

# Linear Algebra

In this section, we present some linear algebra results that are useful in the context of this course. For more information, you can refer to the MAT-1200 course, Deisenroth, Faisal, and Ong (2020) (in English), and Grifone (2024) (in French).

## 1 Some matrix properties

Let  $M_{n,m}(\mathbb{R})$  be the set of matrices with  $n$  rows and  $m$  columns whose entries belong to  $\mathbb{R}$ . Let  $M_n(\mathbb{R})$  be the set of square matrices of size  $n$ , i.e., with  $n$  rows and  $n$  columns whose entries belong to  $\mathbb{R}$ . Let  $M$ ,  $N$ , and  $P$  be matrices in  $M_{n,m}(\mathbb{R})$ . Let  $A$  and  $B$  be matrices in  $M_n(\mathbb{R})$ . Let  $I_n$  be the identity matrix of size  $n$ , i.e., containing 1s on the diagonal and 0s on the elements outside the diagonal. Let  $u$  and  $v$  in  $\mathbb{R}^n$ , i.e., column vectors of size  $n$ .

### Properties of the inverse of matrices

Suppose that the matrices  $A$  and  $B$  are invertible. Then the matrix product  $AB$  is invertible and is given by:

$$(AB)^{-1} = B^{-1}A^{-1}.$$

### Proof

Let  $C = AB$  and  $D = B^{-1}A^{-1}$ . Then

$$\begin{aligned} CD &= ABB^{-1}A^{-1} \\ &= AA^{-1} \\ &= I_n \end{aligned}$$

Similarly, we find that  $DC = I_n$ . Thus,  $AB$  is invertible and its inverse is given by  $B^{-1}A^{-1}$ .

### Properties of the determinant of matrices

Considering the matrices defined at the beginning of the section, we have:

1.  $\det(A^\top) = \det(A)$ ,
2.  $\det(AB) = \det(A)\det(B)$ ,
3.  $\det(A^{-1}) = 1/\det(A)$ .

### Proof

The proofs of properties 1 and 2 are technical and are omitted, but can be found, for example, [here](#). As for the third property, by definition, we have  $AA^{-1} = I_n$ . The determinant of  $I_n$  is equal to 1 (product of the elements on the diagonal). Therefore,  $\det(AA^{-1}) = 1$ . However, according to the second property,  $\det(AA^{-1}) = \det(A)\det(A^{-1})$ . We therefore have  $\det(A^{-1}) = 1/\det(A)$ .

### Properties of the trace of matrices

Considering the matrices defined at the beginning of the section, we have:

1.  $\text{tr}(A) = \text{tr}(A^\top)$ ,
2.  $\text{tr}(A + B) = \text{tr}(A) + \text{tr}(B)$ ,
3.  $\text{tr}(MN^\top) = \text{tr}(N^\top M)$ .

### Proof

For a square matrix  $A$ , let  $a_{ij}$  be the element of matrix  $A$  in row  $i$  and column  $j$ . The trace of  $A$  is given by the sum of the diagonal elements, i.e.  $\text{tr}(A) = \sum_{i=1}^n a_{ii}$ .

1. Since transposition does not change the diagonal elements, the result is straightforward.
2. Let  $C = A + B$ . Since  $A$  and  $B$  are square matrices,  $C$  is a square matrix. We have  $c_{ij} = a_{ij} + b_{ij}$  for all  $i, j = 1, \dots, n$ . Therefore

$$\text{tr}(A + B) = \text{tr}(C) = \sum_{i=1}^n c_{ii} = \sum_{i=1}^n a_{ii} + b_{ii} = \sum_{i=1}^n a_{ii} + \sum_{i=1}^n b_{ii} = \text{tr}(A) + \text{tr}(B).$$

3. The matrices  $MN^\top$  and  $N^\top M$  are square, with dimensions  $n \times n$  and  $m \times m$

respectively, so we can calculate their traces. Let  $C = MN^\top$  and  $D = N^\top M$ .

$$\text{tr}(MN^\top) = \text{tr}(C) = \sum_{i=1}^n c_{ii} = \sum_{i=1}^n \sum_{j=1}^m m_{ij}n_{ji} = \sum_{j=1}^m \sum_{i=1}^n n_{ji}m_{ij} = \sum_{j=1}^m d_{jj} = \text{tr}(D) = \text{tr}(N^\top M).$$

#### Definition

1. Let  $A$  be a symmetric matrix in  $M_n(\mathbb{R})$ .  $A$  is **positive definite** if  $u^\top Au > 0$  for all  $u \in \mathbb{R}^n$  such that  $u \neq 0$ .
2. Let  $A \in M_n(\mathbb{R})$ .  $A$  is **orthogonal** if  $A^\top A = AA^\top = I_n$ .

## 2 Eigenvalues and eigenvectors

#### Definition

Let  $A \in M_n(\mathbb{R})$ . We say that  $\lambda \in \mathbb{R}$  is an **eigenvalue** of  $A$  if there exists a nonzero vector  $u \in \mathbb{R}^n$  such that

$$Au = \lambda u. \quad (1)$$

The vector  $u$  is called an **eigenvector** of  $A$  corresponding to the eigenvalue  $\lambda$ .

The set of real numbers  $\lambda$  satisfying Equation 1 is called the **spectrum** of the matrix  $A$  and is denoted by  $\text{sp}(A)$ .

#### Property of eigenvectors

1. If  $u$  is an eigenvector of  $A$  corresponding to an eigenvalue  $\lambda$ , then the vector  $cu$ ,  $c \in \mathbb{R}^*$  is also an eigenvector of  $A$  corresponding to  $\lambda$ .
2. If  $A$  is symmetric and  $u_1$  and  $u_2$  are eigenvectors corresponding to different eigenvalues of  $A$ , then  $u_1$  and  $u_2$  are orthogonal, i.e.  $u_1^\top u_2 = 0$ .

#### Proof

1. Let  $c \in \mathbb{R}^*$  and  $u$  be an eigenvector of  $A$  associated with the eigenvalue  $\lambda$ . We have:

$$A(cu) = cAu = c\lambda u = \lambda(cu).$$

Therefore, the vector  $cu$  is also an eigenvector of  $A$  associated with the eigenvalue  $\lambda$ .

2. Let  $\lambda_1$  and  $\lambda_2$  be the eigenvalues associated with  $u_1$  and  $u_2$ , such that  $\lambda_1 \neq \lambda_2$ . We

have  $Au_1 = \lambda_1 u_1$  and  $Au_2 = \lambda_2 u_2$ . Then

$$\lambda_1 u_1^\top u_2 = u_1^\top Au_2 = \lambda_2 u_1^\top u_2.$$

This implies that  $(\lambda_1 - \lambda_2)u_1^\top u_2 = 0$ . However,  $\lambda_1 \neq \lambda_2$ . Therefore, necessarily,  $u_1^\top u_2 = 0$ .

This second property will be useful when we look at dimension reduction and, in particular, principal component analysis.

#### Characterization of matrices with their eigenvalues

1. If  $A$  is symmetric, then **all** its eigenvalues are real.
2. If  $A$  is positive definite, then **all** its eigenvalues are strictly positive.

#### Proof

1. Consider the more general case where  $A$  is a Hermitian matrix. The matrix  $A$  is equal to the transpose of its conjugate, denoted  $A^*$ . Let  $\lambda$  be an eigenvalue associated with an eigenvector  $u$ , which may be complex. We have:

$$\bar{u}^\top Au = \bar{u}^\top \lambda u = \lambda \bar{u}^\top u, \quad (2)$$

$$\bar{u}^\top Au = \bar{u}^\top A^* u = \overline{Au}^\top u = \bar{\lambda} \bar{u}^\top u. \quad (3)$$

This implies that  $(\lambda - \bar{\lambda})\bar{u}^\top u = 0$ . Since  $u \neq 0$ , we have  $\lambda = \bar{\lambda}$ . Therefore,  $\lambda \in \mathbb{R}$ .

2. Consider  $u$ , an eigenvector of  $A$  associated with the eigenvalue  $\lambda$ . We have that  $u^\top Au = \lambda u^\top u$ . However, since  $u \neq 0$ ,  $u^\top u \neq 0$ . Therefore,

$$\lambda = \frac{u^\top Au}{u^\top u}.$$

Since  $A$  is positive definite,  $u^\top Au > 0$  for all nonzero vectors  $u$ . We can therefore deduce that  $\lambda > 0$ .

### 3 Diagonalization of matrices

#### Definition

Let  $A \in M_n(\mathbb{R})$ . We say that  $A$  is **diagonalizable** if there exists a non-singular matrix  $P \in M_n(\mathbb{R})$  and a diagonal matrix  $D \in M_n(\mathbb{R})$  such that

$$P^{-1}AP = D \iff A = PDP^{-1}.$$

#### Spectral decomposition theorem

Let  $A$  be a symmetric matrix in  $M_n(\mathbb{R})$  and  $\lambda_1, \dots, \lambda_n$  its  $n$  eigenvalues. Then there exists an orthogonal matrix  $P$  in  $M_n(\mathbb{R})$  such that

$$A = P\Lambda P^\top, \quad \text{where } \Lambda = \text{diag}(\lambda_1, \dots, \lambda_n).$$

If  $A$  has  $n$  distinct positive eigenvalues, then we can take  $P$  to be the matrix whose  $k$ th column is the normalized eigenvector corresponding to the  $k$ th eigenvalue  $\lambda_k$  of  $A$ .

Given two symmetric matrices,  $A$  and  $B$ , how can we determine the vector  $u$  such that  $u^\top Au$  is maximal, knowing that  $u^\top Bu = 1$ ? We simply take  $u$  as the eigenvector of  $B^{-1}A$  associated with  $\lambda$ , the maximal eigenvalue of  $B^{-1}A$ . We thus obtain

$$u^\top Au = u^\top \lambda Mu = \lambda U^\top Mu = \lambda.$$

#### Characterization of the determinant and trace of matrices with their eigenvalues

If  $A$  has eigenvalues (real, but not necessarily distinct)  $\lambda_1, \dots, \lambda_n$ , then

1.  $\det(A) = \prod_{i=1}^n \lambda_i$
2.  $\text{tr}(A) = \sum_{i=1}^n \lambda_i$ .

#### Proof

Using the spectral decomposition theorem, there exists an invertible matrix  $P$  such that  $A = P\Lambda P^{-1}$ , where  $\Lambda$  is a diagonal matrix containing the eigenvalues. We therefore have, for the determinant,

$$\det(A) = \det(P\Lambda P^{-1}) = \det(P)\det(\Lambda)\det(P^{-1}) = \det(P)\det(\Lambda)\det(P)^{-1} = \det(\Lambda) = \prod_{i=1}^n \lambda_i,$$

and, for the trace,

$$\mathrm{tr}(A) = \mathrm{tr}(P\Lambda P^{-1}) = \mathrm{tr}(P^{-1}P\Lambda) = \mathrm{tr}(\Lambda) = \sum_{i=1}^n \lambda_i.$$

## References

- Deisenroth, Marc Peter, A. Aldo Faisal, and Cheng Soon Ong. 2020. *Mathematics for Machine Learning*. 1st ed. Cambridge University Press. <https://doi.org/10.1017/9781108679930>.
- Grifone, Joseph. 2024. *Algèbre Linéaire*. 7e edition. Toulouse: CEPADUES.