TLDR

Quick summary of today's notes. Lecture starts on next page.

- Let n be a positive integer and let A and B be $n \times n$ matrices.
- It always holds that $\det A = \det A^T$.
- If A is invertible then $\det A \neq 0$. If A is not invertible then $\det A = 0$.
- It always holds that $\det AB = (\det A)(\det B)$.
- A matrix is *triangular* if it looks like

$$\begin{bmatrix} * & * & * & * \\ 0 & * & * & * \\ 0 & 0 & * & * \\ 0 & 0 & 0 & * \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} * & 0 & 0 & 0 \\ * & * & 0 & 0 \\ * & * & * & 0 \\ * & * & * & * \end{bmatrix}$$

  where the $*$'s are arbitrary entries.

  Let $a_{ij} \in \mathbb{R}$ denote the entry of A in the ith row and jth column.

  If A is triangular then $\boxed{\det A = a_{11}a_{22}a_{33}\cdots a_{nn}}$ = the product of the diagonal entries of A.

  The matrix A is *diagonal* if $a_{ij} = 0$ whenever $i \neq j$. Diagonal matrices are triangular.

- Here is an algorithm to compute $\det A$:
  - Perform a series of row operations to transform A to a matrix E in echelon form.
  - Keep track of a scalar $\mathsf{denom} \in \mathbb{R}$ as you do this. Start with $\mathsf{denom} = 1$.
  - Whenever you swap two rows of A, multiply denom by -1.
  - Whenever you multiply a row of A by a nonzero number, multiply denom by that number.
  - Then $\boxed{\det A = \dfrac{\det E}{\mathsf{denom}} = \dfrac{\text{product of diagonal entries of } E}{\mathsf{denom}}}$.

- Here is another way to compute $\det A$.

  Again write a_{ij} for the entry of A in row i and column j.

  Also let $A^{(i,j)}$ be the matrix formed from A by deleting row i and column j.

  Then $\boxed{\det A = a_{11} \det A^{(1,1)} - a_{12} \det A^{(1,2)} + a_{13} \det A^{(1,3)} - \cdots - (-1)^n a_{1n} \det A^{(1,n)}}$.

  This formula is complicated and inefficient for generic matrices.

  It is useful when many entries of A are equal to zero, since then the formula has few terms.

  Also, when $n \leq 3$ and you expand all the terms in this formula, you get the identities

$$\det \begin{bmatrix} a & b \\ c & d \end{bmatrix} = ad - bc \quad \text{and} \quad \det \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} = a(ei - fh) - b(di - fg) + c(dh - eg).$$

1 Last time: introduction to determinants

Let n be a positive integer.

A *permutation matrix* is a square matrix formed by rearranging the columns of the identity matrix.

Equivalently, a permutation matrix is a square matrix whose entries are all 0 or 1, and that has exactly one nonzero entry in each row and in each column.

Let S_n be the set of $n \times n$ permutation matrices.

If A is an $n \times n$ matrix and $X \in S_n$, then AX has the same columns as A but in a different order.

The columns of A are "permuted" by X to form AX.

Example. The six elements of S_3 are

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

Given $X \in S_n$ and an arbitrary $n \times n$ matrix A:

- Define $\mathsf{prod}(X, A)$ to be the product of the entries of A in the nonzero positions of X.
- Define $\mathsf{inv}(X)$ to be the number of 2×2 submatrices of X equal to $\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$.

To form a 2×2 submatrix of X, choose any two rows and any two columns, not necessarily adjacent, and then take the 4 entries determined by those rows and columns.

Each 2×2 submatrix of a permutation matrix is either

$$\begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \text{ or } \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \text{ or } \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \text{ or } \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \text{ or } \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \text{ or } \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \text{ or } \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}.$$

Example. $\mathsf{prod}\left(\begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}, \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix}\right) = cdh$

Example. $\mathsf{inv}\left(\begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}\right) = 2$ and $\mathsf{inv}\left(\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\right) = 0$ and $\mathsf{inv}\left(\begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix}\right) = 3.$

Definition. The *determinant* of an $n \times n$ matrix A is the number given by the formula

$$\boxed{\det A = \sum_{X \in S_n} \mathsf{prod}(X, A)(-1)^{\mathsf{inv}(X)}}$$

This general formula simplifies to the following expressions for $n = 1, 2, 3$:

$$\det \begin{bmatrix} a \end{bmatrix} = a.$$

$$\det \begin{bmatrix} a & b \\ c & d \end{bmatrix} = ad - bc.$$

$$\det \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} = a(ei - fh) - b(di - fg) + c(dh - ef).$$

For $n \geq 4$, our formula for $\det A$ is a sum with at least 24 terms, which is not easy to compute by hand (or with a computer, for slightly larger n). We will describe a better way to compute determinants today.

The most important properties of the determinant are described by the following theorem:

Theorem. The determinant is the unique function $\det : \{n \times n \text{ matrices}\} \to \mathbb{R}$ with these 3 properties:

(1) $\boxed{\det I_n = 1}$.

(2) If B is formed by switching two columns in an $n \times n$ matrix A, then $\boxed{\det A = -\det B}$.

(3) Suppose A, B, and C are $n \times n$ matrices with columns

$$A = \left[\begin{array}{cccc} a_1 & a_2 & \dots & a_n \end{array}\right] \quad \text{and} \quad B = \left[\begin{array}{cccc} b_1 & b_2 & \dots & b_n \end{array}\right] \quad \text{and} \quad C = \left[\begin{array}{cccc} c_1 & c_2 & \dots & c_n \end{array}\right].$$

Assume there is an index i where $a_i = pb_i + qc_i$ for numbers $p, q \in \mathbb{R}$.

Assume also that $a_j = b_j = c_j$ for all other indices $j \in \{1, 2, \dots, i-1, i+1, i+2, \dots, n\}$.

Then $\boxed{\det A = p \det B + q \det C}$.

Corollary. If A is a square matrix that is not invertible then $\det A = 0$.

Corollary. If A is a permutation matrix then $\det A = (-1)^{\mathsf{inv}(A)}$.

Proof. $\mathsf{prod}(X, Y) = 0$ if X and Y are different $n \times n$ permutation matrices, but $\mathsf{prod}(X, X) = 1$. □

2 More properties of the determinant

Recall that A^T denotes the transpose of a matrix A (the matrix whose rows are the columns of A).

Lemma. If $X \in S_n$ then $X^T \in S_n$ and $\mathsf{inv}(X) = \mathsf{inv}(X^T)$.

Proof. Transposing a permutation matrix does not affect the # of 2×2 submatrices equal to $\left[\begin{array}{cc} 0 & 1 \\ 1 & 0 \end{array}\right]$. □

Corollary. If A is any square matrix then $\det A = \det(A^T)$.

Proof. If $X \in S_n$ then $\mathsf{prod}(X, A) = \mathsf{prod}(X^T, A^T)$, so our formula for the determinant gives

$$\det A = \sum_{X \in S_n} \mathsf{prod}(X, A)(-1)^{\mathsf{inv}(X)} = \sum_{X \in S_n} \mathsf{prod}(X^T, A^T)(-1)^{\mathsf{inv}(X^T)}.$$

As X ranges over all elements of S_n, the transpose X^T also ranges over all elements of S_n.
The second sum is therefore equal to $\sum_{X \in S_n} \mathsf{prod}(X, A^T)(-1)^{\mathsf{inv}(X)} = \det(A^T)$. □

Corollary. If A is a square matrix with two equal rows then $\det A = 0$.

Proof. In this case A^T has two equal columns, so $0 = \det A^T = \det A$. □

The following lemma is a weaker form of a statement we will prove later in the lecture.

Lemma. Let A and B be $n \times n$ matrices with $\det A \neq 0$. Then $\det(AB) = (\det A)(\det B)$.

Proof. Define $f : \{\ n \times n \text{ matrices } \} \to \mathbb{R}$ to be the function $f(M) = \frac{\det(AM)}{\det A}$.

Then f has the defining properties of the determinant, so must be equal to det since det is the unique function with these properties. In more detail:

- We have $f(I_n) = \frac{\det(AI_n)}{\det A} = \frac{\det A}{\det A} = 1$.
- If M' is given by swapping two columns in M, then AM' is given by swapping the two corresponding columns in AM, so $f(M') = \frac{\det(AM')}{\det A} = \frac{-\det(AM)}{\det A} = -f(M)$.
- If column i of M is p times column i of M' plus q times column i of M'' and all other columns of M, M', and M'' are equal, then the same is true of AM, AM', and AM'' so

$$f(M) = \frac{\det(AM)}{\det A} = \frac{p\det(AM') + q\det(AM'')}{\det A} = pf(M') + qf(M'').$$

These properties uniquely characterize det, so f and det must be the same function.

Therefore $f(B) = \frac{\det(AB)}{\det A} = \det B$ for any $n \times n$ matrix B, so $\det(AB) = (\det A)(\det B)$. □

3 Determinants of triangular and invertible matrices

An $n \times n$ matrix A is *upper-triangular* if all of its nonzero entries occur in positions on or above the diagonal positions $(1, 1), (2, 2), (3, 3), \dots, (n, n)$. Such a matrix looks like

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

where the $*$ entries can be any numbers. The zero matrix is considered to be upper-triangular.

An $n \times n$ matrix A is *lower-triangular* if all of its nonzero entries occur in positions on or below the diagonal positions. Such a matrix looks like

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

where the $*$ entries can again be any numbers. The zero matrix is also considered to be lower-triangular.

The transpose of an upper-triangular matrix is lower-triangular, and vice versa.

We say that a matrix is *triangular* if it is either upper- or lower-triangular.

A matrix is *diagonal* if it is both upper- and lower-triangular.

This happens precisely when all nonzero entries are on the diagonal: $\begin{bmatrix} * & 0 & 0 & 0 \\ 0 & * & 0 & 0 \\ 0 & 0 & * & 0 \\ 0 & 0 & 0 & * \end{bmatrix}$

The *diagonal entries* of A are the numbers that occur in positions $(1, 1), (2, 2), (3, 3), \dots, (n, n)$.

Proposition. If A is a triangular matrix then $\det A$ is the product of the diagonal entries of A.

For example, we have $\det \begin{bmatrix} a & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & c \end{bmatrix} = abc$.

Proof. Assume A is upper-triangular. If $X \in S_n$ and $X \neq I_n$ then at least one nonzero entry of X is in a position below the diagonal, in which case $\mathsf{prod}(X, A)$ is a product of numbers which includes 0 (since all positions below the diagonal in A contain zeros) and is therefore 0.

Hence $\det A = \sum_{X \in S_n} \mathsf{prod}(X, A)(-1)^{\mathsf{inv}(X)} = \mathsf{prod}(I_n, A) =$ the product of the diagonal entries of A.

If A is lower-triangular then the same result follows since $\det A = \det(A^T)$. □

Lemma. If A is an $n \times n$ matrix then $\det A$ is a nonzero multiple of $\det(\mathsf{RREF}(A))$.

Proof. Suppose B is obtained from A by an elementary row operation. To prove the lemma, it is enough to show that $\det B$ is a nonzero multiple of $\det A$. There are three possibilities for B:

1. If B is formed by swapping two rows of A then $B = XA$ for a permutation matrix $X \in S_n$.

   Therefore $\det B = \det(XA) = (\det X)(\det A) = \pm \det A$.

2. Suppose B is formed by rescaling a row of A by a nonzero scalar $\lambda \in \mathbb{R}$.

   Then $B = DA$ where D is a diagonal matrix of the form

$$D = \begin{bmatrix} 1 & & & & & & \\ & \ddots & & & & & \\ & & 1 & & & & \\ & & & \lambda & & & \\ & & & & 1 & & \\ & & & & & \ddots & \\ & & & & & & 1 \end{bmatrix}$$

   and in this case $\det D = \lambda \neq 0$, so $\det B = \det(DA) = (\det D)(\det A) = \lambda \det A$.

3. Suppose B is formed by adding a multiple of row i of A to row j.

   Then $B = TA$ for a triangular matrix T whose diagonal entries are all 1 and whose only other nonzero entry appears in column i and row j.

   For example, if $n = 4$ and B is formed by adding 5 times row 2 of A to row 3 then

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

   We therefore have $\det B = \det(TA) = (\det T)(\det A) = \det A$.

This shows that performing any elementary row operation to A multiplies $\det A$ by a nonzero number. It follows that $\det(\mathsf{RREF}(A))$ is a sequence of nonzero numbers times $\det A$. □

This brings us to an important property of the determinant that is worth remembering.

Theorem. An $n \times n$ matrix A is an invertible if and only if $\det A \neq 0$.

Proof. We have already seen that if A is not invertible then $\det A = 0$.

Assume A is invertible. Then $\mathsf{RREF}(A) = I_n$, so $\det(\mathsf{RREF}(A)) = \det I_n = 1$.

Hence $\det A \neq 0$ since $\det A$ is a nonzero multiple of $\det(\mathsf{RREF}(A))$. □

Our next goal is to show that the determinant is a *multiplicative function*.

Lemma. Let A and B be $n \times n$ matrices. If A or B is not invertible then AB is not invertible.

Proof. Let X and Y be $n \times n$ matrices.

We have seen that X and Y are inverses of each other if $XY = I_n$, in which case also $YX = I_n$.

Suppose AB is invertible with inverse X. Then $(AB)X = X(AB) = I_n$.

Then A is invertible with $A^{-1} = BX$ since $A(BX) = (AB)X = I_n$.

Likewise, B is invertible with $B^{-1} = XA$ since $(XA)B = X(AB) = I_n$.

Thus, if A or B is not invertible then AB cannot be invertible. □

Theorem. If A and B are any $n \times n$ matrices then $\det(AB) = (\det A)(\det B)$.

Proof. We already proved this in the case when $\det A \neq 0$.

If $\det A = 0$, then A is not invertible, so AB is not invertible either, so $\det(AB) = 0 = (\det A)(\det B)$. □

It is difficult to derive this theorem directly from the formula $\det A = \sum_{X \in S_n} \mathsf{prod}(X, A)(-1)^{\mathsf{inv}(X)}$.

Example. We have $\det \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} = 4 - 6 = -2$ and $\det \begin{bmatrix} 2 & 3 \\ 4 & 5 \end{bmatrix} = 10 - 12 = -2$.

On the other hand, $\det\left(\begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} \begin{bmatrix} 2 & 3 \\ 4 & 5 \end{bmatrix} \right) = \det \begin{bmatrix} 10 & 13 \\ 22 & 29 \end{bmatrix} = 290 - 286 = 4$.

4 Computing determinants

Our proof that $\det A$ is a nonzero multiple of $\det(\mathsf{RREF}(A))$ can be turned into an effective algorithm.

<u>Algorithm to compute $\det A$ (useful when A is larger than 3×3).</u>

Input: an $n \times n$ matrix A.

1. Start by setting a scalar $\mathsf{denom} = 1$.
2. Row reduce A to an echelon form E. It is not necessary to bring A all the way to *reduced* echelon form. We just need to row reduce A until we get an upper triangular matrix.

   Each time you perform a row operation in this process, modify denom as follows:

   (a) When you switch two rows, multiply denom by -1.

   (b) When you multiply a row by a nonzero scalar λ, multiply denom by λ.

   (c) When you add a multiple of a row to another row, don't do anything to denom.

The determinant $\det E$ is the product of the diagonal entries of E

The determinant of A is given by $\det A = \dfrac{\det E}{\mathsf{denom}}$.

Example. We reduce the following matrix to echelon form:

$$A = \begin{bmatrix} 1 & 3 & 5 \\ 0 & -3 & -9 \\ 2 & 4 & 6 \end{bmatrix} \qquad \mathsf{denom} = 1$$

$$\sim \begin{bmatrix} 1 & 3 & 5 \\ 0 & -3 & -9 \\ 0 & -2 & -4 \end{bmatrix} \qquad \text{(we added a multiple of row 1 to row 3)} \quad \mathsf{denom} = 1$$

$$\sim \begin{bmatrix} 1 & 3 & 5 \\ 0 & 1 & 3 \\ 0 & -2 & -4 \end{bmatrix} \qquad \text{(we multiplied row 2 by } -1/3\text{)} \quad \mathsf{denom} = -1/3$$

$$\sim \begin{bmatrix} 1 & 3 & 5 \\ 0 & 1 & 3 \\ 0 & 0 & 2 \end{bmatrix} = E \qquad \text{(we added a multiple of row 2 to row 3)} \quad \mathsf{denom} = -1/3$$

Therefore $\det A = \frac{\det E}{\mathsf{denom}} = \frac{1\cdot 1\cdot 2}{-1/3} = -6.$

Another algorithm to compute $\det A$ (useful when A has many entries equal to zero).

Define $A^{(i,j)}$ to be the submatrix formed by removing row i and column j from A.

For example, if $A = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix}$ then $A^{(1,2)} = \begin{bmatrix} d & f \\ g & i \end{bmatrix}$.

Theorem. If A is the $n \times n$ matrix with entry a_{ij} row i and column j, then

(1) $\boxed{\det A = a_{11} \det A^{(1,1)} - a_{12} \det A^{(1,2)} + a_{13} \det A^{(1,3)} - \dots - (-1)^n a_{1n} \det A^{(1,n)}}$.

(2) $\boxed{\det A = a_{11} \det A^{(1,1)} - a_{21} \det A^{(2,1)} + a_{31} \det A^{(3,1)} - \dots - (-1)^n a_{n1} \det A^{(n,1)}.}$

Note that each $A^{(1,j)}$ or $A^{(j,1)}$ is a square matrix smaller than A.

Thus $\det A^{(1,j)}$ or $\det A^{(j,1)}$ can be computed by the same formula on a smaller scale.

Proof. The second formula follows from the first formula since $\det A = \det(A^T)$. (Why?)

The first formula is a consequence of the formula for $\det A$ we derived last lecture. One needs to show

$$-(-1)^j a_{1j} \det A^{(1,j)} = \sum_{X \in S_n^{(j)}} \mathsf{prod}(X, A)(-1)^{\mathsf{inv}(X)}$$

where $S_n^{(j)}$ is the set of $n \times n$ permutation matrices which have a 1 in column j of the first row.

Summing the left expression over $j = 1, 2, \dots, n$ gives the desired formula.

Summing the right expression over $j = 1, 2, \dots, n$ gives $\sum_{X \in S_n} \mathsf{prod}(X, A)(-1)^{\mathsf{inv}(X)} = \det A$. □

Example. This result can be used to derive our formula for the determinant of a 3-by-3 matrix:

$$\det \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} = a \det \begin{bmatrix} e & f \\ h & i \end{bmatrix} - b \det \begin{bmatrix} d & f \\ g & i \end{bmatrix} + c \det \begin{bmatrix} d & e \\ g & h \end{bmatrix} = a(ef - hi) - b(di - fg) + c(dh - eg).$$

5 Vocabulary

Keywords from today's lecture:

1. **Upper-triangular matrix**.

   A square matrix of the form $\begin{bmatrix} * & * & * & * \\ 0 & * & * & * \\ 0 & 0 & * & * \\ 0 & 0 & 0 & * \end{bmatrix}$ with zeros in all positions below the main diagonal.

2. **Lower-triangular matrix**.

   A square matrix of the form $\begin{bmatrix} * & 0 & 0 & 0 \\ * & * & 0 & 0 \\ * & * & * & 0 \\ * & * & * & * \end{bmatrix}$ with zeros in all positions above the main diagonal.

   The transpose of an upper-triangular matrix.

3. **Triangular matrix**.

   A matrix that is either upper-triangular or lower-triangular.

4. **Diagonal matrix**.

   A square matrix of the form $\begin{bmatrix} * & 0 & 0 & 0 \\ 0 & * & 0 & 0 \\ 0 & 0 & * & 0 \\ 0 & 0 & 0 & * \end{bmatrix}$ with zeros in all non-diagonal positions.

   A matrix that is both upper-triangular and lower-triangular.