ = [19 \ 0]$$

$$-\frac{1}{45}[3 \ 15]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-45 \ 0] \\ = [1 \ 0]$$

$$-\frac{1}{45}[59 \ 220]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-585 \ -225] \\ = [13 \ 5]$$

$$-\frac{1}{45}[92 \ 340]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-900 \ -360] \\ = [20 \ 8]$$

$$-\frac{1}{45}[61 \ 245]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-675 \ -180] \\ = [15 \ 4]$$

$$-\frac{1}{45}[60 \ 75]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[0 \ -675] \\ = [0 \ 15]$$

$$-\frac{1}{45}[18 \ 90]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-270 \ 0] \\ = [6 \ 0]$$

$$-\frac{1}{45}[120 \ 330]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-720 \ -810] \\ = [16 \ 18]$$

$$-\frac{1}{45}[125 \ 325]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-675 \ -900] \\ = [15 \ 20]$$

$$-\frac{1}{45}[27 \ 90]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-225 \ -135] \\ = [5 \ 3]$$

$$-\frac{1}{45}[96 \ 345]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-900 \ -405] \\ = [20 \ 9]$$

$$-\frac{1}{45}[70 \ 245]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-630 \ -315] \\ = [14 \ 7]$$

$$-\frac{1}{45}[36 \ 45]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[0 \ -405] \\ = [0 \ 9]$$

$$-\frac{1}{45}[66 \ 240]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-630 \ -270] \\ = [14 \ 6]$$

$$-\frac{1}{45}[117 \ 315]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-675 \ -810] \\ = [15 \ 18]$$

$$-\frac{1}{45}[43 \ 200]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-585 \ -45]$$

$$=[13 \ 1]$$

$$-\frac{1}{45}[96 \ 345]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-900 \ -405]$$

$$=[20 \ 9]$$

$$-\frac{1}{45}[101 \ 295]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-675 \ -630]$$

$$=[15 \ 14]$$

$$-\frac{1}{45}[57 \ 285]\begin{pmatrix} 5 & -15 \\ -4 & 3 \end{pmatrix} = -\frac{1}{45}[-855 \ 0]$$

$$=[19 \ 0]$$

3	18	25	16	20	15	7	18	1	16	8	25	0	9	19	0	1	0	13	5
C	R	Y	P	T	O	G	R	A	P	H	Y	_	I	S	_	A	_	M	E
20	8	15	4	0	15	6	0	16	18	15	20	5	3	20	9	14	7	0	9
T	H	O	D	_	O	F	_	P	R	O	T	E	C	T	I	N	G	_	I
14	6	15	18	16	1	20	9	15	14	19	0								
N	F	O	R	M	A	T	I	O	N	S	_								

The message is: *Cryptography is a Method of Protecting Informations*

### Exercise

Write the matrix  $A$  with a key word **MATH**, then decode the cryptogram

117 9 456 132 386 62 260 104 413 161 104 8

### Solution

M A T H  
13 1 20 8

$$A = \begin{pmatrix} 13 & 1 \\ 20 & 8 \end{pmatrix}$$

$$A^{-1} = \frac{1}{84} \begin{pmatrix} 8 & -1 \\ -20 & 13 \end{pmatrix}$$

With the cryptogram:

[117 9] [456 132] [386 62] [260 104] [413 161] [104 8]

$$\frac{1}{84} \begin{bmatrix} 117 & 9 \end{bmatrix} \begin{pmatrix} 8 & -1 \\ -20 & 13 \end{pmatrix} = \frac{1}{84} \begin{bmatrix} 756 & 0 \end{bmatrix} \\ = \begin{bmatrix} 9 & 0 \end{bmatrix}$$

$$\frac{1}{84} \begin{bmatrix} 456 & 132 \end{bmatrix} \begin{pmatrix} 8 & -1 \\ -20 & 13 \end{pmatrix} = \frac{1}{84} \begin{bmatrix} 1,008 & 1,260 \end{bmatrix} \\ = \begin{bmatrix} 12 & 15 \end{bmatrix}$$

$$\frac{1}{84} \begin{bmatrix} 386 & 62 \end{bmatrix} \begin{pmatrix} 8 & -1 \\ -20 & 13 \end{pmatrix} = \frac{1}{84} \begin{bmatrix} 1,848 & 420 \end{bmatrix} \\ = \begin{bmatrix} 22 & 5 \end{bmatrix}$$

$$\frac{1}{84} \begin{bmatrix} 260 & 104 \end{bmatrix} \begin{pmatrix} 8 & -1 \\ -20 & 13 \end{pmatrix} = \frac{1}{84} \begin{bmatrix} 0 & 1,092 \end{bmatrix} \\ = \begin{bmatrix} 0 & 13 \end{bmatrix}$$

$$\frac{1}{84} \begin{bmatrix} 413 & 161 \end{bmatrix} \begin{pmatrix} 8 & -1 \\ -20 & 13 \end{pmatrix} = \frac{1}{84} \begin{bmatrix} 84 & 1,680 \end{bmatrix} \\ = \begin{bmatrix} 1 & 20 \end{bmatrix}$$

$$\frac{1}{84} \begin{bmatrix} 104 & 8 \end{bmatrix} \begin{pmatrix} 8 & -1 \\ -20 & 13 \end{pmatrix} = \frac{1}{84} \begin{bmatrix} 672 & 0 \end{bmatrix} \\ = \begin{bmatrix} 8 & 0 \end{bmatrix}$$

9 0 12 15 22 5 0 13 1 20 8 0  
I - L O V E - M A T H -

The message is: *I love math*

### Exercise

Write the matrix  $A$  with a key word **MATH**, then decode the cryptogram

438 150 145 37 240 96 635 191 445 157 260 104 413 161 104 8

### Solution

M A T H  
13 1 20 8

$$A = \begin{pmatrix} 13 & 1 \\ 20 & 8 \end{pmatrix}$$

$$A^{-1} = \frac{1}{84} \begin{pmatrix} 8 & -1 \\ -20 & 13 \end{pmatrix}$$



With the cryptogram:

$$\begin{bmatrix} 438 & 150 \end{bmatrix} \begin{bmatrix} 145 & 37 \end{bmatrix} \begin{bmatrix} 240 & 96 \end{bmatrix} \begin{bmatrix} 635 & 191 \end{bmatrix} \begin{bmatrix} 445 & 157 \end{bmatrix}$$

$$\begin{bmatrix} 260 & 104 \end{bmatrix} \begin{bmatrix} 413 & 161 \end{bmatrix} \begin{bmatrix} 104 & 8 \end{bmatrix}$$

$$\frac{1}{84} \begin{bmatrix} 438 & 150 \end{bmatrix} \begin{pmatrix} 8 & -1 \\ -20 & 13 \end{pmatrix} = \frac{1}{84} \begin{bmatrix} 504 & 1,512 \end{bmatrix}$$

$$= \begin{bmatrix} 6 & 18 \end{bmatrix}$$

$$\frac{1}{84} \begin{bmatrix} 145 & 37 \end{bmatrix} \begin{pmatrix} 8 & -1 \\ -20 & 13 \end{pmatrix} = \frac{1}{84} \begin{bmatrix} 420 & 336 \end{bmatrix}$$

$$= \begin{bmatrix} 5 & 4 \end{bmatrix}$$

$$\frac{1}{84} \begin{bmatrix} 240 & 96 \end{bmatrix} \begin{pmatrix} 8 & -1 \\ -20 & 13 \end{pmatrix} = \frac{1}{84} \begin{bmatrix} 0 & 1,008 \end{bmatrix}$$

$$= \begin{bmatrix} 0 & 12 \end{bmatrix}$$

$$\frac{1}{84} \begin{bmatrix} 635 & 191 \end{bmatrix} \begin{pmatrix} 8 & -1 \\ -20 & 13 \end{pmatrix} = \frac{1}{84} \begin{bmatrix} 1,260 & 1,848 \end{bmatrix}$$

$$= \begin{bmatrix} 15 & 22 \end{bmatrix}$$

$$\frac{1}{84} \begin{bmatrix} 445 & 157 \end{bmatrix} \begin{pmatrix} 8 & -1 \\ -20 & 13 \end{pmatrix} = \frac{1}{84} \begin{bmatrix} 420 & 1,596 \end{bmatrix}$$

$$= \begin{bmatrix} 5 & 19 \end{bmatrix}$$

$$\frac{1}{84} \begin{bmatrix} 260 & 104 \end{bmatrix} \begin{pmatrix} 8 & -1 \\ -20 & 13 \end{pmatrix} = \frac{1}{84} \begin{bmatrix} 0 & 1,092 \end{bmatrix}$$

$$= \begin{bmatrix} 0 & 13 \end{bmatrix}$$

$$\frac{1}{84} \begin{bmatrix} 413 & 161 \end{bmatrix} \begin{pmatrix} 8 & -1 \\ -20 & 13 \end{pmatrix} = \frac{1}{84} \begin{bmatrix} 84 & 1,680 \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 20 \end{bmatrix}$$

$$\frac{1}{84} \begin{bmatrix} 104 & 8 \end{bmatrix} \begin{pmatrix} 8 & -1 \\ -20 & 13 \end{pmatrix} = \frac{1}{84} \begin{bmatrix} 672 & 0 \end{bmatrix}$$

$$= \begin{bmatrix} 8 & 0 \end{bmatrix}$$

6 18 5 4 0 12 15 22 5 19 0 13 1 20 8 0  
F R E D - L O V E S - M A T H -

The message is: *Fred loves math*

### Exercise

Consider the invertible matrix:  $A = \begin{pmatrix} 1 & -2 & 2 \\ -1 & 1 & 3 \\ 1 & -1 & -4 \end{pmatrix}$

Decode the cryptogram

$$\begin{array}{cccccccccccc} 1 & -5 & 11 & 19 & -25 & -45 & 11 & -16 & -28 & 20 & -29 & -27 \\ 12 & -12 & -53 & 40 & -61 & -35 & 8 & -17 & 7 & & & \end{array}$$

### Solution

$$|A| = 1$$

$$A^{-1} = \begin{pmatrix} -1 & -10 & -8 \\ -1 & -6 & -5 \\ 0 & -1 & -1 \end{pmatrix}$$

With the cryptogram:

$$\begin{array}{cccc} [1 & -5 & 11] & [19 & -25 & -45] & [11 & -16 & -28] & [20 & -29 & -27] \\ [12 & -12 & -53] & [40 & -61 & -35] & [8 & -17 & 7] & & & \end{array}$$

$$[1 \quad -5 \quad 11] \begin{pmatrix} -1 & -10 & -8 \\ -1 & -6 & -5 \\ 0 & -1 & -1 \end{pmatrix} = [4 \quad 9 \quad 6]$$

$$[19 \quad -25 \quad -45] \begin{pmatrix} -1 & -10 & -8 \\ -1 & -6 & -5 \\ 0 & -1 & -1 \end{pmatrix} = [6 \quad 5 \quad 18]$$

$$[11 \quad -16 \quad -28] \begin{pmatrix} -1 & -10 & -8 \\ -1 & -6 & -5 \\ 0 & -1 & -1 \end{pmatrix} = [5 \quad 14 \quad 20]$$

$$[20 \quad -29 \quad -27] \begin{pmatrix} -1 & -10 & -8 \\ -1 & -6 & -5 \\ 0 & -1 & -1 \end{pmatrix} = [9 \quad 1 \quad 12]$$

$$[12 \quad -12 \quad -53] \begin{pmatrix} -1 & -10 & -8 \\ -1 & -6 & -5 \\ 0 & -1 & -1 \end{pmatrix} = [0 \quad 5 \quad 17]$$

$$[40 \quad -61 \quad -35] \begin{pmatrix} -1 & -10 & -8 \\ -1 & -6 & -5 \\ 0 & -1 & -1 \end{pmatrix} = [21 \quad 1 \quad 20]$$

$$\begin{bmatrix} 8 & -17 & 7 \end{bmatrix} \begin{pmatrix} -1 & -10 & -8 \\ -1 & -6 & -5 \\ 0 & -1 & -1 \end{pmatrix} = \begin{bmatrix} 9 & 15 & 14 \end{bmatrix}$$

4 9 6 6 5 18 5 14 20 9 1 12 0 5 17 21 1 20 9 15 14  
D I F F E R E N T I A L \_ E Q U A T I O N

The message is: *Differential Equation.*

### Exercise

Determine the key word, then decode the given cryptogram

6 18 5 4 15 13 1 20 8  
102 649 238 57 324 112 128 622 207  
180 613 290 102 360 259 151 580 297

*Hint:* First row is the key

### Solution

The key word from the first row is

6 18 5 4 15 13 1 20 8  
f r e d o m a t h

Since it has 9 numbers, then the matrix is  $9 = 3^2$  which is  $3 \times 3$

$$A = \begin{pmatrix} 6 & 18 & 5 \\ 4 & 15 & 13 \\ 1 & 20 & 8 \end{pmatrix}$$

$$|A| = -857$$

$$\begin{aligned} A^{-1} &= -\frac{1}{857} \begin{pmatrix} -140 & -44 & 159 \\ -19 & 43 & -58 \\ 65 & -102 & 18 \end{pmatrix} \\ &= \frac{1}{857} \begin{pmatrix} 140 & 44 & -159 \\ 19 & -43 & 58 \\ -65 & 102 & -18 \end{pmatrix} \end{aligned}$$

With the cryptogram:

$\begin{bmatrix} 102 & 649 & 238 \end{bmatrix}$   $\begin{bmatrix} 57 & 324 & 112 \end{bmatrix}$   $\begin{bmatrix} 128 & 622 & 207 \end{bmatrix}$   
 $\begin{bmatrix} 180 & 613 & 290 \end{bmatrix}$   $\begin{bmatrix} 102 & 360 & 259 \end{bmatrix}$   $\begin{bmatrix} 151 & 580 & 297 \end{bmatrix}$

$$\frac{1}{857}[102 \quad 649 \quad 238] \begin{pmatrix} 140 & 44 & -159 \\ 19 & -43 & 58 \\ -65 & 102 & -18 \end{pmatrix} = \frac{1}{857}[11,141 \quad 857 \quad 17,140]$$

$$=[13 \quad 1 \quad 20]$$

$$\frac{1}{857}[57 \quad 324 \quad 112] \begin{pmatrix} 140 & 44 & -159 \\ 19 & -43 & 58 \\ -65 & 102 & -18 \end{pmatrix} = \frac{1}{857}[6,856 \quad 0 \quad 7,713]$$

$$=[8 \quad 0 \quad 9]$$

$$\frac{1}{857}[128 \quad 622 \quad 207] \begin{pmatrix} 140 & 44 & -159 \\ 19 & -43 & 58 \\ -65 & 102 & -18 \end{pmatrix} = \frac{1}{857}[16,283 \quad 0 \quad 11,998]$$

$$=[19 \quad 0 \quad 14]$$

$$\frac{1}{857}[180 \quad 613 \quad 290] \begin{pmatrix} 140 & 44 & -159 \\ 19 & -43 & 58 \\ -65 & 102 & -18 \end{pmatrix} = \frac{1}{857}[17,997 \quad 11,141 \quad 1,714]$$

$$=[21 \quad 13 \quad 2]$$

$$\frac{1}{857}[102 \quad 360 \quad 259] \begin{pmatrix} 140 & 44 & -159 \\ 19 & -43 & 58 \\ -65 & 102 & -18 \end{pmatrix} = \frac{1}{857}[4,285 \quad 15,426 \quad 0]$$

$$=[5 \quad 18 \quad 0]$$

$$\frac{1}{857}[151 \quad 580 \quad 297] \begin{pmatrix} 140 & 44 & -159 \\ 19 & -43 & 58 \\ -65 & 102 & -18 \end{pmatrix} = \frac{1}{857}[12,855 \quad 11,998 \quad 4,285]$$

$$=[15 \quad 14 \quad 5]$$

13   1   20   8   0   9   19   0   14   21   13   2   5   18   0   15   14   5  
*M   A   T   H   -   I   S   -   N   U   M   B   E   R   -   O   N   E*

The message is: *Math is number one*

## Exercise

Determine the key word, then decode the given cryptogram

5	17	21	1	20	9	15	14	19
259	863	783	77	378	357	301	448	565
106	266	318	325	365	485	301	522	653
326	653	738	10	566	495	115	640	555
290	791	762	115	474	507	119	332	279
305	454	513	339	645	611	226	341	426
260	338	368	406	657	830	270	649	590
110	337	418	74	318	330	261	561	469
114	426	390	160	543	372	89	535	441
323	842	783	97	344	245	84	601	444
424	851	944	175	262	339	379	698	755
226	341	426	37	454	217	156	694	536

## Solution

The key word from the first row, because all the numbers are between 0 and 26, alphabetic letter.

Since it has 9 numbers, then the matrix is  $9 = 3^2$  which is  $3 \times 3$ .

Therefore,

$$A = \begin{pmatrix} 5 & 17 & 21 \\ 1 & 20 & 9 \\ 15 & 14 & 19 \end{pmatrix}$$

0 = _	4 = D	8 = H	12 = L	16 = P	20 = T	24 = X
1 = A	5 = E	9 = I	13 = M	17 = Q	21 = U	25 = Y
2 = B	6 = F	10 = J	14 = N	18 = R	22 = V	26 = Z
3 = C	7 = G	11 = K	15 = O	19 = S	23 = W	

The key word is:

5 17 21 1 20 9 15 14 19  
E Q U A T I O N S

$$A = \begin{pmatrix} 5 & 17 & 21 \\ 1 & 20 & 9 \\ 15 & 14 & 19 \end{pmatrix}$$

$$|A| = -2,764$$

$$A^{-1} = -\frac{1}{2,764} \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix}$$

With the cryptogram:

[259 863 783] [77 378 357] [301 448 565] [106 266 318]  
 [325 365 485] [301 522 653] [326 653 738] [103 566 495]  
 [115 640 555] [290 791 762] [115 474 507] [119 332 279]  
 [305 454 513] [339 645 611] [226 341 426] [260 338 368]  
 [406 657 830] [270 649 590] [110 337 418] [74 318 330]  
 [261 561 469] [114 426 390] [160 543 372] [89 535 441]  
 [323 842 783] [97 344 245] [84 601 444] [424 851 944]  
 [175 262 339] [379 698 755] [226 341 426] [37 454 217]  
 [156 694 536]

To decode a message given the matrix A.

$$-\frac{1}{2,764} [259 \ 863 \ 783] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-58,044 \ -52,516 \ -24,876]$$

$$= [21 \ 19 \ 9]$$

$$-\frac{1}{2,764} [77 \ 378 \ 357] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-38,696 \ -19,348 \ 0]$$

$$= [14 \ 7 \ 0]$$

$$-\frac{1}{2,764} [301 \ 448 \ 565] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-33,168 \ -2,764 \ -44,224]$$

$$= [12 \ 1 \ 16]$$

$$-\frac{1}{2,764} [106 \ 266 \ 318] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-33,168 \ -2,764 \ -8,292]$$

$$= [12 \ 1 \ 3]$$

$$-\frac{1}{2,764} [325 \ 365 \ 485] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-13,820 \ 0 \ -55,280]$$

$$= [5 \ 0 \ 20]$$

$$-\frac{1}{2,764} [301 \ 522 \ 653] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-49,752 \ -2,764 \ -38,696]$$

$$= [18 \ 1 \ 14]$$

$$-\frac{1}{2,764} [326 \ 653 \ 738] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-52,516 \ -16,584 \ -41,460]$$

$$= [19 \ 6 \ 15]$$

$$-\frac{1}{2,764} [103 \ 566 \ 495] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-49,752 \ -35,932 \ 0]$$

$$= [18 \ 13 \ 0]$$

$$-\frac{1}{2,764} [115 \ 640 \ 555] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-55,280 \ -41,460 \ 0]$$

$$= [20 \ 15 \ 0]$$

$$-\frac{1}{2,764} [290 \ 791 \ 762] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-52,516 \ -41,460 \ -33,168]$$

$$= [19 \ 15 \ 12]$$

$$-\frac{1}{2,764} [115 \ 474 \ 507] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-60,808 \ -13,820 \ 0]$$

$$= [22 \ 5 \ 0]$$

$$-\frac{1}{2,764} [119 \ 332 \ 279] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-11,056 \ -24,876 \ -16,584]$$

$$= [4 \ 9 \ 6]$$

$$-\frac{1}{2,764} [305 \ 454 \ 513] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-16,584 \ -13,820 \ -49,752]$$

$$= [6 \ 5 \ 18]$$

$$-\frac{1}{2,764} [339 \ 645 \ 611] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-13,820 \ -38,696 \ -55,280] \\ = [5 \ 14 \ 20]$$

$$-\frac{1}{2,764} [226 \ 341 \ 426] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-24,876 \ -2,764 \ -33,168] \\ = [9 \ 1 \ 12]$$

$$-\frac{1}{2,764} [260 \ 338 \ 368] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [0 \ 13,820 \ -46,988] \\ = [0 \ 5 \ 17]$$

$$-\frac{1}{2,764} [406 \ 657 \ 830] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-58,044 \ -2,764 \ -55,280] \\ = [21 \ 1 \ 20]$$

$$-\frac{1}{2,764} [270 \ 649 \ 590] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-24,876 \ -41,460 \ -38,696] \\ = [9 \ 15 \ 14]$$

$$-\frac{1}{2,764} [110 \ 337 \ 418] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-52,516 \ 0 \ -2,764] \\ = [19 \ 0 \ 1]$$

$$-\frac{1}{2,764} [74 \ 318 \ 330] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-38,696 \ -11,056 \ 0] \\ = [14 \ 4 \ 0]$$

$$-\frac{1}{2,764} [261 \ 561 \ 469] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-2,764 \ -44,224 \ -44,224] \\ = [1 \ 16 \ 16]$$



$$-\frac{1}{2,764} \begin{bmatrix} 114 & 426 & 390 \end{bmatrix} \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} \begin{bmatrix} -33,168 & -24,876 & -8,292 \end{bmatrix}$$

$$= [12 \quad 9 \quad 3]$$

$$-\frac{1}{2,764} \begin{bmatrix} 160 & 543 & 372 \end{bmatrix} \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} \begin{bmatrix} -2,764 & -55,280 & -24,876 \end{bmatrix}$$

$$= [1 \quad 20 \quad 9]$$

$$-\frac{1}{2,764} \begin{bmatrix} 89 & 535 & 441 \end{bmatrix} \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} \begin{bmatrix} -41,460 & -38,696 & 0 \end{bmatrix}$$

$$= [15 \quad 14 \quad 0]$$

$$-\frac{1}{2,764} \begin{bmatrix} 323 & 842 & 783 \end{bmatrix} \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} \begin{bmatrix} -44,224 & -49,752 & -41,460 \end{bmatrix}$$

$$= [16 \quad 18 \quad 15]$$

$$-\frac{1}{2,764} \begin{bmatrix} 97 & 344 & 245 \end{bmatrix} \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} \begin{bmatrix} -5,528 & -33,168 & -13,820 \end{bmatrix}$$

$$= [2 \quad 12 \quad 5]$$

$$-\frac{1}{2,764} \begin{bmatrix} 84 & 601 & 444 \end{bmatrix} \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} \begin{bmatrix} -35,932 & -52,516 & 0 \end{bmatrix}$$

$$= [13 \quad 19 \quad 0]$$

$$-\frac{1}{2,764} \begin{bmatrix} 424 & 851 & 944 \end{bmatrix} \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} \begin{bmatrix} -63,572 & -24,876 & -55,280 \end{bmatrix}$$

$$= [23 \quad 9 \quad 20]$$

$$-\frac{1}{2,764} \begin{bmatrix} 175 & 262 & 339 \end{bmatrix} \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} \begin{bmatrix} -22,112 & 0 & -24,876 \end{bmatrix}$$

$$= [8 \quad 0 \quad 9]$$

$$-\frac{1}{2,764} [379 \ 698 \ 755] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-38,696 \ -24,876 \ -55,280]$$

$$= [14 \ 9 \ 20]$$

$$-\frac{1}{2,764} [226 \ 341 \ 426] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-24,876 \ -2,764 \ -33,168]$$

$$= [9 \ 1 \ 12]$$

$$-\frac{1}{2,764} [37 \ 454 \ 217] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [0 \ -60,808 \ -2,764]$$

$$= [0 \ 22 \ 1]$$

$$-\frac{1}{2,764} [156 \ 694 \ 536] \begin{pmatrix} 254 & -29 & -267 \\ 116 & -220 & -24 \\ -286 & 185 & 83 \end{pmatrix} = -\frac{1}{2,764} [-33,168 \ -58,044 \ -13,820]$$

$$= [12 \ 21 \ 5]$$

0 = _	4 = D	8 = H	12 = L	16 = P	20 = T	24 = X
1 = A	5 = E	9 = I	13 = M	17 = Q	21 = U	25 = Y
2 = B	6 = F	10 = J	14 = N	18 = R	22 = V	26 = Z
3 = C	7 = G	11 = K	15 = O	19 = S	23 = W	

21 19 9 14 7 0 12 1 16 12 1 3 5 0 20 18 1 14 19 6 15  
 U S I N G - L A P L A C E - T R A N S F O  
 18 13 0 20 15 0 19 15 12 22 5 0 4 9 6 6 5 18 5 14 20  
 R M - T O - S O L V E - D I F F E R E N T  
 9 1 12 0 5 17 21 1 20 9 15 14 19 0 1 14 4 0 1 16 16  
 I A L - E Q U A T I O N S - A N D - A P P  
 12 9 3 1 20 9 15 14 0 16 18 15 2 12 5 13 19 0 23 9 20  
 L I C A T I O N - P R O B L E M S - W I T  
 8 0 9 14 9 20 9 1 12 0 22 1 12 21 5  
 H - I N I T I A L - V A L U E

The message is:

*Using Laplace Transform to Solve Differential Equations and Application Problems with Initial Value*