

# Applied Linear Algebra



## 1 Matrices and Gaussian Elimination

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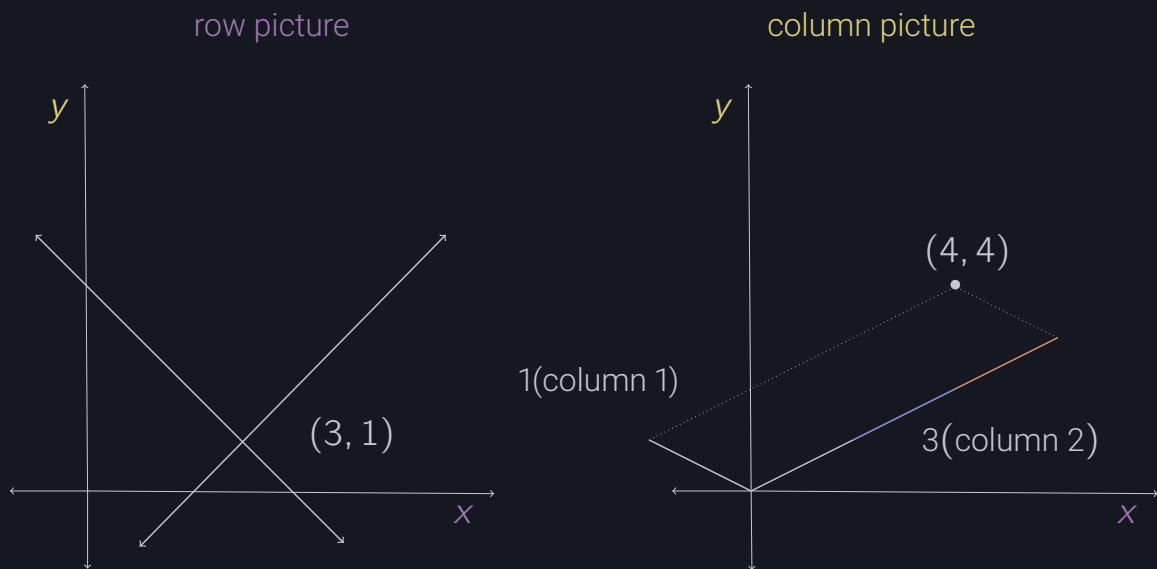
# 1 Matrices and Gaussian Elimination



## 1.2 The Geometry of Linear Equations

### Problems 1–12

- For the equations  $x + y = 4$ ,  $2x - 2y = 4$ , draw the row picture (two intersecting lines) and the column picture (combination of two columns equal to the column vector  $(4,4)$  on the right side).



### 1.2.1

- Solve to find a combination of the columns that equals  $b$ :

$$u - v - w = b_1$$

$$v + w = b_2$$

$$w = b_3$$

$$\implies w = b_3$$

$$\implies v = b_2 - b_3$$

$$\implies u = b_1 + v + w = b_1 + b_2$$

- Describe the intersection of the three planes  $u + v + w + z = 6$  and  $u + w + z = 4$  and  $u + w = 2$  (all in four-dimensional space). Is it a line or a point or an empty set? What is the intersection if the fourth plane  $u = -1$  is included? Find a fourth equation that leaves us with no solution.

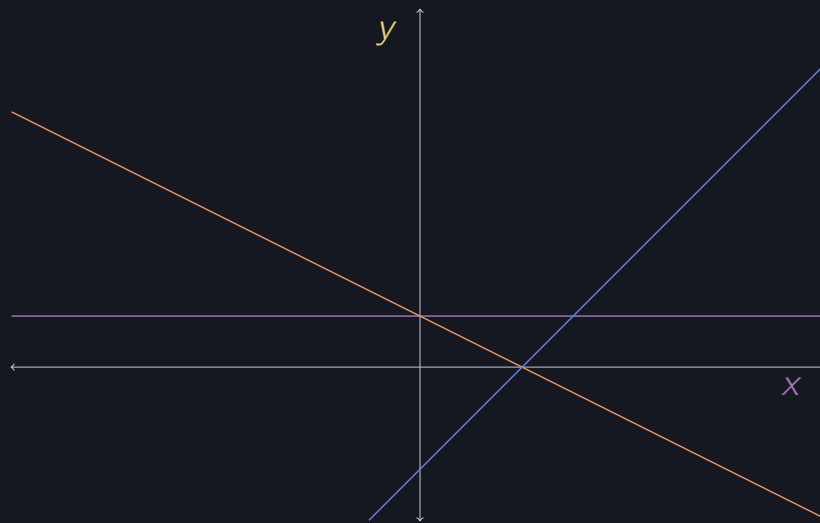
- A line; as  $u + w = 2$  is only a line. A fourth plane with  $u = -1$  would produce a normally intersecting point. Any addition equation when  $u + w \neq 2$  would produce an inconsistent equation.

4. Sketch these three lines and decide if the equations are solvable:

$$x + 2y = 2$$

$$x - y = 2$$

$$y = 1$$



#### 1.2.4

##### Inconsistent; multiple points of intersect

What happens if all right-hand sides are zero? Is there any nonzero choice of right-hand sides that allows the three lines to intersect at the same point?

- If all the solutions were zero, then it would be a trivial solution.
  - Yes, e.g.,  $x - y = -1$  would produce a single point of intersection.
5. Find two points on the line of intersection of the three planes  $t = 0$  and  $z = 0$  and  $x + y + z + t = 1$  in four-dimensional space.

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

6. When  $b = (2, 5, 7)$ , find a solution  $(u, v, w)$  to equation (4) different from the solution  $(1, 0, 1)$  mentioned in the text.
- Since there are infinite solutions, and if  $\mathbf{s}$  vector describing one solution and  $\lambda$  is any scalar, then  $\mathbf{s}\lambda$  is also a solution. E.g.,  $(1, 0, 1)42 = (42, 0, 42)$

8. Explain why the system

$$\begin{aligned}u + v + w &= 2 \\u + 2v + 3w &= 1 \\v + 2w &= 0\end{aligned}$$

is singular by finding a combination of the three equations that adds up to  $0 = 1$ . What value should replace the last zero on the right side to allow the equations to have solutions—and what is one of the solutions?

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

- Replacing the last zero with  $-1$  would yield infinite solutions. One solution would be  $[3, -1, 0]^T$
9. The column picture for the previous exercise (singular system) is

$$u \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} + v \begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix} + w \begin{bmatrix} 1 \\ 3 \\ 2 \end{bmatrix} = b$$

Show that the three columns on the left lie in the same plane by expressing the third as a combination of the first two. What are all the solutions  $(u, v, w)$  if  $b$  is the zero vector  $(0, 0, 0)$ ?

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

- If  $b$  is equal to the zero vector  $\mathbf{0}$  then the solutions are equal to the kernel<sup>2</sup> i.e.,  $-1x_1, 2x_2, 0x_3 = \mathbf{0}$
10. Under what condition on  $y_1, y_2, y_3$  do the points  $(0, y_1), (1, y_2), (2, y_3)$  lie on a straight line?
- Question 9 describes the state at which they are collinear, i.e.,  $y_3 = 2y_2 - y_1$
11. These equations are certain to have the solution  $x = y = 0$ . For which values of  $a$  is there a whole line of solutions?

$$\begin{aligned}ax + 2y &= 0 \\2x + ay &= 0\end{aligned}$$

- Only the scalars that make the lines linearly dependent, i.e.,  $a = 2, -2$

## Problems 17–23

17. The first of these equations plus the second equals the third:

$$\begin{aligned}x + y + z &= 2 \\x + 2y + z &= 3 \\2x + 3y + 2z &= 5\end{aligned}$$

The first two planes meet along a line. The third plane contains that line, because if  $x, y, z$  satisfy the first two equations then they also **span all of  $\mathbb{R}^3$** . The equations have infinitely many solutions (the whole line  $L$ ). Find three solutions.

◦  $\mathbf{v} = (4, 4, 0)$ ,  $\mathbf{w} = (6, 3, 2)$ ,  $\mathbf{u} = 2\mathbf{v} + -1\mathbf{w}$

18. Move the third plane in Problem 17 to a parallel plane  $2x + 3y + 2z = 9$ . Now the three equations have no solution—*why not*? The first two planes meet along the line  $L$ , but the third plane doesn't that **cross** that line.

19. In Problem 17 the columns are  $(1, 1, 2)$  and  $(1, 2, 3)$  and  $(1, 1, 2)$ . This is a “singular case” because the third column is **linearly dependent**. Find two combinations of the columns that give  $\mathbf{b} = (2, 3, 5)$ . This is only possible for  $\mathbf{b} = (4, 6, c)$  if  $c = 10$

20. Normally 4 “planes” in four-dimensional space meet at a **tensor**. Normally 4 column vectors in four-dimensional space can combine to produce  $\mathbf{b}$ . What combination of  $(1, 0, 0, 0)$ ,  $(1, 1, 0, 0)$ ,  $(1, 1, 1, 0)$ ,  $(1, 1, 1, 1)$  produces  $\mathbf{b} = (3, 3, 3, 2)$ ?  $(1, 0, 0, -2)$ ? What 4 equations for  $x, y, z, t$  are you solving? A **lower triangular matrix**, i.e.,

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

21. When equation 1 is added to equation 2, which of these are changed: the planes in the row picture, the column picture, the coefficient matrix, the solution?

◦ Row operations do not change the solution. Row 2 is changed, thus the second plane is changed. **All columns are changed.**?



## 1.3 Gaussian Elimination

### Problems 6, 7

6. Choose a coefficient  $b$  that makes this system singular. Then choose a right-hand side  $g$  that makes it solvable. Find two solutions in that singular case.

$$2x + by = 16$$

$$4x + 8y = g$$

$$2x + 4y = 16$$

$$4x + 8y = 32$$

- Since  $R_2$  is just a multiple of  $R_1$ , then solving for  $x, y$ , with one variable = 0, in the first equation will yield two solutions, i.e.,  $(8, 0), (0, 4)$
7. For which numbers  $a$  does elimination break down (a) permanently, and (b) temporarily?

$$ax + 3y = -3$$

$$4x + 6y = 6$$

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

- Permanently:  $a = 2$  (linearly dependent, no solution)
- Temporarily:  $a = 0$ ;

$$\left[ \begin{array}{cc|c} 4 & 6 & 6 \\ 0 & 3 & -3 \end{array} \right] \rightarrow \left[ \begin{array}{cc|c} 1 & 0 & 3 \\ 0 & 1 & -1 \end{array} \right]$$
$$y = -1, \quad x = 3$$

### Problems 17, 18, 19

17. Which number  $q$  makes this system singular and which right-hand side  $t$  gives it infinitely many solutions? Find the solution that has  $z = 1$ .

$$x + 4y - 2z = 1$$

$$x + 7y - 6z = 6$$

$$3y + qz = t$$

$$x + 4y - 2z = 1$$

$$x + 7y - 6z = 6$$

$$3y + -4z = 5$$

- If  $q = -4$ , then  $R_3$  would have no pivot
- If  $t = 5$ , then there would be finite solutions,  $R_3$  would be linearly dependent with  $R_2$

18. It is impossible for a system of linear equations to have exactly two solutions. Explain why.

- If  $(x, y, z)$  and  $(X, Y, Z)$  are two solutions, what is the other one?
  - There is no other *one*, there would be infinitely many.
- If 25 planes meet at two points, where else do they meet?
  - Every other single point, they would span all of  $\mathbb{R}^3$

19. Three planes can fail to have an intersection point, when no two planes are parallel. The system is singular if row 3 of  $\mathbf{A}$  is a **linearly dependent; a combination** of the first two rows. Find a third equation that can't be solved if  $x + y + z = 0$  and  $x - 2y - z = 1$ .

$$x + y + z = 0$$

$$x - 2y - z = 1$$

$R_1 + R_2 \neq 1 \rightarrow$  parallel; no solution, e.g.,

$$2x - y = 42$$

## Problems 30, 31

30. Use elimination to solve

$$u + v + w = 6$$

$$u + 2v + 2w = 11$$

$$2u + 3v - 4w = 3$$

$$u + v + w = 7$$

$$u + 2v + 2w = 10$$

$$2u + 3v - 4w = 3$$

$$\text{rref} \left( \left[ \begin{array}{ccc|c} 1 & 1 & 1 & 6 \\ 1 & 2 & 2 & 11 \\ 2 & 3 & -4 & 3 \end{array} \right] \right) \rightarrow \left[ \begin{array}{ccc|c} 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 3 \\ 0 & 0 & 1 & 2 \end{array} \right]$$

$$\text{rref} \left( \left[ \begin{array}{ccc|c} 1 & 1 & 1 & 7 \\ 1 & 2 & 2 & 10 \\ 2 & 3 & -4 & 3 \end{array} \right] \right) \rightarrow \left[ \begin{array}{ccc|c} 1 & 0 & 0 & 4 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 2 \end{array} \right]$$

31. For which three numbers  $a$  will elimination fail to give three pivots?

$$ax + 2y + 3z = b_1$$

$$ax + ay + 4z = b_2$$

$$ax + ay + az = b_3$$

- For  $a = 0$ , multiple failures.
- For  $a = 2$ , columns 0, 1 would be equal.
- For  $a = 4$ , rows 1, 2 would be equal.



## 1.4 Matrix Notation and Matrix Multiplication

### Problems 4, 10, 17, 19

4. If an  $m \times n$  matrix  $\mathbf{A}$  multiplies an  $n$ -dimensional vector  $\mathbf{x}$ , how many separate multiplications are involved? What if  $\mathbf{A}$  multiplies an  $n \times p$  matrix  $\mathbf{B}$ ?

- $m \cdot n$  multiplications; number of rows times the length of  $\mathbf{x}$ .
- $m \cdot n \cdot p$ ; same as above, except accounting for each additional column  $p$ .

10. True or false? Give a specific counterexample when false.

- If rows 1 and 3 of  $\mathbf{B}$  are the same, so are rows 1 and 3 of  $\mathbf{AB}$ .
- **✗ false**; matrix multiplication is done by the rows of the left matrix and the columns of the right, the rows may be the same, but if a column between the two are different, then there would be different multiplications occurring, e.g.,

$$\begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 4 & 2 & 0 \\ 1 & 1 & 1 \end{bmatrix} = \begin{bmatrix} 12 & 8 & 4 \\ 30 & 20 & 10 \\ 38 & 32 & 16 \end{bmatrix}$$

- If columns 1 and 3 of  $\mathbf{B}$  are the same, so are columns 1 and 3 of  $\mathbf{AB}$ .
- **✓ true**;
- If rows 1 and 3 of  $\mathbf{A}$  are the same, so are rows 1 and 3 of  $\mathbf{AB}$ .
- **✓ true**
- $(\mathbf{AB})^2 = \mathbf{A}^2 \mathbf{B}^2$ .
- **✗ false** (most of the time), e.g.,

$$\mathbf{A} = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} 1 & 1 & 1 \\ 4 & 2 & 0 \\ 1 & 1 & 1 \end{bmatrix}$$
$$\mathbf{AB}^2 = \begin{bmatrix} 144 & 64 & 16 \\ 900 & 400 & 100 \\ 2304 & 1024 & 256 \end{bmatrix} \neq \begin{bmatrix} 74 & 26 & 10 \\ 452 & 152 & 52 \\ 1154 & 386 & 130 \end{bmatrix} = \mathbf{A}^2 \mathbf{B}^2$$

17. Which of the following matrices are guaranteed to equal  $(\mathbf{A} + \mathbf{B})^2$ ?

- $\mathbf{A}^2 + 2\mathbf{AB} + \mathbf{B}^2$ ,
- ✓**  $\mathbf{A}(\mathbf{A} + \mathbf{B}) + \mathbf{B}(\mathbf{A} + \mathbf{B})$
- ✓**  $(\mathbf{A} + \mathbf{B})(\mathbf{B} + \mathbf{A})$ ,
- ✓**  $\mathbf{A}^2 + \mathbf{AB} + \mathbf{BA} + \mathbf{B}^2$

19. A fourth way to multiply matrices is columns of **A** times rows of **B**:

$$\mathbf{AB} = (\text{column 1})(\text{row 1}) + \cdots + (\text{column } n)(\text{row } n) = \text{sum of simple matrices.}$$

Give a  $2 \times 2$  example of this important rule for matrix multiplication.

$$\begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} \begin{bmatrix} a & b \\ c & d \end{bmatrix} = \left( a \begin{bmatrix} 1 \\ 3 \end{bmatrix} + c \begin{bmatrix} 2 \\ 4 \end{bmatrix} \right) b \begin{bmatrix} 1 \\ 3 \end{bmatrix} + d \begin{bmatrix} 2 \\ 4 \end{bmatrix}$$

Useful, as the left matrix can be thought of as the **weights that scale** the elements of the columns of the right matrix.

### Problems 30, 31

30. Multiply these matrices:

$$\begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{bmatrix} \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} 1 & 0 & 0 \\ -1 & 1 & 0 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 2 & 3 \\ 1 & 3 & 1 \\ 1 & 4 & 0 \end{bmatrix}.$$

$$\begin{bmatrix} 9 & 8 & 7 \\ 6 & 5 & 4 \\ 3 & 2 & 1 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} 1 & 2 & 3 \\ 0 & 1 & -2 \\ 0 & 2 & -3 \end{bmatrix} \quad \text{respectively}$$

- The former multiplication performs two operations (left: swaps top and bottom columns, right: swaps left and right columns), while the latter subtracts row 1 from both row 2 and row 3.

31. This  $4 \times 4$  matrix needs which elimination matrices **E**<sub>21</sub> and **E**<sub>32</sub> and **E**<sub>43</sub>?

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

- $e_{21} = -\frac{1}{2}$ ,  $e_{32} = -\frac{2}{3}$ ,  $e_{43} = -\frac{3}{4}$
- I suspect the fractions will tend towards  $-1$  if the matrix was expanded upon in a similar fusion?

## Problems 34, 35, 38, 42

34. Multiply these matrices in the orders  $FE$  and  $EF$  and  $E^2$ :

$$E = \begin{bmatrix} 1 & 0 & 0 \\ a & 1 & 0 \\ b & 0 & 1 \end{bmatrix} \quad F = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & c & 1 \end{bmatrix}$$

$$FE = \begin{bmatrix} 1 & 0 & 0 \\ a & 1 & 0 \\ ac + b & c & 1 \end{bmatrix} \quad EF = \begin{bmatrix} 1 & 0 & 0 \\ a & 1 & 0 \\ b & c & 1 \end{bmatrix} \quad E^2 = \begin{bmatrix} 1 & 0 & 0 \\ 2a & 1 & 0 \\ 2b & 0 & 1 \end{bmatrix}$$

35. ↓

- (a) Suppose all columns of  $B$  are the same. Then all columns of  $EB$  are the same, because each one is  $E$  times  $B_{1n}$ .
- (b) Suppose all rows of  $B$  are  $[1 \ 2 \ 4]$ . Show by example that all rows of  $EB$  are not  $[1 \ 2 \ 4]$ . It is true that those rows are multiples of  $[1 \ 2 \ 4]$ 
  - E.g., if  $e_{12} = 2$ , then  $m_2$  of  $EB$  would be  $[3 \ 6 \ 12]$

38. If  $AB = I$  and  $BC = I$ , use the associative law to prove  $A = C$ .

$$A = A(BC)$$

$$A = (AB)C$$

$$A = C$$

42. True or false?

- (a) If  $A^2$  is defined then  $A$  is necessarily square.
  - ✓ true; inner dimensions must match, i.e., dimensions of  $n_1 = m_2$ . Thus,  $A$  must be square.
- (b) If  $AB$  and  $BA$  are defined, then  $A$  and  $B$  are square.
  - ✗ false; if  $A = 6 \times 9$  and  $B = 9 \times 6$  allows for valid pre- and post-multiplication of  $B$ .
- (c) If  $AB$  and  $BA$  are defined, then  $AB$  and  $BA$  are square.
  - ✓ true; see above example, each case will still yield square matrices. Not a proof, but I can't see another way to falsify (b).
- (d) If  $AB = B$  then  $A = I$ 
  - ✗ false; e.g.,  $B = 0$

## 1.5 Triangular Factors and Row Exchanges

### Problems 1, 6, 7, 12, 14, 18, 19

1. When is an upper triangular matrix nonsingular (a full set of pivots)?

6. Find  $E^2$  and  $E^8$  and  $E^{-1}$  if

$$E = \begin{bmatrix} 1 & 0 \\ 6 & 1 \end{bmatrix}$$

7. Find the products  $FGH$  and  $HGF$  if (with upper triangular zeros omitted)

$$F = \begin{bmatrix} 1 & & & \\ 2 & 1 & & \\ 0 & 0 & 1 & \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad G = \begin{bmatrix} 1 & & & \\ 0 & 1 & & \\ 0 & 2 & 1 & \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad H = \begin{bmatrix} 1 & & & \\ 0 & 1 & & \\ 0 & 0 & 1 & \\ 0 & 0 & 2 & 1 \end{bmatrix}$$

12. How could you factor  $A$  into a product  $UL$ , upper triangular times lower triangular? Would they be the same factors as in  $A = LU$ ?

14. Write down all six of the  $3 \times 3$  permutation matrices, including  $P = I$ . Identify their inverses, which are also permutation matrices. The inverses satisfy  $PP^{-1} = I$  and are on the same list.

18. Decide whether the following systems are singular or nonsingular, and whether they have no solution, one solution, or infinitely many solutions:

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

19. Which numbers  $a, b, c$  lead to row exchanges? Which make the matrix singular?

$$A = \begin{bmatrix} 1 & 2 & 0 \\ a & 8 & 3 \\ 0 & b & 5 \end{bmatrix} \quad \text{and} \quad A = \begin{bmatrix} c & 2 \\ 6 & 4 \end{bmatrix}$$

### Problems 25–30

25. When zero appears in a pivot position,  $A = LU$  is not possible (we need nonzero pivots  $d, f, i$  in  $U$ )! Show directly why these are both impossible:

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

26.

27.

28.

29.

30.

## Problems 32, 33, 35, 42, 43

◦

## 1.6 Inverses and Transposes

**Problems 3, 10, 12, 13, 18, 20, 21**

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**Problems 28–30**

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**Problems 40–43**

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**Problems 49–59**

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## 1.7 Special Matrices and Applications

**Problems 1, 2, 5, 6**

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**Problems 7, 8, 10**

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