Lecture Notes: Matrix Algebra
Part C: Determinants and Pivoting

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Outline

Determinants of Order 2: Definition

Consider again the pair of linear equations

$$\begin{array}{ccccc} a_{11}x_1 & + & a_{12}x_2 & = & b_1 \\ a_{21}x_1 & + & a_{12}x_2 & = & b_2 \end{array}$$

with its associated coefficient matrix

$$\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}$$

Let us define the number $D := a_{11}a_{22} - a_{21}a_{12}$.

We saw earlier that, provided that $D \neq 0$,
the two simultaneous equations have a unique solution given by

$$x_1 = \frac{1}{D}(b_1 a_{22} - b_2 a_{12}), \quad x_2 = \frac{1}{D}(b_2 a_{11} - b_1 a_{21})$$

This number D is called the determinant of the matrix $\mathbf{A}$.

It is denoted by either $\det(\mathbf{A})$, or more concisely, by $|\mathbf{A}|$.

Determinants of Order 2: Simple Rule

Thus, for any 2×2 matrix $\mathbf{A}$, its determinant D is

$$|\mathbf{A}| = \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} = a_{11}a_{22} - a_{21}a_{12}$$

For this special case of order 2 determinants, a simple rule is:

1. multiply the diagonal elements together;
2. multiply the off-diagonal elements together;
3. subtract the product of the off-diagonal elements from the product of the diagonal elements.

Exercise

Show that the determinant satisfies

$$|\mathbf{A}| = a_{11}a_{22} \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} + a_{21}a_{12} \begin{vmatrix} 0 & 1 \\ 1 & 0 \end{vmatrix}$$

Transposing the Rows or Columns

Example

Consider the two 2×2 matrices $\mathbf{A} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$, $\quad \mathbf{T} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$.

Note that $\mathbf{T}$ is orthogonal.

Also, one has $\mathbf{AT} = \begin{pmatrix} b & a \\ d & c \end{pmatrix}$ and $\mathbf{TA} = \begin{pmatrix} c & d \\ a & b \end{pmatrix}$.

Here $\mathbf{T}$ is a transposition matrix which interchanges:
(i) the columns of $\mathbf{A}$ in $\mathbf{AT}$;
(ii) the rows of $\mathbf{A}$ in $\mathbf{TA}$.

Evidently $|\mathbf{T}| = -1$ and $|\mathbf{TA}| = |\mathbf{AT}| = (bc - ad) = -|\mathbf{A}|$.

So interchanging either the two rows or the two columns of $\mathbf{A}$ (but not both) changes the sign of $|\mathbf{A}|$.

Sign Adjusted Transpositions

Example

Next, consider the following three 2×2 matrices:

$$\mathbf{A} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}, \quad \mathbf{T} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \hat{\mathbf{T}} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

Note that, like $\mathbf{T}$, the matrix $\hat{\mathbf{T}}$ is orthogonal.

Here one has $\mathbf{A}\hat{\mathbf{T}} = \begin{pmatrix} b & -a \\ d & -c \end{pmatrix}$ and $\hat{\mathbf{T}}\mathbf{A} = \begin{pmatrix} -c & -d \\ a & b \end{pmatrix}$.

Evidently $|\hat{\mathbf{T}}| = 1$ and $|\hat{\mathbf{T}}\mathbf{A}| = |\mathbf{A}\hat{\mathbf{T}}| = (ad - bc) = |\mathbf{A}|$.

The same is true of its transpose (and inverse) $\hat{\mathbf{T}}^\top = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$.

This key property makes both $\hat{\mathbf{T}}$ and $\hat{\mathbf{T}}^\top$
sign adjusted versions of the transposition matrix $\mathbf{T}$.

Cramer's Rule in the 2×2 Case

Using determinant notation, the solution to the equations

$$\begin{array}{ccccc} a_{11}x_1 & + & a_{12}x_2 & = & b_1 \\ a_{21}x_1 & + & a_{12}x_2 & = & b_2 \end{array}$$

can be written in the alternative form

$$x_1 = \frac{1}{D}\begin{vmatrix} b_1 & a_{12} \\ b_2 & a_{22} \end{vmatrix}, \qquad x_2 = \frac{1}{D}\begin{vmatrix} a_{11} & b_1 \\ a_{21} & b_2 \end{vmatrix}$$

This accords with Cramer's rule,
which says that the solution to $\mathbf{Ax} = \mathbf{b}$ is the vector $\mathbf{x} = (x_i)_{i=1}^n$
each of whose components x_i is the fraction with:

1. denominator equal to the determinant D
of the coefficient matrix $\mathbf{A}$ (provided, of course, that $D \neq 0$);
2. numerator equal to the determinant of the matrix $[\mathbf{A}_{-i}/\mathbf{b}]$
formed from $\mathbf{A}$ by excluding its ith column,
then replacing it with the $\mathbf{b}$ vector of right-hand side elements,
while keeping all the columns in their original order.

Determinants of Order 3: Definition

Determinants of order 3 can be calculated
from those of order 2 according to the formula

$$\begin{aligned} |\mathbf{A}| &= a_{11} \begin{vmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{vmatrix} - a_{12} \begin{vmatrix} a_{21} & a_{23} \\ a_{31} & a_{33} \end{vmatrix} + a_{13} \begin{vmatrix} a_{21} & a_{22} \\ a_{31} & a_{32} \end{vmatrix} \\ &= \sum_{j=1}^{3} (-1)^{1+j} a_{1j} |\mathbf{C}_{1j}| \end{aligned}$$

where, for $j = 1, 2, 3$, the 2×2 matrix $\mathbf{C}_{1j}$ is the $(1, j)$-cofactor
obtained by removing both row 1 and column j from the matrix $\mathbf{A}$.

The result is the following sum

$$\begin{aligned} |\mathbf{A}| = a_{11}a_{22}a_{33} - a_{11}a_{23}a_{32} + a_{12}a_{23}a_{31} \\ - a_{12}a_{21}a_{33} + a_{13}a_{21}a_{32} - a_{13}a_{22}a_{31} \end{aligned}$$

of $3! = 6$ terms, each the product of 3 elements chosen
so that each row and each column is represented just once.

Determinants of Order 3: Cofactor Expansion

The determinant expansion

$$|\mathbf{A}| = a_{11}a_{22}a_{33} - a_{11}a_{23}a_{32} + a_{12}a_{23}a_{31} - a_{12}a_{21}a_{33} + a_{13}a_{21}a_{32} - a_{13}a_{22}a_{31}$$

is very symmetric, suggesting (correctly)
that the cofactor expansion along the first row (a_{11}, a_{12}, a_{13})

$$|\mathbf{A}| = \sum_{j=1}^{3} (-1)^{1+j} a_{1j} |\mathbf{C}_{1j}|$$

gives the same answer as the other cofactor expansions

$$|\mathbf{A}| = \sum_{j=1}^{3} (-1)^{r+j} a_{rj} |\mathbf{C}_{rj}| = \sum_{i=1}^{3} (-1)^{i+s} a_{is} |\mathbf{C}_{is}|$$

along, respectively:

- the rth row (a_{r1}, a_{r2}, a_{r3})
- the sth column (a_{1s}, a_{2s}, a_{3s})

Determinants of Order 3: Alternative Expressions

One way of condensing the notation

$$|\mathbf{A}| = a_{11}a_{22}a_{33} - a_{11}a_{23}a_{32} + a_{12}a_{23}a_{31} - a_{12}a_{21}a_{33} + a_{13}a_{21}a_{32} - a_{13}a_{22}a_{31}$$

is to reduce it to $|\mathbf{A}| = \sum_{\pi \in \Pi_3} \operatorname{sgn}(\pi) \prod_{i=1}^{3} a_{i\pi(i)}$
for the sign function $\Pi_3 \ni \pi \mapsto \operatorname{sgn}(\pi) \in \{-1, +1\}$.

The six values of $\operatorname{sgn}(\pi)$ can be read off as

$$\begin{array}{lllllllll} \operatorname{sgn}(\pi^{123}) & = & +1; & \operatorname{sgn}(\pi^{132}) & = & -1; & \operatorname{sgn}(\pi^{231}) & = & +1; \\ \operatorname{sgn}(\pi^{213}) & = & -1; & \operatorname{sgn}(\pi^{312}) & = & +1; & \operatorname{sgn}(\pi^{321}) & = & -1. \end{array}$$

Exercise

Verify these values for each of the six $\pi \in \Pi_3$ by:

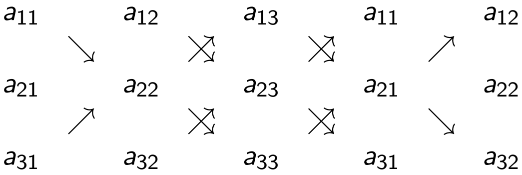
1. *calculating the number of inversions directly;*
2. *expressing each π as the product of transpositions, and then counting these.*

Sarrus's Rule: Diagram

An alternative way to evaluate determinants only of order 3
is to add two new columns
that repeat the first and second columns:

$$\begin{matrix} a_{11} & a_{12} & a_{13} & a_{11} & a_{12} \\ a_{21} & a_{22} & a_{23} & a_{21} & a_{22} \\ a_{31} & a_{32} & a_{33} & a_{31} & a_{32} \end{matrix}$$

Then add lines/arrows going up to the right or down to the right,
as shown below



Note that some pairs of arrows in the middle cross each other.

Sarrus's Rule Defined

Now:

1. multiply along the three lines falling to the right,
   then sum these three products, to obtain

$$a_{11}\, a_{22}\, a_{33} + a_{12}\, a_{23}\, a_{31} + a_{13}\, a_{21}\, a_{32}$$

2. multiply along the three lines rising to the right,
   then sum these three products, giving the sum a minus sign,
   to obtain

$$-a_{11}\, a_{23}\, a_{32} - a_{12}\, a_{21}\, a_{33} - a_{13}\, a_{22}\, a_{31}$$

The sum of all six terms exactly equals the earlier formula for $|\mathbf{A}|$.

Note that this method, known as Sarrus's rule,
does not generalize to determinants of order higher than 3.

Outline

The Determinant Function

For each $n \in \mathbb{N}$, let $\mathcal{M}_{n \times n}$ denote the domain of $n \times n$ matrices.
It is evidently a copy of the space $\mathbb{R}^{n \times n} = \mathbb{R}^{n^2}$.

Definition

For all $n \in \mathbb{N}$, the determinant function

$$\mathcal{M}_{n \times n} \ni \mathbf{A} \mapsto \det \mathbf{A} = |\mathbf{A}| := \sum_{\pi \in \Pi_n} \operatorname{sgn}(\pi) \prod_{i=1}^{n} a_{i\pi(i)} \in \mathbb{R}$$

specifies the determinant $|\mathbf{A}|$ of each $n \times n$ matrix $\mathbf{A}$
as a function of its n row vectors $(\mathbf{a}_i^\top)_{i=1}^n = \left((a_{ij})_{j=1}^n\right)_{i=1}^n$. □

Here the multiplier $\operatorname{sgn}(\pi)$ attached to each product of n terms
can be regarded as the sign adjustment
associated with the permutation $\pi \in \Pi_n$.

A Four-Part Exercise

Exercise

Use the formula on the previous slide to calculate $|\mathbf{A}|$ *when* $\mathbf{A}$ *is:*

1. *the general* 2×2 *matrix* $\begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}$ *;*
2. *any* 3×3 *matrix of the form* $\begin{pmatrix} a_{11} & a_{12} & 0 \\ 0 & a_{22} & 0 \\ 0 & 0 & a_{33} \end{pmatrix}$ *with at most one non-zero term off the diagonal;*
3. *any* 3×3 *matrix of the form* $\begin{pmatrix} a_{11} & a_{12} & 0 \\ a_{21} & a_{22} & 0 \\ 0 & 0 & a_{33} \end{pmatrix}$ *with at most two non-zero terms off the diagonal;*
4. *any* $n \times n$ *diagonal matrix* $\mathbf{D} = \mathbf{diag}(d_1, d_2, \ldots, d_n)$*.*

Functions of the Rows of a Matrix

For a general natural number $n \in \mathbb{N}$, consider any function

$$\mathcal{M}_{n \times n} \ni \mathbf{A} \mapsto D(\mathbf{A}) = D\left(\langle \mathbf{a}_i^\top \rangle_{i=1}^n\right) \in \mathbb{R}$$

whose domain $\mathcal{M}_{n \times n}$ is the set of all $n \times n$ matrices $\mathbf{A}$, regarded as a collection of n row vectors $\langle \mathbf{a}_i^\top \rangle_{i=1}^n$.

Notation: For each fixed $r \in \mathbb{N}_n$, let $D(\mathbf{A}_{-r}/\mathbf{b}_r^\top)$

denote the new value $D(\mathbf{a}_1^\top, \ldots, \mathbf{a}_{r-1}^\top, \mathbf{b}_r^\top, \mathbf{a}_{r+1}^\top, \ldots, \mathbf{a}_n^\top)$
of the function $\mathbf{A} \mapsto D(\mathbf{A})$ after the rth row $\mathbf{a}_r^\top$ of the matrix $\mathbf{A}$
has been replaced by the new row vector $\mathbf{b}_r^\top \in \mathbb{R}^n$,
with all the other $n-1$ rows remaining fixed.

Row Multilinearity

Definition

The function $\mathcal{M}_{n \times n} \ni \mathbf{A} \mapsto D(\mathbf{A})$ of the n rows $\langle \mathbf{a}_i^\top \rangle_{i=1}^n$ of $\mathbf{A}$ is (row) multilinear just in case, for each row number $i \in \mathbb{N}_n$, for each pair $\mathbf{b}_i^\top, \mathbf{c}_i^\top \in \mathbb{R}^n$ of new versions of row i, and for each pair of scalars $\lambda, \mu \in \mathbb{R}$, one has

$$D(\mathbf{A}_{-i}/\lambda \mathbf{b}_i^\top + \mu \mathbf{c}_i^\top) = \lambda D(\mathbf{A}_{-i}/\mathbf{b}_i^\top) + \mu D(\mathbf{A}_{-i}/\mathbf{c}_i^\top) \quad \square$$

Formally, the mapping $\mathbb{R}^n \ni \mathbf{a}_i^\top \mapsto D(\mathbf{A}_{-i}/\mathbf{a}_i^\top) \in \mathbb{R}$ is required to be linear, for fixed each row $i \in \mathbb{N}_n$.

That is, D is a linear function of the ith row vector $\mathbf{a}_i^\top$ on its own, when all the other rows $\mathbf{a}_h^\top$ $(h \neq i)$ are fixed.

Determinants are Row Multilinear

Theorem

For all $n \in \mathbb{N}$, the earlier definition implies that the determinant mapping

$$\mathcal{M}_{n \times n} \ni \mathbf{A} \mapsto |\mathbf{A}| := \sum\nolimits_{\pi \in \Pi_n} \operatorname{sgn}(\pi) \prod\nolimits_{i=1}^{n} a_{i\pi(i)} \in \mathbb{R}$$

is a row multilinear function of its n row vectors $(\mathbf{a}_i^\top)_{i=1}^n$.

Proof.

For each fixed row $r \in \mathbb{N}_n$, the determinant mapping satisfies

$$\begin{aligned} & \det(\mathbf{A}_{-r}/\lambda \mathbf{b}_r^\top + \mu \mathbf{c}_r^\top) \\ = \; & \sum\nolimits_{\pi \in \Pi_n} \operatorname{sgn}(\pi) \left(\lambda b_{r\pi(r)} + \mu c_{r\pi(r)}\right) \prod\nolimits_{i \neq r} a_{i\pi(i)} \\ = \; & \sum\nolimits_{\pi \in \Pi_n} \operatorname{sgn}(\pi) \left[\lambda b_{r\pi(r)} \prod\nolimits_{i \neq r} a_{i\pi(i)} + \mu c_{r\pi(r)} \prod\nolimits_{i \neq r} a_{i\pi(i)}\right] \\ = \; & \lambda \det(\mathbf{A}_{-r}/\mathbf{b}_r^\top) + \mu \det(\mathbf{A}_{-r}/\mathbf{c}_r^\top) \end{aligned}$$

This confirms multilinearity. □

Outline

The Eight Basic Rules: Background and Explanation

EMEA is an acronym for our undergraduate textbook
Essential Mathematics for Economic Analysis.

EMEAn is an abbreviation for the n edition.

Some of you may have used EMEA5,
but EMEA6 did appear in 2021.

The eight rules labelled 1–8 here appear as Rules A–H in:

- Section 16.4 of EMEA5
  — see Theorem 16.4.1 on page 636;
- Section 13.4 of EMEA6
  — see Theorem 13.4.1 on page 509.

Of the eight rules:

- Rule 6 plays a key role when discussing pivoting subsequently;
- Rules 1–6 and Rule 8 will be confirmed here;
- a proof of Rule 7, which uses pivoting in a key way,
  is deferred until the next Segment D.

The Eight Basic Rules: Statement

Let $|\mathbf{A}|$ denote the determinant of any $n \times n$ matrix $\mathbf{A}$.

1. $|\mathbf{A}| = 0$ if all the elements in a row (or column) of $\mathbf{A}$ are 0.
2. $|\mathbf{A}^\top| = |\mathbf{A}|$, where $\mathbf{A}^\top$ is the transpose of $\mathbf{A}$.
3. If all the elements in a single row (or column) of $\mathbf{A}$ are multiplied by a scalar α, so is its determinant.
4. If two rows (or two columns) of $\mathbf{A}$ are interchanged, the determinant changes sign, but not its absolute value.
5. If two of the rows (or columns) of $\mathbf{A}$ are proportional, then $|\mathbf{A}| = 0$.
6. The value of the determinant of $\mathbf{A}$ is unchanged if any multiple of one row (or one column) is added to a different row (or column) of $\mathbf{A}$.
7. The determinant of the product $|\mathbf{AB}|$ of two $n \times n$ matrices equals the product $|\mathbf{A}| \cdot |\mathbf{B}|$ of their determinants.
8. If α is any scalar, then $|\alpha\mathbf{A}| = \alpha^n|\mathbf{A}|$.

Verifying the Transpose Rule 2

The transpose rule 2 is very useful: it implies that for any statement $\mathcal{S}$ about how $|\mathbf{A}|$ depends on the rows of $\mathbf{A}$, there is an equivalent "transpose" statement $\mathcal{S}^\top$ about how $|\mathbf{A}|$ depends on the columns of $\mathbf{A}$.

Exercise

Verify Rule 2 directly for 2×2 *and then for* 3×3 *matrices.*

Proof of Rule 2 The expansion formula implies that

$$|\mathbf{A}| = \sum_{\pi \in \Pi} \operatorname{sgn}(\pi) \prod_{i=1}^{n} a_{i\pi(i)} = \sum_{\pi \in \Pi} \operatorname{sgn}(\pi) \prod_{j=1}^{n} a_{\pi^{-1}(j)j}$$

But we proved earlier that $\operatorname{sgn}(\pi^{-1}) = \operatorname{sgn}(\pi)$.

Also $a_{\pi^{-1}(j)j} = a^\top_{j\pi^{-1}(j)}$ by definition of transpose.

Hence, because $\pi \leftrightarrow \pi^{-1}$ is a bijection on the set Π, the expansion formula with π replaced by π^{-1} implies that $|\mathbf{A}| = \sum_{\pi^{-1} \in \Pi} \operatorname{sgn}(\pi^{-1}) \prod_{j=1}^{n} a^\top_{j\pi^{-1}(j)} = |\mathbf{A}^\top|$. $\square$

Verifying the Alternation Rule 4

Recall the notation $\tau_{r,s}$ for the transposition of $r, s \in \mathbb{N}_n$.

Let $\mathbf{A}_{r \leftrightarrow s}$ denote the matrix that results from applying $\tau_{r,s}$ to the rows of the matrix $\mathbf{A}$ — i.e., interchanging rows r and s.

Theorem

Given any $n \times n$ matrix $\mathbf{A}$ and any transposition $\tau_{r,s}$, one has $\det \mathbf{A}_{r \leftrightarrow s} = -\det \mathbf{A}$.

Proof.

Write τ for $\tau_{r,s}$. Then, because $\pi \leftrightarrow \tau^{-1} \circ \pi$ is a bijection on Π_n and $\operatorname{sgn}(\tau^{-1} \circ \pi) = -\operatorname{sgn}(\pi)$ for all $\pi \in \Pi_n$, we have

$$\begin{aligned}
\det \mathbf{A}_{r \leftrightarrow s} &= \textstyle\sum_{\pi \in \Pi_n} \operatorname{sgn}(\pi) \prod_{i=1}^n a_{\tau(i),\pi(i)} \\
&= \textstyle\sum_{\pi \in \Pi_n} \operatorname{sgn}(\pi) \prod_{i=1}^n a_{i,(\tau^{-1} \circ \pi)(i)} \\
&= -\textstyle\sum_{\pi \in \Pi_n} \operatorname{sgn}(\tau^{-1} \circ \pi) \prod_{i=1}^n a_{i,(\tau^{-1} \circ \pi)(i)} \\
&= -\textstyle\sum_{\pi \in \Pi_n} \operatorname{sgn}(\pi) \prod_{i=1}^n a_{i,\pi(i)} = -\det \mathbf{A} \quad \square
\end{aligned}$$

The Duplication Rule, and Rule 8

The following duplication rule is a special case of Rule 5.

Proposition

If two different rows r and s of $\mathbf{A}$ are equal, then $|\mathbf{A}| = 0$.

Proof.

Suppose that rows r and s of $\mathbf{A}$ are equal.

Then $\mathbf{A}_{r \leftrightarrow s} = \mathbf{A}$, and so $|\mathbf{A}_{r \leftrightarrow s}| = |\mathbf{A}|$.

Yet the alternation Rule 4 implies that $|\mathbf{A}_{r \leftrightarrow s}| = -|\mathbf{A}|$.

Hence $|\mathbf{A}| = -|\mathbf{A}|$, implying that $|\mathbf{A}| = 0$. □

Rule 8: $|\alpha \mathbf{A}| = \alpha^n |\mathbf{A}|$ for any $\alpha \in \mathbb{R}$.

Proof.

The expansion formula implies that

$$\begin{aligned} |\alpha \mathbf{A}| &= \sum_{\pi \in \Pi} \operatorname{sgn}(\pi) \prod_{i=1}^{n} (\alpha a_{i\pi(i)}) \\ &= \alpha^n \sum_{\pi \in \Pi} \operatorname{sgn}(\pi) \prod_{i=1}^{n} a_{i\pi(i)}) = \alpha^n |\mathbf{A}| \end{aligned}$$ □

First Implications of Multilinearity: Rules 1 and 3

Recall the notation $\mathbf{A}_{-r}/\mathbf{b}_r^\top$ for the matrix that results after the rth row $\mathbf{a}_r^\top$ of $\mathbf{A}$ has been replaced by $\mathbf{b}_r^\top$.

With this notation, the matrix $\mathbf{A}_{-r}/\alpha\mathbf{a}_r^\top$ is the result of replacing the rth row $\mathbf{a}_r^\top$ of $\mathbf{A}$ by $\alpha\mathbf{a}_r^\top$.

That is, it is the result of multiplying the rth row $\mathbf{a}_r^\top$ of $\mathbf{A}$ by the scalar α.

Rule 3: If all the elements in a single row of $\mathbf{A}$ are multiplied by a scalar α, so is its determinant.

Proof.

By multilinearity one has $|\mathbf{A}_{-r}/\alpha\mathbf{a}_r^\top| = \alpha|\mathbf{A}_{-r}/\mathbf{a}_r^\top| = \alpha|\mathbf{A}|$. □

Rule 1: $|\mathbf{A}| = 0$ if all the elements in a row of $\mathbf{A}$ are 0.

Proof.

This follows from putting $\alpha = 0$ in Rule 3. □

More Implications of Multilinearity: Rule 5

Rule 5: If two rows of $\mathbf{A}$ are proportional, then $|\mathbf{A}| = 0$.

Proof.

Suppose that $\mathbf{a}_r^\top = \alpha \mathbf{a}_s^\top$ where $r \neq s$.

Then $|\mathbf{A}| = |\mathbf{A}_{-r}/(\alpha \mathbf{a}_s^\top)_r| = \alpha |\mathbf{A}_{-r}/(\mathbf{a}_s^\top)_r| = 0$ by duplication. □

More Implications of Multilinearity: Rule 6

Rule 6: $|\mathbf{A}|$ is unchanged if any multiple of one row is added to a different row of $\mathbf{A}$.

Proof.

For the matrix $\mathbf{A}_{-r}/(\mathbf{a}_r^\top + \alpha \mathbf{a}_s^\top)_r$, where α times row s of $\mathbf{A}$ has been added to row r, row multilinearity implies that

$$|\mathbf{A}_{-r}/(\mathbf{a}_r^\top + \alpha \mathbf{a}_s^\top)_r| = |\mathbf{A}_{-r}/(\mathbf{a}_r^\top)_r| + \alpha |\mathbf{A}_{-r}/(\mathbf{a}_s^\top)_r|$$

But $\mathbf{A}_{-r}/(\mathbf{a}_r^\top)_r = \mathbf{A}$ and $\mathbf{A}_{-r}/(\mathbf{a}_s^\top)_r$ has a copy of row s in row r.

By the duplication rule, it follows that $|\mathbf{A}_{-r}/(\mathbf{a}_s^\top)_r| = 0$ and so

$$\begin{aligned} |\mathbf{A}_{-r}/(\mathbf{a}_r^\top + \alpha \mathbf{a}_s^\top)_r| &= |\mathbf{A}_{-r}/(\mathbf{a}_r^\top)_r| + \alpha |\mathbf{A}_{-r}/(\mathbf{a}_s^\top)_r| \\ &= |\mathbf{A}| + 0 = |\mathbf{A}| \end{aligned}$$

□

Verification of the Product Rule 7: Diagonal Case

Recall that Rule 7 is the product rule stating that $|\mathbf{AB}| = |\mathbf{A}| \cdot |\mathbf{B}|$.

Later we will use pivoting to verify this rule for general matrices.

Here we consider the special case when the first matrix $\mathbf{A}$
is the $n \times n$ diagonal matrix $\mathbf{D} = \mathbf{diag}(d_1, d_2, \ldots, d_n)$.

Proposition

For any $n \times n$ matrix $\mathbf{B}$, one has $|\mathbf{DB}| = |\mathbf{D}| \cdot |\mathbf{B}| = \left(\prod_{k=1}^n d_k\right) |\mathbf{B}|$.

Proof.

First, note that $\mathbf{DB}$ is the matrix that results from simultaneously multiplying each row $i = 1, 2, \ldots, n$ of $\mathbf{B}$
by the corresponding diagonal element d_i of $\mathbf{D}$.

By Rule 3 applied n times,
the result of all these n simultaneous multiplications
is that the determinant is multiplied by the n-fold product $\prod_{i=1}^n d_i$.

So $|\mathbf{DB}| = \prod_{i=1}^n d_i \cdot |\mathbf{B}|$.

But $\mathbf{D}$ is diagonal, so $|\mathbf{D}| = \prod_{i=1}^n d_i$, and $|\mathbf{DB}| = |\mathbf{D}| \cdot |\mathbf{B}|$. $\square$

Outline

Triangular Matrices: Definition

Definition

A square matrix is upper (resp. lower) triangular
if all its non-zero off diagonal elements are above and to the right
(resp. below and to the left) of the diagonal
— i.e., in the upper (resp. lower) triangle
bounded by the principal diagonal.

- The elements of an upper triangular matrix $\mathbf{U}$ satisfy $(\mathbf{U})_{ij} = 0$ whenever $i > j$.
- The elements of a lower triangular matrix $\mathbf{L}$ satisfy $(\mathbf{L})_{ij} = 0$ whenever $i < j$.

Products of Upper Triangular Matrices

Theorem

The product $\mathbf{W} = \mathbf{UV}$ *of any two upper triangular matrices* $\mathbf{U}, \mathbf{V}$
is upper triangular,
with diagonal elements $w_{ii} = u_{ii} v_{ii}$ $(i = 1, \ldots, n)$ *equal*
to the product of the corresponding diagonal elements of $\mathbf{U}, \mathbf{V}$.

Proof.

Given any two upper triangular $n \times n$ matrices $\mathbf{U}$ and $\mathbf{V}$,
one has $u_{ik} v_{kj} = 0$ unless both $i \leq k$ and $k \leq j$.

So the elements $(w_{ij})^{n \times n}$ of their product $\mathbf{W} = \mathbf{UV}$ satisfy

$$w_{ij} = \begin{cases} \sum_{k=i}^{j} u_{ik} v_{kj} & \text{if } i \leq j \\ 0 & \text{if } i > j \end{cases}$$

Hence $\mathbf{W} = \mathbf{UV}$ is upper triangular.

Finally, when $j = i$ the above sum collapses to just one term,
and $w_{ii} = u_{ii} v_{ii}$ for $i = 1, \ldots, n$. □

Triangular Matrices: Exercises

Exercise

Prove that the transpose:

1. $\mathbf{U}^\top$ *of any upper triangular matrix* $\mathbf{U}$ *is lower triangular;*
2. $\mathbf{L}^\top$ *of any lower triangular matrix* $\mathbf{L}$ *is upper triangular.*

Exercise

Consider the matrix $\mathbf{E}_{r+\alpha q}$
that represents the elementary row operation
of adding a multiple of α *times row* q *to row* r, *with* $r \neq q$.

Under what conditions is $\mathbf{E}_{r+\alpha q}$
(i) upper triangular? (ii) lower triangular?

Hint: Apply the row operation to the identity matrix $\mathbf{I}$.

Answer: (i) if and only if $q > r$; (ii) if and only if $q < r$.

Products of Lower Triangular Matrices

Theorem

The product of any two lower triangular matrices is lower triangular.

Proof.

Given any two lower triangular matrices $\mathbf{L}, \mathbf{M}$,
taking transposes shows that $(\mathbf{L}\mathbf{M})^\top = \mathbf{M}^\top \mathbf{L}^\top = \mathbf{U}$,
where the product $\mathbf{U}$ is upper triangular,
as the product of upper triangular matrices.

Hence $\mathbf{L}\mathbf{M} = \mathbf{U}^\top$ is lower triangular,
as the transpose of an upper triangular matrix. □

Determinants of Triangular Matrices

Theorem

The determinant of any $n \times n$ upper triangular matrix $\mathbf{U}$ *equals the product of all the elements on its principal diagonal.*

Proof.

Recall the expansion formula $|\mathbf{U}| = \sum_{\pi \in \Pi} \operatorname{sgn}(\pi) \prod_{i=1}^{n} u_{i\pi(i)}$ where Π denotes the set of permutations on $\{1, 2, \ldots, n\}$.

Because $\mathbf{U}$ is upper triangular, one has $u_{i\pi(i)} = 0$ unless $i \leq \pi(i)$.

So $\prod_{i=1}^{n} u_{i\pi(i)} = 0$ unless $i \leq \pi(i)$ for all $i = 1, 2, \ldots, n$.

But the identity ι is the only permutation $\pi \in \Pi$ that satisfies $i \leq \pi(i)$ for all $i \in \mathbb{N}_n$.

Because $\operatorname{sgn}(\iota) = +1$, the expansion reduces to the single term

$$|\mathbf{U}| = \operatorname{sgn}(\iota) \prod_{i=1}^{n} u_{i\iota(i)} = \prod_{i=1}^{n} u_{ii}$$

This is the product of the n diagonal elements, as claimed. □

Invertible Triangular Matrices

Similarly $|\mathbf{L}| = \prod_{i=1}^{n} \ell_{ii}$ for any lower triangular matrix $\mathbf{L}$.

Evidently:

Corollary

*A triangular matrix (upper or lower) has a non-zero determinant, and so is invertible,
if and only if no element on its principal diagonal is 0.*

The Product Rule 7 for Triangular Determinants

Example

Let **A** and **B** be $n \times n$ matrices where:
(i) either both are upper triangular; or (ii) both are lower triangular.

We showed earlier that the product $\mathbf{C} = \mathbf{AB}$ is also triangular.

We also showed that diagonal elements $c_{ii} = a_{ii} b_{ii}$ of the product equal the product of the diagonal elements of **A** and **B**.

Also, recall that the determinant of a triangular matrix, either upper or lower, equals the product of its diagonal elements.

It follows that

$$\begin{aligned} |\mathbf{C}| &= \prod_{i=1}^{n} c_{ii} = \prod_{i=1}^{n} a_{ii} b_{ii} \\ &= \left(\prod_{i=1}^{n} a_{ii}\right)\left(\prod_{i=1}^{n} b_{ii}\right) = |\mathbf{A}| \cdot |\mathbf{B}| \end{aligned}$$

Outline

Three Simultaneous Equations

Consider the following system
of three simultaneous equations in three unknowns,
which depends upon two "exogenous" constants a and b:

$$\begin{array}{rcrcrcl} x & + & y & - & z & = & 1 \\ x & - & y & + & 2z & = & 2 \\ x & + & 2y & + & az & = & b \end{array}$$

It can be expressed, using an augmented 3×4 matrix, as :

$$\left(\begin{array}{rrr|r} 1 & 1 & -1 & 1 \\ 1 & -1 & 2 & 2 \\ 1 & 2 & a & b \end{array}\right)$$

Perhaps even more useful is the doubly augmented 3×7 matrix:

$$\left(\begin{array}{rrr|r|rrr} 1 & 1 & -1 & 1 & 1 & 0 & 0 \\ 1 & -1 & 2 & 2 & 0 & 1 & 0 \\ 1 & 2 & a & b & 0 & 0 & 1 \end{array}\right)$$

whose last 3 columns are those of the 3×3 identity matrix $\mathbf{I}_3$.

Pivoting: First Step

Start with the doubly augmented 3×7 matrix:

$$\begin{array}{ccc|c|ccc} 1 & 1 & -1 & 1 & 1 & 0 & 0 \\ 1 & -1 & 2 & 2 & 0 & 1 & 0 \\ 1 & 2 & a & b & 0 & 0 & 1 \end{array}$$

First, pivot about the element in row 1 and column 1
to eliminate or "zeroize" the other elements of column 1.

This elementary row operation requires us to subtract row 1
from both rows 2 and 3.

It is equivalent to multiplying by the matrix $\mathbf{E}_1 = \begin{pmatrix} 1 & 0 & 0 \\ -1 & 1 & 0 \\ -1 & 0 & 1 \end{pmatrix}$.

Note: this is the result of applying the same row operations to $\mathbf{I}_3$.

The resulting 3×7 matrix is:

$$\begin{array}{ccc|c|ccc} 1 & 1 & -1 & 1 & 1 & 0 & 0 \\ 0 & -2 & 3 & 1 & -1 & 1 & 0 \\ 0 & 1 & a+1 & b-1 & -1 & 0 & 1 \end{array}$$

Pivoting: Second Step

Including another copy of the identity matrix at the end gives:

$$\begin{array}{ccc|c|ccc|ccc} 1 & 1 & -1 & 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & -2 & 3 & 1 & -1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & a+1 & b-1 & -1 & 0 & 1 & 0 & 0 & 1 \end{array}$$

Next, we pivot about the element in row 2 and column 2.

Specifically, add half the second row
to both the first and third rows to obtain:

$$\begin{array}{ccc|c|ccc|ccc} 1 & 0 & \frac{1}{2} & \frac{3}{2} & \frac{1}{2} & \frac{1}{2} & 0 & 1 & \frac{1}{2} & 0 \\ 0 & -2 & 3 & 1 & -1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & a+\frac{5}{2} & b-\frac{1}{2} & -\frac{3}{2} & \frac{1}{2} & 1 & 0 & \frac{1}{2} & 1 \end{array}$$

Again, the pivot operation is equivalent to pre-multiplying

by the matrix $\mathbf{E}_2 = \begin{pmatrix} 1 & \frac{1}{2} & 0 \\ 0 & 1 & 0 \\ 0 & \frac{1}{2} & 1 \end{pmatrix}$,

which is the result of applying the same row operation to $\mathbf{I}_3$.

The Augmented Matrix After Downward Pivoting

The resulting augmented matrix is $\begin{array}{ccc|c} 1 & 0 & \frac{1}{2} & \frac{3}{2} \\ 0 & -2 & 3 & 1 \\ 0 & 0 & a+\frac{5}{2} & b-\frac{1}{2} \end{array}$

whose top two rows and columns form a 2×2 diagonal matrix.

Thus, the two steps of pivoting have eliminated:

- x, the 1st variable, from both the 2nd and 3rd equations;
- y, the 2nd variable, from both the 1st and 3rd equations.

To conclude, we need to treat two different cases:

Case 1: if $a + \frac{5}{2} \neq 0$, the 3×3 coefficient matrix is upper triangular, with a non-zero diagonal;

Case 2: if $a + \frac{5}{2} = 0$, the 3×3 coefficient matrix takes the partitioned form $\begin{pmatrix} \mathbf{D}_{2\times 2} & \mathbf{B}_{2\times 1} \\ \mathbf{0}_{1\times 2} & 0 \end{pmatrix}$ where $\mathbf{D}_{2\times 2}$ is a 2×2 diagonal matrix.

Case 1: Third Pivoting Step

In case 1 when $a + \frac{5}{2} \neq 0$, we will complete solving the equation by pivoting a third time about the 3, 3 element to reach a diagonal matrix whose diagonal terms are non-zero.

Starting with the augmented matrix $\begin{array}{ccc|c} 1 & 0 & \frac{1}{2} & \frac{3}{2} \\ 0 & -2 & 3 & 1 \\ 0 & 0 & a+\frac{5}{2} & b-\frac{1}{2} \end{array}$

and with $c = 1/(a + \frac{5}{2})$, we pivot about the 3, 3 element by adding: (i) $-\frac{1}{2} \cdot c$ times row 3 to row 1; (ii) $-3 \cdot c$ times row 3 to row 2.

The final augmented matrix that results

from this last pivot operation is $\begin{array}{ccc|c} 1 & 0 & 0 & \frac{3}{2} - \frac{1}{2}c(b-\frac{1}{2}) \\ 0 & -2 & 0 & 1 - 3c(b-\frac{1}{2}) \\ 0 & 0 & a+\frac{5}{2} & b-\frac{1}{2} \end{array}$

The coefficient matrix has become diagonal, with all its diagonal elements non-zero.

This makes the resulting equations easy to solve.

Case 1: Solution of the Equation System

The three pivoting operations we have completed have reduced the equation system to

$$\begin{aligned} x &= \tfrac{3}{2} - \tfrac{1}{2}c(b - \tfrac{1}{2}) \\ -2y &= 1 - 3c(b - \tfrac{1}{2}) \\ (a + \tfrac{5}{2})z &= b - \tfrac{1}{2} \end{aligned}$$

Because $c = 1/(a + \frac{5}{2})$, this gives the unique solution

$$x = \tfrac{3}{2} - \tfrac{1}{2}c(b - \tfrac{1}{2}), \quad y = -\tfrac{1}{2} + \tfrac{3}{2}c(b - \tfrac{1}{2}), \quad z = c(b - \tfrac{1}{2})$$

Case 2: Pivoting Concludes after Two Steps

In case 2, when $a + \frac{5}{2} = 0$, after two steps of pivoting,

the augmented matrix has been reduced to $\begin{array}{ccc|c} 1 & 0 & \frac{1}{2} & \frac{3}{2} \\ 0 & -2 & 3 & 1 \\ 0 & 0 & 0 & b - \frac{1}{2} \end{array}$

This takes the partitioned form $\begin{pmatrix} \mathbf{D}_{2\times 2} & \mathbf{B}_{2\times 1} \\ \mathbf{0}_{1\times 2} & 0 \end{pmatrix}$ where:

$\mathbf{D}_{2\times 2}$ is a 2×2 diagonal matrix with non-zero diagonal elements;

$\mathbf{B}_{2\times 1}$ is a 2×1 matrix, or a 2×1 column vector $\mathbf{b}_{2\times 1}$.

Case 2: Dependent Equations

In case 2A, when $b \neq \frac{1}{2}$, neither the last equation, nor the system as a whole, has any solution.

In case 2B, when $b = \frac{1}{2}$, the third equation is redundant.

Then the augmented matrix for the remaining two equations reduces to $\begin{array}{ccc|c} 1 & 0 & \frac{1}{2} & \frac{3}{2} \\ 0 & -2 & 3 & 1 \end{array}$

The associated equation system has a general solution

$$x = \tfrac{3}{2} - \tfrac{1}{2}z \quad \text{and} \quad y = \tfrac{3}{2}z - \tfrac{1}{2}$$

where z is an arbitrary scalar.

In particular, there is a one-dimensional set of solutions along the unique straight line in $\mathbb{R}^3$ that passes through both: (i) $(\frac{3}{2}, -\frac{1}{2}, 0)$, when $z = 0$; (ii) $(1, 1, 1)$, when $z = 1$.

Outline

Row and Column Operations

Definition

For each $m, n \in \mathbb{N}$, let $\mathcal{M}_{m \times n}$ denote the family of all $m \times n$ matrices.

- A row operation is a mapping $\mathcal{M}_{m \times n} \ni \mathbf{X} \mapsto \mathbf{EX} \in \mathcal{M}_{m \times n}$ represented by an $m \times m$ matrix $\mathbf{E}$ that pre-multiplies (or multiplies on the left) any $\mathbf{X} \in \mathcal{M}_{m \times n}$.
- Similarly, a column operation is a mapping $\mathcal{M}_{m \times n} \ni \mathbf{Y} \mapsto \mathbf{YE} \in \mathcal{M}_{m \times n}$ represented by an $n \times n$ matrix $\mathbf{E}$ that post-multiplies (or multiplies on the right) any $\mathbf{Y} \in \mathcal{M}_{m \times n}$. □

Given any $k \in \mathbb{N}$, note that $\mathbf{E}$ is the $k \times k$ matrix which results from applying either the row or the column operation represented by $\mathbf{E}$ to the identity matrix $\mathbf{I}_k$.

Three Kinds of Elementary Row Operation

The pivoting operations used in the previous example
are examples of row operations
that belong to a special category of elementary row operation.

Textbooks (including ours) usually specify
the following three kinds of elementary row operation $\mathbf{A} \mapsto \mathbf{EA}$:

1. rescale one row $r \in \mathbb{N}_m$ by multiplying it
   by a scalar $\alpha \in \mathbb{R} \setminus \{0\}$;
2. swap two rows $r, s \in \mathbb{N}_m$ with $r \neq s$;
3. pivot by adding one rescaled row s to another row r.

In the next few slides we will describe each of these in detail.

There are obviously similar elementary column operations.

Type 1: Rescaling One Row

For each $r \in \mathbb{N}_m$ and each scalar $\alpha \in \mathbb{R} \setminus \{0\}$,
let the $m \times m$ matrix $\mathbf{E}_{r\times\alpha}$ represent the rescaling operation that, when applied to any $m \times n$ matrix $\mathbf{A}$, multiplies row r of $\mathbf{A}$ by α.

The elements of $\mathbf{E}_{r\times\alpha}$, which are those of $\mathbf{E}_{r\times\alpha}\mathbf{I}_m$, are given by

$$(\mathbf{E}_{r\times\alpha})_{ij} = \begin{cases} \delta_{ij} & \text{if } i \neq r \\ \alpha\delta_{ij} & \text{if } i = r \end{cases} \quad \text{for all } (i,j) \in \mathbb{N}_m \times \mathbb{N}_m$$

This implies that $\mathbf{E}_{r\times\alpha} = \mathbf{diag}(1, \ldots, 1, \alpha, 1, \ldots, 1)$,
which differs from $\mathbf{I}_m$ in at most the (r, r) element.

Suppose $m = n$, so the determinant $|\mathbf{A}|$ is well defined.

Then Rule 3 for determinants implies that $|\mathbf{E}_{r\times\alpha}\mathbf{A}| = \alpha|\mathbf{A}|$.

Putting $\mathbf{A} = \mathbf{I}_m$ in this equality implies that

$$|\mathbf{E}_{r\times\alpha}| = |\mathbf{E}_{r\times\alpha}\mathbf{I}_m| = \alpha|\mathbf{I}_m| = \alpha$$

Only in the trivial case when $\alpha = 1$ and so $\mathbf{E}_{r\times\alpha} = \mathbf{I}_m$
does $\mathbf{E}_{r\times\alpha}$ "preserve the determinant"
in the sense that $|\mathbf{E}_{r\times\alpha}\mathbf{A}| = |\mathbf{A}|$.

Type 2: Swapping Two Rows

For each distinct pair $r, s \in \mathbb{N}_m$,
let the $m \times m$ matrix $\mathbf{E}_{r \leftrightarrow s}$ represent the swap operation that, when applied to any $m \times n$ matrix $\mathbf{A}$,
results in row r of $\mathbf{A}$ becoming row s of $\mathbf{E}_{r \leftrightarrow s}\mathbf{A}$, and vice versa.

The elements of $\mathbf{E}_{r \leftrightarrow s}$, which are those of $\mathbf{E}_{r \leftrightarrow s}\mathbf{I}_m$, are given by

$$(\mathbf{E}_{r \leftrightarrow s})_{ij} = \begin{cases} \delta_{ij} & \text{if } i \notin \{r, s\} \\ \delta_{sj} & \text{if } i = r \\ \delta_{rj} & \text{if } i = s \end{cases} \qquad \text{for all } (i,j) \in \mathbb{N}_m \times \mathbb{N}_m$$

Suppose $m = n$, so the determinant $|\mathbf{A}|$ is well defined.

Then Rule 4 for determinants implies that $|\mathbf{E}_{r \leftrightarrow s}\mathbf{A}| = -|\mathbf{A}|$.

Putting $\mathbf{A} = \mathbf{I}_m$ in this equality implies that

$$|\mathbf{E}_{r \leftrightarrow s}| = |\mathbf{E}_{r \leftrightarrow s}\mathbf{I}_m| = -|\mathbf{I}_m| = -1$$

Because $|\mathbf{E}_{r \leftrightarrow s}\mathbf{A}| = |\mathbf{A}|$ only if $|\mathbf{A}| = 0$,
this matrix is not "determinant preserving".

Type 3: Pivoting by Adding One Rescaled Row to Another

For each distinct pair $r, s \in \mathbb{N}_m$ and each scalar $\alpha \in \mathbb{R}$,
let the $m \times m$ matrix $\mathbf{E}_{r+\alpha s}$ represent
the elementary row pivot operation which,
when applied to any $m \times n$ matrix $\mathbf{A}$,
adds α times its row s to its row r, without affecting any other row.

The elements of $\mathbf{E}_{r+\alpha s}$, which are those of $\mathbf{E}_{r+\alpha s}\mathbf{I}_m$,
are given for all $(i, j) \in \mathbb{N}_m \times \mathbb{N}_m$ by

$$(\mathbf{E}_{r+\alpha s})_{ij} = \left\{ \begin{array}{ll} \delta_{ij} & \text{if } i \neq r \\ \delta_{ij} + \alpha\delta_{sj} & \text{if } i = r \end{array} \right\} = \delta_{ij} + \alpha\delta_{ir}\delta_{sj}$$

Thus $\mathbf{E}_{r+\alpha s} = \mathbf{I}_m + \alpha\mathbf{1}_{rs}$ where $\mathbf{1}_{rs}$ denotes the $m \times m$ matrix
whose only non-zero element is 1 in row r and column s.

In particular $\mathbf{E}_{r+\alpha s}$ is upper or lower triangular
according as $r < s$ or $r > s$,
or equivalently, according as row r is above or below row s.

Outline

Determinant Preserving Operations: Definition

Definition

For each $m, n \in \mathbb{N}$,
let $\mathcal{M}_{m \times n}$ denote the family of all $m \times n$ matrices.

The row operation $\mathcal{M}_{m \times n} \ni \mathbf{X} \mapsto \mathbf{EX} \in \mathcal{M}_{m \times n}$
that is represented by the $m \times m$ matrix $\mathbf{E}$
is determinant preserving just in case,
given any $m \times m$ matrix $\mathbf{A}$, one has $|\mathbf{EA}| = |\mathbf{A}|$.

Similarly, the column operation $\mathcal{M}_{m \times n} \ni \mathbf{Y} \mapsto \mathbf{YE} \in \mathcal{M}_{m \times n}$
that is represented by the $n \times n$ matrix $\mathbf{E}$
is determinant preserving just in case,
given any $n \times n$ matrix $\mathbf{A}$, one has $|\mathbf{AE}| = |\mathbf{A}|$. □

Properties of Determinant Preserving Operations, I

Lemma

If a square matrix $\mathbf{E}$ *represents either a row or column operation that is determinant preserving, then* $|\mathbf{E}| = 1$.

Proof.

Because $\mathbf{I}$ is a diagonal matrix, putting $\mathbf{X} = \mathbf{I}$ or $\mathbf{Y} = \mathbf{I}$ in the definition of determinant preservation gives:

1. $|\mathbf{E}| = |\mathbf{EI}| = |\mathbf{I}| = 1$ in the case of a row operation;
2. $|\mathbf{E}| = |\mathbf{IE}| = |\mathbf{I}| = 1$ in the case of a column operation. □

Properties of Determinant Preserving Operations, II

Proposition

Suppose that the two $k \times k$ matrices $\mathbf{E}_1$ and $\mathbf{E}_2$ both represent determinant preserving row (resp. column) operations.

Then the $k \times k$ product matrix $\mathbf{E}_1 \mathbf{E}_2$ also represents a determinant preserving row (resp. column) operation.

Proof.

Given any $k \times n$ matrix $\mathbf{X}$, because $\mathbf{E}_2 \mathbf{X}$ is a $k \times n$ matrix, determinant preservation of both $\mathbf{E}_1$ and $\mathbf{E}_2$ implies that

$$|(\mathbf{E}_1 \mathbf{E}_2)\mathbf{X}| = |\mathbf{E}_1(\mathbf{E}_2 \mathbf{X})| = |\mathbf{E}_2 \mathbf{X}| = |\mathbf{X}|$$

Similarly, given any $m \times k$ matrix $\mathbf{Y}$,
because $\mathbf{Y}\mathbf{E}_1$ is an $m \times k$ matrix,
determinant preservation of both $\mathbf{E}_1$ and $\mathbf{E}_2$ implies that

$$|\mathbf{Y}(\mathbf{E}_1 \mathbf{E}_2)| = |(\mathbf{Y}\mathbf{E}_1)\mathbf{E}_2| = |\mathbf{Y}\mathbf{E}_1| = |\mathbf{Y}| \qquad \square$$

Elementary Pivoting Is Determinant Preserving

Given any triple $(r, s, \alpha) \in \mathbb{N}_m \times \mathbb{N}_m \times \mathbb{R}$ with $r \neq s$,
the $m \times m$ matrix $\mathbf{E}_{r+\alpha s}$ represents the elementary pivot row operation $\mathcal{M}_{m\times n} \ni \mathbf{X} \mapsto \mathbf{E}_{r+\alpha s}\mathbf{X} \in \mathcal{M}_{m\times n}$
of adding α times row s of the matrix $\mathbf{X}$ to its row r.

Similarly, the $n \times n$ matrix $(\mathbf{E}_{r+\alpha s})^\top$ represents the elementary pivot column operation $\mathcal{M}_{m\times n} \ni \mathbf{Y} \mapsto \mathbf{Y}(\mathbf{E}_{r+\alpha s})^\top \in \mathcal{M}_{m\times n}$
of adding α times column s of the matrix $\mathbf{Y}$ to its column r.

Consider any $m \times n$ matrix $\mathbf{A}$ with $n = m$,
so that $\mathbf{A}$ has a well defined determinant $|\mathbf{A}|$.

Then Rule 6 for determinants implies that

$$|\mathbf{E}_{r+\alpha s}\mathbf{A}| = |\mathbf{A}(\mathbf{E}_{r+\alpha s})^\top| = |\mathbf{A}|$$

In this sense, both the row operation represented by $\mathbf{E}_{r+\alpha s}$
and the column operation represented by $(\mathbf{E}_{r+\alpha s})^\top$
are determinant preserving.

Determinant Preserving Row Swaps

The second elementary row operation $\mathbf{E}_{r \leftrightarrow s}$ of swapping is not determinant preserving without a key modification.

Let $\hat{\mathbf{T}}_{rs} = \mathbf{E}_{s \times (-1)} \mathbf{E}_{r \leftrightarrow s}$ denote the $m \times m$ matrix that describes the combined row operation of:

1. first interchanging rows r and s, as in $\mathbf{E}_{r \leftrightarrow s}$;
2. but then adjusting or correcting the sign of row s by multiplying it by -1, as in $\mathbf{E}_{s \times (-1)}$.

From Rules 3 and 4 for determinants, given any $m \times m$ matrix $\mathbf{Y}$, we have $|\mathbf{E}_{r \leftrightarrow s} \mathbf{X}| = -|\mathbf{X}|$ and then

$$|\hat{\mathbf{T}}_{rs} \mathbf{X}| = |\mathbf{E}_{s \times (-1)} (\mathbf{E}_{r \leftrightarrow s} \mathbf{X})| = (-1) |\mathbf{E}_{r \leftrightarrow s} \mathbf{X}| = |\mathbf{X}|$$

So $\mathbf{X} \mapsto \hat{\mathbf{T}}_{rs} \mathbf{X}$ is a determinant preserving row operation.

Determinant Preserving Column Swaps

Note that, if the $m \times m$ matrix $\mathbf{R}$ represents a row operation $\mathbf{X} \mapsto \mathbf{RX}$ on $m \times n$ matrices $\mathbf{X}$, then its transpose $\mathbf{R}^\top$ represents a column operation $\mathbf{Y} \mapsto \mathbf{YA}^\top$ on $n \times m$ matrices $\mathbf{Y}$.

In particular, because $\mathbf{X} \mapsto \hat{\mathbf{T}}_{rs}\mathbf{X}$
is a determinant preserving row operation,
it follows that $\mathbf{Y} \mapsto \mathbf{Y}(\hat{\mathbf{T}}_{rs})^\top$
is a determinant preserving column operation.

Outline

Permutation Matrices: Definition

Definition

Given any permutation $\pi \in \Pi_n$ on $\mathbb{N}_n = \{1, 2, \ldots, n\}$,
define $\mathbf{P}^\pi$ as the $n \times n$ permutation matrix
whose elements satisfy $p^\pi_{\pi(i),j} = \delta_{i,j}$ or equivalently $p^\pi_{i,j} = \delta_{\pi^{-1}(i),j}$.

That is, the rows of the identity matrix $\mathbf{I}_n$ are permuted
so that for each $i = 1, 2, \ldots, n$, its ith row vector $(\mathbf{e}_i)^\top$,
whose jth element is δ_{ij} for each $j \in \mathbb{N}_n$,
is moved to become row $\pi(i)$ of $\mathbf{P}^\pi$,
whose jth element is $\delta_{ij} = p^\pi_{\pi(i),j}$ for each $j \in \mathbb{N}_n$. □

Permutation Matrices: 2×2 Examples

Example

There are two 2×2 permutation matrices, which are given by:

$$\mathbf{P}^{12} = \mathbf{I}_2; \quad \mathbf{P}^{21} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}.$$

Their signs, and their determinants, are respectively $+1$ and -1.

Permutation Matrices: 3×3 Examples

Example

There are $3! = 6$ permutation matrices in 3 dimensions given by:

$$\mathbf{P}^{123} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \mathbf{P}^{132} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \mathbf{P}^{213} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\mathbf{P}^{231} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix} \quad \mathbf{P}^{312} = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \quad \mathbf{P}^{321} = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

Their signs equal their determinants, which satisfy

$$\begin{aligned} |\mathbf{P}^{123}| &= |\mathbf{P}^{231}| = |\mathbf{P}^{312}| = +1 \\ \text{and} \quad |\mathbf{P}^{132}| &= |\mathbf{P}^{213}| = |\mathbf{P}^{321}| = -1 \end{aligned}$$

Multiplying a Matrix by a Permutation Matrix

Lemma

Given any $n \times n$ matrix $\mathbf{A}$, for each permutation $\pi \in \Pi_n$ the corresponding permutation matrix $\mathbf{P}^\pi$ satisfies

$$(\mathbf{P}^\pi \mathbf{A})_{\pi(i),j} = a_{ij} = (\mathbf{A}\mathbf{P}^\pi)_{i,\pi(j)}$$

Proof.

For each pair $(i,j) \in \mathbb{N}_n^2$, one has

$$(\mathbf{P}^\pi \mathbf{A})_{\pi(i),j} = \sum_{k=1}^{n} p^\pi_{\pi(i),k} a_{kj} = \sum_{k=1}^{n} \delta_{ik} a_{kj} = a_{ij}$$

and also

$$(\mathbf{A}\mathbf{P}^\pi)_{i,\pi(j)} = \sum_{k=1}^{n} a_{ik} p^\pi_{k,\pi(j)} = \sum_{k=1}^{n} a_{ik} \delta_{kj} = a_{ij} \qquad \square$$

So $\left\{ \begin{array}{c} \text{premultiplying} \\ \text{postmultiplying} \end{array} \right\}$ $\mathbf{A}$ by $\mathbf{P}^\pi$ applies π to $\mathbf{A}$'s $\left\{ \begin{array}{c} \text{rows} \\ \text{columns} \end{array} \right\}$.

Multiplying Permutation Matrices

Theorem

Given the composition $\pi \circ \rho$ of two permutations $\pi, \rho \in \Pi_n$, the associated permutation matrices satisfy $\mathbf{P}^\pi \mathbf{P}^\rho = \mathbf{P}^{\pi \circ \rho}$.

Proof.

For each pair $(i, j) \in \mathbb{N}_n^2$, one has

$$\begin{aligned}
(\mathbf{P}^\pi \mathbf{P}^\rho)_{ij} &= \sum_{k=1}^n p_{ik}^\pi \, p_{kj}^\rho \;=\; \sum_{k=1}^n \delta_{\pi^{-1}(i),k} \, \delta_{\rho^{-1}(k),j} \\
&= \sum_{k=1}^n \delta_{(\rho^{-1} \circ \pi^{-1})(i), \rho^{-1}(k)} \, \delta_{\rho^{-1}(k),j} \\
&= \sum_{\ell=1}^n \delta_{(\pi \circ \rho)^{-1}(i),\ell} \, \delta_{\ell,j} \;=\; \delta_{(\pi \circ \rho)^{-1}(i),j} \\
&= p_{ij}^{\pi \circ \rho} \;=\; (\mathbf{P}^{\pi \circ \rho})_{ij} \qquad \square
\end{aligned}$$

Corollary

If $\pi = \pi^1 \circ \pi^2 \circ \cdots \circ \pi^q$, then $\mathbf{P}^\pi = \mathbf{P}^{\pi^1} \mathbf{P}^{\pi^2} \cdots \mathbf{P}^{\pi^q}$.

Proof.

By induction on q, using the result of the Theorem. $\square$

Any Permutation Matrix Is Orthogonal

Proposition

Any permutation matrix $\mathbf{P}^\pi$ *satisfies* $\mathbf{P}^\pi(\mathbf{P}^\pi)^\top = (\mathbf{P}^\pi)^\top \mathbf{P}^\pi = \mathbf{I}_n$, *so is orthogonal.*

Proof.

Because π is a permutation on $\mathbb{N}_n$, for each pair $(i, j) \in \mathbb{N}_n^2$, one has

$$\begin{aligned} [\mathbf{P}^\pi(\mathbf{P}^\pi)^\top]_{ij} &= \textstyle\sum_{k=1}^n p_{ik}^\pi p_{jk}^\pi = \sum_{k=1}^n \delta_{\pi^{-1}(i),k}\, \delta_{\pi^{-1}(j),k} \\ &= \delta_{\pi^{-1}(i),\pi^{-1}(j)} = \delta_{ij} \end{aligned}$$

and also

$$\begin{aligned} [(\mathbf{P}^\pi)^\top \mathbf{P}^\pi]_{ij} &= \textstyle\sum_{k=1}^n p_{ki}^\pi p_{kj}^\pi = \sum_{k=1}^n \delta_{\pi^{-1}(k),i}\, \delta_{\pi^{-1}(k),j} \\ &= \textstyle\sum_{\ell=1}^n \delta_{\ell,i}\, \delta_{\ell,j} = \delta_{ij} \qquad \square \end{aligned}$$

Transposition Matrices

A special case of a permutation matrix
is a transposition or swap $\mathbf{T}_{rs}$ of rows r and s.

As the matrix $\mathbf{I}$ with rows r and s transposed, it satisfies

$$(\mathbf{T}_{rs})_{ij} = \begin{cases} \delta_{ij} & \text{if } i \notin \{r, s\} \\ \delta_{sj} & \text{if } i = r \\ \delta_{rj} & \text{if } i = s \end{cases}$$

Remark

Distinguish carefully between the two operations of:

1. *swapping the two particular rows or columns r and s of a matrix $\mathbf{A}$, which results from applying $\mathbf{T}_{rs}$ or $\mathbf{T}_{rs}^\top$ to $\mathbf{A}$;*
2. *transposing an entire matrix from $\mathbf{A}$ to $\mathbf{A}^\top$, which results from converting each row vector of $\mathbf{A}$ into a column vector of $\mathbf{A}^\top$, and vice versa.*

Transposition Matrices: Exercise

Exercise

1. *Prove that: (i)* $\mathbf{T}_{rs}$ *is symmetric and orthogonal;*
   (ii) $\mathbf{T}_{rs} = \mathbf{T}_{sr}$*; (iii)* $\mathbf{T}_{rs}\mathbf{T}_{sr} = \mathbf{T}_{sr}\mathbf{T}_{rs} = \mathbf{I}$.
2. *Prove that, if* $\mathbf{A}$ *is any* $m \times n$ *matrix, then:*
   (i) if $\mathbf{T}_{rs}$ *is* $m \times m$*,*
   then $\mathbf{T}_{rs}\mathbf{A}$ *is* $\mathbf{A}$ *with rows* r *and* s *interchanged;*
   (ii) if $\mathbf{T}_{rs}$ *is* $n \times n$*,*
   then $\mathbf{A}\mathbf{T}_{rs}$ *is* $\mathbf{A}$ *with columns* r *and* s *interchanged.*

Determinants with Permuted Rows: Theorem

Theorem

Given any $n \times n$ *matrix* $\mathbf{A}$ *and any permutation* $\pi \in \Pi_n$,
one has $|\mathbf{P}^\pi \mathbf{A}| = |\mathbf{A}\mathbf{P}^\pi| = \operatorname{sgn}(\pi)\,|\mathbf{A}|$.

The proof appears on the next slide.

Meanwhile, putting $\mathbf{A} = \mathbf{I}$ in the theorem gives immediately:

Corollary

Given any permutation $\pi \in \Pi_n$,
the associated permutation matrix $\mathbf{P}^\pi$ *satisfies* $|\mathbf{P}^\pi| = \operatorname{sgn}(\pi)$.

Determinants with Permuted Rows: Proof

Proof.

The expansion formula for determinants gives

$$|\mathbf{P}^\pi \mathbf{A}| = \sum_{\rho \in \Pi_n} \operatorname{sgn}(\rho) \prod_{i=1}^{n} (\mathbf{P}^\pi \mathbf{A})_{i,\rho(i)}$$

But for each $i \in \mathbb{N}_n$, $\rho \in \Pi_n$, one has $(\mathbf{P}^\pi \mathbf{A})_{i,\rho(i)} = a_{\pi^{-1}(i),\rho(i)}$, so

$$\begin{aligned} |\mathbf{P}^\pi \mathbf{A}| &= \sum_{\rho \in \Pi_n} \operatorname{sgn}(\rho) \prod_{i=1}^{n} a_{\pi^{-1}(i),\rho(i)} \\ &= [1/\operatorname{sgn}(\pi)] \sum_{\pi \circ \rho \in \Pi_n} \operatorname{sgn}(\pi \circ \rho) \prod_{i=1}^{n} a_{i,(\pi \circ \rho)(i)} \\ &= \operatorname{sgn}(\pi) \sum_{\sigma \in \Pi_n} \operatorname{sgn}(\sigma) \prod_{i=1}^{n} a_{i,\sigma(i)} \ = \ \operatorname{sgn}(\pi)\, |\mathbf{A}| \end{aligned}$$

because $\operatorname{sgn}(\pi \circ \rho) = \operatorname{sgn}(\pi) \operatorname{sgn}(\rho)$ and $1/\operatorname{sgn}(\pi) = \operatorname{sgn}(\pi)$, whereas there is an obvious bijection $\Pi_n \ni \rho \leftrightarrow \pi \circ \rho = \sigma \in \Pi_n$ on the set of permutations Π_n.

The proof that $|\mathbf{A}\mathbf{P}^\pi| = \operatorname{sgn}(\pi)\, |\mathbf{A}|$ is sufficiently similar to be left as an exercise. □

The Alternation Rule for Determinants

Corollary

Given any $n \times n$ matrix $\mathbf{A}$
and any transposition τ_{rs} with associated transposition matrix $\mathbf{T}_{rs}$,
one has $|\mathbf{T}_{rs}\mathbf{A}| = |\mathbf{A}\mathbf{T}_{rs}| = -|\mathbf{A}|$.

Proof.

Apply the previous theorem in the special case
when $\pi = \tau_{rs}$ and so $\mathbf{P}^\pi = \mathbf{T}_{rs}$.

Then, because $\text{sgn}(\pi) = \text{sgn}(\tau_{rs}) = -1$,
the equality $|\mathbf{P}^\pi\mathbf{A}| = \text{sgn}(\pi)\,|\mathbf{A}|$ implies that $|\mathbf{T}_{rs}\mathbf{A}| = -|\mathbf{A}|$. □

We have shown that, for any $n \times n$ matrix $\mathbf{A}$, given any:

1. permutation $\pi \in \mathbb{N}_n$, one has $|\mathbf{P}^\pi\mathbf{A}| = |\mathbf{A}\mathbf{P}^\pi| = \text{sgn}(\pi)\,|\mathbf{A}|$;
2. transposition τ_{rs}, one has $|\mathbf{T}_{rs}\mathbf{A}| = |\mathbf{A}\mathbf{T}_{rs}| = -|\mathbf{A}|$.

Sign Adjusted Transposition Matrices

We define the sign adjusted $m \times m$ transposition matrix $\hat{\mathbf{T}}_{rs}$
so that, given any $m \times n$ matrix $\mathbf{A}$, the matrix $\hat{\mathbf{T}}_{rs}\mathbf{A}$ is the result of:
(i) first swapping rows r and s of the matrix $\mathbf{A}$;
(ii) then multiplying row s in the result by -1.

Because it is the matrix $\mathbf{I}$ with rows r and s transposed,
and then row s multiplied by -1,
the matrix $\hat{\mathbf{T}}_{rs}$ has elements that satisfy

$$(\hat{\mathbf{T}}_{rs})_{ij} = \begin{cases} \delta_{ij} & \text{if } i \notin \{r, s\} \\ \delta_{sj} & \text{if } i = r \\ -\delta_{rj} & \text{if } i = s \end{cases}$$

Rules 3 and 4 together imply that $|\hat{\mathbf{T}}_{rs}| = |(-1)\mathbf{T}_{rs}| = 1$.

In the special case of any $m \times m$ matrix $\mathbf{A}$, this implies
that the determinants satisfy $|\hat{\mathbf{T}}_{rs}\mathbf{A}| = |(-1)\mathbf{T}_{rs}\mathbf{A}| = |\mathbf{A}|$.

2×2 and 3×3 Sign Adjusted Transposition Matrices

Example

1. The two different 2×2 sign adjusted transposition matrices are $\hat{\mathbf{T}}_{12} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$ and $\hat{\mathbf{T}}_{21} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} = (\hat{\mathbf{T}}_{12})^\top = -\hat{\mathbf{T}}_{12}$.
2. There are six 3×3 sign adjusted transposition matrices.

   The first two satisfy $\hat{\mathbf{T}}_{12} = (\hat{\mathbf{T}}_{21})^\top = \begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$.

   Two others satisfy $\hat{\mathbf{T}}_{13} = (\hat{\mathbf{T}}_{31})^\top = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{pmatrix}$.

   The last two satisfy $\hat{\mathbf{T}}_{23} = (\hat{\mathbf{T}}_{32})^\top = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{pmatrix}$.

Inverses of Sign Adjusted Transposition Matrices

Exercise

1. *Verify that, because* $\hat{\mathbf{T}}_{12}\hat{\mathbf{T}}_{21} = \hat{\mathbf{T}}_{21}\hat{\mathbf{T}}_{12} = \mathbf{I}_2$, *the two* 2×2 *matrices* $\hat{\mathbf{T}}_{12}$ *and* $\hat{\mathbf{T}}_{21}$ *are inverses.*
2. *Verify that whenever* $r, s \in \mathbb{N}_3$ *with* $r \neq s$, *the two* 3×3 *matrices* $\hat{\mathbf{T}}_{rs}$ *and* $\hat{\mathbf{T}}_{sr}$ *are inverses.*

Harder: *Verify directly that whenever* $r, s \in \mathbb{N}_m$ *with* $r \neq s$, *the two* $m \times m$ *matrices* $\hat{\mathbf{T}}_{rs}$ *and* $\hat{\mathbf{T}}_{sr}$ *satisfy* $\hat{\mathbf{T}}_{rs} = (\hat{\mathbf{T}}_{sr})^\top$ *and are inverses.*

Sign Adjusted Permutation Matrices

Given any permutation matrix $\mathbf{P}$,
there is a unique permutation π such that $\mathbf{P} = \mathbf{P}^\pi$.

Suppose that $\pi = \tau_{r_1 s_1} \circ \cdots \circ \tau_{r_\ell s_\ell}$ is any one of the several ways in which the permutation π can be decomposed into a composition of transpositions.

Then $\mathbf{P} = \prod_{k=1}^{\ell} \mathbf{T}_{r_k s_k}$ and $|\mathbf{PA}| = (-1)^\ell |\mathbf{A}|$ for any $\mathbf{A}$.

Definition

Say that $\hat{\mathbf{P}}$ is a sign adjusted version of $\mathbf{P} = \mathbf{P}^\pi$ just in case it can be expressed as the product $\hat{\mathbf{P}} = \prod_{k=1}^{\ell} \hat{\mathbf{T}}_{r_k s_k}$ of sign adjusted transpositions satisfying $\mathbf{P} = \prod_{k=1}^{\ell} \mathbf{T}_{r_k s_k}$.

Then it is easy to prove by induction on ℓ that for every $n \times n$ matrix $\mathbf{A}$ one has $|\hat{\mathbf{P}}\mathbf{A}| = |\mathbf{A}\hat{\mathbf{P}}| = |\mathbf{A}|$.

Recall that all the elements of a permutation matrix $\mathbf{P}$ are 0 or 1.

A sign adjustment of $\mathbf{P}$ involves changing some of the 1 elements into -1 elements, while leaving all the 0 elements unchanged.