Review of Linear Algebra

CSE 547 / STAT 548 at the University of Washington

Acknowledgment: This note was originally compiled by Jessica Su for CS 224W at Standard with substantial modifications by Yikun Zhang in Winter 2023 and Spring 2024 for CSE 547 / STAT 548 at UW. Parts of this note are adapted from Lecture 8 of Professor Yen-Chi Chen's [1] and Professor Michael Perlman's lecture notes (Perlman, 2020) for STAT 512 at UW. Other good references about linear algebra includes Horn and Johnson (2012); Axler (2015) and notes from CS 224W at Stanford:

- http://snap.stanford.edu/class/cs224w-2014/recitation/linear_algebra/LA_Slides.pdf,
- http://snap.stanford.edu/class/cs224w-2015/recitation/linear_algebra.pdf.

Note: We only discuss the vectors and matrices with real entries in this note, though the stated results also hold for complex entries.

1 Vector Space, Span, and Linear Independence

Vector space: A *vector space* over the real numbers $\mathbb{R}$ is a set of vectors that is closed under additions with an identity as the zero vector $\mathbf{0}$ and additive inverses in the set. It is also closed under scalar multiplications of the vectors by elements in $\mathbb{R}$.
The most common vector space in Machine Learning is the Euclidean space $\mathbb{R}^n$, which consists of all ordered n-tuples of real numbers. A vector of $\mathbb{R}^n$ can be denoted by

$$\boldsymbol{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$$

or a row vector $\boldsymbol{x}^T = [x_1, ..., x_n]$, where $x_i, i = 1, ..., n$ are called its *components* or *coordinates*.

1.1 Vector Operations

Dot/Inner product: The geometric properties of $\mathbb{R}^n$ are derived from the *Euclidean dot product* defined as:

$$\langle \boldsymbol{x}, \boldsymbol{y} \rangle = \boldsymbol{x}^T \boldsymbol{y} = x_1 y_1 + \cdots + x_n y_n = \sum_{i=1}^n x_i y_i,$$

[1] See http://faculty.washington.edu/yenchic/20A_stat512.html.

where $\boldsymbol{x} = [x_1, ..., x_n]^T$ and $\boldsymbol{y} = [y_1, ..., y_n]^T$ are in $\mathbb{R}^n$.

Orthogonality: Two vectors in $\mathbb{R}^n$ are *orthogonal* if and only if their dot product is zero. In $\mathbb{R}^2$, we also call orthogonal vectors perpendicular.

Norm: The standard ℓ_2-norm or length of a vector $\boldsymbol{x} = [x_1, ..., x_n]^T \in \mathbb{R}^n$ is given by

$$||\boldsymbol{x}||_2 = \sqrt{x_1^2 + \cdots + x_n^2}.$$

Other possible norms in $\mathbb{R}^n$ include

- ℓ_p-norm: $||\boldsymbol{x}||_p = \left(\sum_{i=1}^n x_i^p\right)^{\frac{1}{p}}$. It reduces to the above ℓ_2-norm when $p = 2$.
- ℓ_∞-norm: $||\boldsymbol{x}||_\infty = \max_{i=1,...,n} |x_i|$. Notice that $||\boldsymbol{x}||_\infty \leq ||\boldsymbol{x}||_p \leq n^{\frac{1}{p}} ||\boldsymbol{x}||_\infty$.

When the context is clear, we often write the norm of a vector $\boldsymbol{x}$ as $||\boldsymbol{x}||$. The norms in $\mathbb{R}^n$ can be used to measure distances between data points (or vectors) in $\mathbb{R}^n$.

Triangle inequality: For two vectors $\boldsymbol{x}, \boldsymbol{y}$ and any norm $||\cdot||$ in $\mathbb{R}^n$, the *triangle inequality* states that

$$||\boldsymbol{x} + \boldsymbol{y}|| \leq ||\boldsymbol{x}|| + ||\boldsymbol{y}||,$$

and its reverse version goes as

$$||\boldsymbol{x} - \boldsymbol{y}|| \geq \Big| ||\boldsymbol{x}|| - ||\boldsymbol{y}|| \Big|.$$

1.2 Subspaces and Span

Subspace of $\mathbb{R}^n$: A *subspace* of $\mathbb{R}^n$ is a subset of $\mathbb{R}^n$ that is, by itself, a vector space over $\mathbb{R}$ using the same operations of vector addition and scalar multiplication in $\mathbb{R}^n$. In other words, a subset of $\mathbb{R}^n$ is a subspace precisely when it is closed under these two operations.

Linear combination: A *linear combination* of the vectors $\boldsymbol{v}_1, ..., \boldsymbol{v}_k$ (in $\mathbb{R}^n$) is any expression of the form $a_1\boldsymbol{v}_1 + \cdots + a_k\boldsymbol{v}_k$, where k is a positive integer and $a_1, ..., a_k \in \mathbb{R}$. Note that some of $a_1, ..., a_k$ may be zero.

Span: The *span* of a set $\mathcal{S}$ of vectors consists of all possible linear combinations of finitely many vectors in $\mathcal{S}$, *i.e.*,

$$\operatorname{span} \mathcal{S} = \left\{a_1\boldsymbol{v}_1 + \cdots + a_k\boldsymbol{v}_k : \boldsymbol{v}_1, ..., \boldsymbol{v}_k \in \mathcal{S}, a_1, ..., a_k \in \mathbb{R}, \text{ and } k = 1, 2, ...\right\}.$$

1.3 Linear Independence

The vectors $\boldsymbol{v}_1, ..., \boldsymbol{v}_k$ (in $\mathbb{R}^n$) are *linearly dependent* if and only if there exist $a_1, ..., a_k \in \mathbb{R}$, **not all zero**, such that $a_1\boldsymbol{v}_1 + \cdots + a_k\boldsymbol{v}_k = \boldsymbol{0}$.

A finite set of vectors $\boldsymbol{v}_1, ..., \boldsymbol{v}_k$ (in $\mathbb{R}^n$) is *linearly independent* if it is not linearly dependent. In other words, we cannot write any vector in $\boldsymbol{v}_1, ..., \boldsymbol{v}_k$ in terms of a linear combination of the other vectors.

2 Matrices

A $m \times n$ matrix $A \in \mathbb{R}^{m\times n}$ is an array of mn numbers as

$$A = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mn} \end{bmatrix}.$$

It represents the *linear mapping* (or *linear transformation*) from $\mathbb{R}^n$ to $\mathbb{R}^m$ as

$$\boldsymbol{x} \mapsto A\boldsymbol{x} = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mn} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^n A_{1i}x_i \\ \sum_{i=1}^n A_{2i}x_i \\ \vdots \\ \sum_{i=1}^n A_{mi}x_i \end{bmatrix} \quad \text{for any } \boldsymbol{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \in \mathbb{R}^n.$$

Here, the linearity means that $A(a\boldsymbol{x} + b\boldsymbol{y}) = aA\boldsymbol{x} + bA\boldsymbol{y}$ for any $\boldsymbol{x}, \boldsymbol{y} \in \mathbb{R}^n$ and $a, b \in \mathbb{R}$. In particular, when $m = n$, $A \in \mathbb{R}^{n\times n}$ is called a square matrix.

2.1 Matrix Operations

Matrix addition: If A, B are both $m \times n$ matrices, then the matrix addition is defined as elementwise additions as:

$$[A + B]_{ij} = A_{ij} + B_{ij}.$$

Example 1. Here is an example of a matrix addition for two matrices in $\mathbb{R}^{2\times 2}$ as

$$\begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} + \begin{bmatrix} 5 & 6 \\ 7 & 8 \end{bmatrix} = \begin{bmatrix} 1+5 & 2+6 \\ 3+7 & 4+8 \end{bmatrix} = \begin{bmatrix} 6 & 8 \\ 10 & 12 \end{bmatrix}.$$

Matrix multiplication: For two matrices $A \in \mathbb{R}^{m\times n}, B \in \mathbb{R}^{n\times p}$, the product AB is a $m \times p$ matrix, whose (i, j)-entry is

$$[AB]_{ij} = \sum_{k=1}^n A_{ik}B_{kj}$$

for all $1 \le i \le m$ and $1 \le j \le p$.

Example 2. Here is an example of the matrix multiplication for two square matrices in $\mathbb{R}^{2\times 2}$ as

$$\begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} \cdot \begin{bmatrix} 5 & 6 \\ 7 & 8 \end{bmatrix} = \begin{bmatrix} 1\times 5 + 2\times 7 & 1\times 6 + 2\times 8 \\ 3\times 5 + 4\times 7 & 3\times 6 + 4\times 8 \end{bmatrix} = \begin{bmatrix} 19 & 22 \\ 43 & 50 \end{bmatrix}.$$

We can also multiply non-square matrices when their dimensions are matched (*i.e.*, the number of columns of the first matrix should be equal to the number of rows of the second matrix) as

$$\begin{bmatrix}1 & 2\\3 & 4\\5 & 6\end{bmatrix}\cdot\begin{bmatrix}1 & 2 & 3\\4 & 5 & 6\end{bmatrix}=\begin{bmatrix}1\cdot 1+2\cdot 4 & 1\cdot 2+2\cdot 5 & 1\cdot 3+2\cdot 6\\3\cdot 1+4\cdot 4 & 3\cdot 2+4\cdot 5 & 3\cdot 3+4\cdot 6\\5\cdot 1+6\cdot 4 & 5\cdot 2+6\cdot 5 & 5\cdot 3+6\cdot 6\end{bmatrix}=\begin{bmatrix}9 & 12 & 15\\19 & 26 & 33\\29 & 40 & 51\end{bmatrix}.$$

Properties of matrix multiplications:

- *Associativity*: $(AB)C = A(BC)$.
- *Distributivity:* $A(B + C) = AB + AC$.
- However, matrix multiplication is in general **not** commutative. That is, AB is not necessarily equal to BA.
- The matrix multiplication between a 1-by-n matrix and an n-by-1 matrix is the same as taking the dot product of the corresponding vectors.

Matrix transpose: If $A = [A_{ij}] \in \mathbb{R}^{m\times n}$, then its *transpose* A^T is a $n \times m$ matrix, whose (i, j)-entry is A_{ji}. That is, $[A^T]_{ij} = A_{ji}$.

Example 3. Here is an example of transposing a 3×2 matrix, where we switch the matrix's rows with its columns as

$$\begin{bmatrix}1 & 2\\3 & 4\\5 & 6\end{bmatrix}^T=\begin{bmatrix}1 & 3 & 5\\2 & 4 & 6\end{bmatrix}.$$

Properties of matrix transpose:

- $(A^T)^T = A$ for any matrix $A \in \mathbb{R}^{m\times n}$.
- $(A + B)^T = A^T + B^T$ with $A, B \in \mathbb{R}^{m\times n}$.
- $(AB)^T = B^T A^T$ with $A \in \mathbb{R}^{m\times n}$ and $B \in \mathbb{R}^{n\times p}$.

  Proof. Let $AB = C$ and $(AB)^T = D$. Then,

  $$\begin{aligned}(AB)^T_{ij} &= D_{ij} = C_{ji}\\&= \sum_k A_{jk}B_{ki}\\&= \sum_k (A^T)_{kj}(B^T)_{ik}\\&= \sum_k (B^T)_{ik}(A^T)_{kj}.\end{aligned}$$

  It shows that $D = B^T A^T$ and the result follows. □

Identity matrix: The identity matrix $\boldsymbol{I}_n$ is an $n \times n$ (square) matrix given by

$$\boldsymbol{I}_n = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix},$$

where it has all 1's on the diagonal and 0's everywhere else. It is sometimes abbreviated $\boldsymbol{I}$ when the dimension of the matrix is clear. For any $A \in \mathbb{R}^{m\times n}$, it holds that $A\boldsymbol{I}_n = \boldsymbol{I}_m A$.

Matrix inverse: Given a square matrix $A \in \mathbb{R}^{n\times n}$, its *inverse* A^{-1} (if it exists) is the unique matrix satisfying

$$AA^{-1} = A^{-1}A = \boldsymbol{I}_n.$$

Notice that the inverse of a matrix may not always exist. Those matrices that have an inverse are called *invertible* or *nonsingular*.

Properties of matrix inverse: Whenever the matrices $A, B \in \mathbb{R}^{n\times n}$ are invertible, we have the following properties.

- $(A^{-1})^{-1} = A$.
- $(AB)^{-1} = B^{-1}A^{-1}$.
- $(A^{-1})^T = (A^T)^{-1}$. (It can be proved by noting that $(A^{-1})^T(A^T) = (AA^{-1})^T = \boldsymbol{I}_n$.)
- All the columns (or rows) of A are linearly independent, *i.e.*, $\text{rank}(A) = n$.
- $\det(A) \neq 0$.

Matrix rank: The *rank* of a matrix $A \in \mathbb{R}^{m\times n}$ is the dimension of the linear space spanned by its rows (or columns). One can verify that

- $\text{rank}(A) \leq \min\{m, n\}$ and $\text{rank}(A) = \text{rank}(A^T)$.
- $\text{rank}(AB) \leq \min\{\text{rank}(A), \text{rank}(B)\}$ for any $A \in \mathbb{R}^{m\times n}$ and $B \in \mathbb{R}^{n\times p}$.

Matrix trace: For a square matrix $A \in \mathbb{R}^{n\times n}$, the *trace* of A is defined as

$$\text{tr}(A) = \sum_{i=1}^{n} A_{ii},$$

i.e., it is the sum of all the diagonal entries of A. Specifically, the traces of matrices satisfy the following properties:

- $\text{tr}(aA + bB) = a \cdot \text{tr}(A) + b \cdot \text{tr}(B)$ for any $A, B \in \mathbb{R}^{n\times n}$ and $a, b \in \mathbb{R}$.
- $\text{tr}(A) = \text{tr}(A^T)$ for any $A \in \mathbb{R}^{n\times n}$.
- $\text{tr}(AB) = \text{tr}(BA)$ for any $A \in \mathbb{R}^{m\times n}$ and $B \in \mathbb{R}^{n\times m}$.

Proof. By direct calculations,

$$\begin{aligned}\mathrm{tr}(AB) = \sum_{i=1}^{m} [AB]_{ii} &= \sum_{i=1}^{m}\left(\sum_{k=1}^{n} A_{ik}B_{ki}\right)\\ &= \sum_{k=1}^{n}\left(\sum_{i=1}^{m} B_{ki}A_{ik}\right) = \sum_{k=1}^{n} [BA]_{kk} = \mathrm{tr}(BA).\end{aligned}$$

□

Determinant: For a square matrix $A \in \mathbb{R}^{n\times n}$, its *determinant* $\det(A)$ or $|A|$ is defined as

$$\det(A) = \sum_{\pi}\left(\mathrm{sign}(\pi)\prod_{i=1}^{n} A_{i\pi(i)}\right),$$

where the sum is over all $n!$ permutations $\pi : \{1,...,n\} \to \{1,...,n\}$ and $\mathrm{sign}(\pi) = 1$ or -1 according to whether the minimum number of transpositions (*i.e.*, pairwise interchanges) necessary to achieve it starting from $\{1,...,n\}$ is even or odd. One can also calculate $\det(A)$ through the Laplace expansion by minor along row i or column j as

$$\det(A) = \sum_{k=1}^{n} (-1)^{i+k} A_{ik} \det(M_{ik}) = \sum_{k=1}^{n} (-1)^{k+j} A_{kj} \det(M_{kj}),$$

where $M_{ik} \in \mathbb{R}^{(n-1)\times(n-1)}$ denotes the submatrix of A obtained by removing row i and column k of A. Geometrically, the determinant of $A = [\boldsymbol{a}_1, \boldsymbol{a}_2, ..., \boldsymbol{a}_n] \in \mathbb{R}^{n\times n}$ gives the signed volume of a n-dimensional parallelotope $\mathcal{P} = \{c_1\boldsymbol{a}_1 + \cdots + c_n\boldsymbol{a}_n : c_1, ..., c_n \in [0, 1]\}$, *i.e.*,

$$\det A = \pm \mathrm{Volume}(\mathcal{P}),$$

where $\boldsymbol{a}_1, ..., \boldsymbol{a}_n$ are column vectors of A.

Example 4. We give explicit formulae for computing the determinants of square matrices with dimension less than 3 as:

$$\begin{aligned}\det[A_{11}] &= A_{11},\\ \det\begin{bmatrix} A_{11} & A_{12}\\ A_{21} & A_{22}\end{bmatrix} &= A_{11}A_{22} - A_{12}A_{21},\\ \det\begin{bmatrix} A_{11} & A_{12} & A_{13}\\ A_{21} & A_{22} & A_{23}\\ A_{31} & A_{23} & A_{33}\end{bmatrix} &= A_{11}A_{22}A_{33} + A_{12}A_{23}A_{31} + A_{13}A_{21}A_{32}\\ &\quad - A_{11}A_{23}A_{32} - A_{12}A_{21}A_{33} - A_{13}A_{22}A_{31}.\end{aligned}$$

Properties of determinant: For any $A, B \in \mathbb{R}^{n\times n}$,

- $\det(AB) = \det(A) \cdot \det(B)$.
- $\det(A^{-1}) = [\det(A)]^{-1}$ and $\det(A^T) = \det(A)$.

2.2 Special Types of Matrices

Diagonal matrix: A matrix $D \in \mathbb{R}^{n\times n}$ is *diagonal* if $D_{ij} = 0$ whenever $i \neq j$. We write a diagonal matrix D as

$$D = \operatorname{diag}(d_1, d_2, \ldots, d_n) = \begin{bmatrix} d_1 & 0 & \cdots & 0 \\ 0 & d_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & d_n \end{bmatrix}.$$

One can verify that

$$D^k = \begin{bmatrix} d_1^k & 0 & \cdots & 0 \\ 0 & d_2^k & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & d_n^k \end{bmatrix}.$$

Triangular matrix: A matrix $A \in \mathbb{R}^{n\times n}$ is *lower triangular* if $A_{ij} = 0$ whenever $i < j$. That is, a lower triangular matrix has all its nonzero elements on or below the diagonal. Similarly, a matrix A is *upper triangular* if its transpose A^T is lower triangular. When A is a lower or upper triangular matrix, $\det(A) = \prod_{i=1}^n A_{ii}$.

Orthogonal matrix: A square matrix $U \in \mathbb{R}^{n\times n}$ is orthogonal if $UU^T = U^T U = \boldsymbol{I}_n$. This implies that

- $U^{-1} = U^T$, *i.e.*, the inverse of an orthogonal matrix is its transpose. Moreover, $\det(U) = \pm 1$.
- the rows (or columns) of U form an orthonormal basis for $\mathbb{R}^n$.
- U preserves angles and lengths, *i.e.*, for any vectors $\boldsymbol{x}, \boldsymbol{y} \in \mathbb{R}^n$,

$$\langle U\boldsymbol{x}, U\boldsymbol{y}\rangle = (U\boldsymbol{x})^T(U\boldsymbol{y}) = \boldsymbol{x}^T U^T U \boldsymbol{y} = \langle \boldsymbol{x}, \boldsymbol{y}\rangle \quad \text{and} \quad ||U\boldsymbol{x}||_2^2 = ||x||_2^2\,.$$

Symmetric matrix: A square matrix $A \in \mathbb{R}^{n\times n}$ is symmetric if $A = A^T$, *i.e.*, $A_{ij} = A_{ji}$ for all entries of A.

Projection matrix: A square matrix $P \in \mathbb{R}^{n\times n}$ is a *projection matrix* if it is symmetric and idempotent: $P^2 = P$.

Positive definite matrix: A (real) symmetric matrix $S \in \mathbb{R}^{n\times n}$ is *positive semi-definite (PSD)* if its quadratic form is nonnegative, *i.e.*,

$$\boldsymbol{x}^T S \boldsymbol{x} \geq 0$$

for all $\boldsymbol{x} \in \mathbb{R}^n$. Furthermore, S is *positive definite (PD)* if its quadratic form is strictly positive, *i.e.*,

$$\boldsymbol{x}^T S \boldsymbol{x} > 0$$

for all $\boldsymbol{x} \in \mathbb{R}^n$ with $\boldsymbol{x} \neq \boldsymbol{0}$. Here are some useful properties of PSD or PD matrices.

- A diagonal matrix $D = \text{diag}(d_1, ..., d_n)$ is PSD if and only if $d_i \geq 0$ for all $i = 1, ..., n$. It is PD if and only if $d_i > 0$ for all $i = 1, ..., n$. In particular, the identity matrix $\boldsymbol{I}_n$ is PD.
- If $S \in \mathbb{R}^{n\times n}$ is PSD, then ASA^T is also PSD for any matrix $A \in \mathbb{R}^{m\times n}$.
- If $S \in \mathbb{R}^{n\times n}$ is PD, then ASA^T is also PD for any matrix $A \in \mathbb{R}^{m\times n}$ with full rank $\text{rank}(A) = m \leq n$.
- AA^T is PSD for any matrix $A \in \mathbb{R}^{m\times n}$. AA^T is PD for any matrix $A \in \mathbb{R}^{m\times n}$ with full rank $\text{rank}(A) = m \leq n$.
- $S \in \mathbb{R}^{n\times n}$ is PD $\implies$ S has full rank $\implies$ S^{-1} exists $\implies$ $S^{-1} = (S^{-1})S(S^{-1})^T$ is PD.

2.3 Eigenvalues and Eigenvectors

Given a square matrix $A \in \mathbb{R}^{n\times n}$, $\lambda \in \mathbb{R}$ is an eigenvalue of A with the corresponding eigenvector $\boldsymbol{x} \in \mathbb{R}^n$ and $\boldsymbol{x} \neq \boldsymbol{0}$ if $A\boldsymbol{x} = \lambda\boldsymbol{x}$.

Here, $\boldsymbol{0} \in \mathbb{R}^n$ stands for a vector whose entries are all zero. By convention, the zero vector cannot be an eigenvector of any matrix.

Example 5. If $A = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}$, then the vector $\boldsymbol{x} = \begin{bmatrix} 3 \\ -3 \end{bmatrix}$ is an eigenvector with eigenvalue 1, because

$$A\boldsymbol{x} = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} 3 \\ -3 \end{bmatrix} = \begin{bmatrix} 3 \\ -3 \end{bmatrix} = 1 \times \begin{bmatrix} 3 \\ -3 \end{bmatrix}.$$

2.3.1 Solving for eigenvalues and eigenvectors

We exploit the fact that $A\boldsymbol{x} = \lambda\boldsymbol{x}$ if and only if

$$(A - \lambda\boldsymbol{I}_n)\boldsymbol{x} = 0. \tag{1}$$

(Note that $\lambda\boldsymbol{I}_n$ is the diagonal matrix where all the diagonal entries are λ, and all other entries are zero.)

The equation (1) has a nonzero solution $\boldsymbol{x}$ if and only if $\det(A - \lambda\boldsymbol{I}_n) = 0$; see Section 1.1 in Horn and Johnson (2012). Therefore, we can obtain the eigenvalues of a matrix A by solving the *characteristic equation* $\det(A - \lambda\boldsymbol{I}_n) = 0$ for λ. Once we have done that, you can find the corresponding eigenvector for each eigenvalue λ by solving the system of equations $(A - \lambda\boldsymbol{I}_n)\boldsymbol{x} = \boldsymbol{0}$ for $\boldsymbol{x}$.

Example 6. If $A = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}$, then

$$A - \lambda\boldsymbol{I}_n = \begin{bmatrix} 2-\lambda & 1 \\ 1 & 2-\lambda \end{bmatrix}$$

and

$$\det(A - \lambda \boldsymbol{I}_n) = (2-\lambda)^2 - 1 = \lambda^2 - 4\lambda + 3.$$

Setting it to 0 yields that $\lambda = 1$ and $\lambda = 3$ are possible eigenvalues.

(i) To find the eigenvectors for $\lambda = 1$, we plug λ into the equation $(A - \lambda \boldsymbol{I}_n)\boldsymbol{x} = 0$. This gives us

$$\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Any vector with $x_2 = -x_1$ is a solution to this equation, and in particular, $\begin{bmatrix} 3 \\ -3 \end{bmatrix}$ is one solution.

(ii) To find the eigenvectors for $\lambda = 3$, we again plug λ into the equation and obtain that

$$\begin{bmatrix} -1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Any vector where $x_2 = x_1$ is a solution to this equation.

⋆ **Note:** The above method is never used to calculate eigenvalues and eigenvectors for large matrices in practice. We will introduce the power iterative method in the lecture (Lecture 6: Dimensionality Reduction) to find eigenpairs instead.

2.3.2 Properties of eigenvalues and eigenvectors

- If $A \in \mathbb{R}^{n \times n}$ is symmetric, then all its eigenvalues are real.
- The eigenvalues of any (lower or upper) triangular matrix $A \in \mathbb{R}^{n \times n}$ are its diagonal entries.
- The trace of a matrix $A \in \mathbb{R}^{n \times n}$ is equal to the sum of its eigenvalues, *i.e.*, $\mathrm{tr}(A) = \sum_{i=1}^n \lambda_i$ with $\lambda_1, ..., \lambda_n$ being the eigenvalues of A.
- $\det(A) = \prod_{i=1}^n \lambda_i$, where $\lambda_1, ..., \lambda_n$ is the eigenvalues of $A \in \mathbb{R}^{n \times n}$.
- A symmetric matrix is PSD (PD) if all its eigenvalues are nonnegative (positive).
- The eigenvalues of a projection matrix are either 1 or 0.

2.4 Matrix Norms

Frobenius norm: Given a matrix $A \in \mathbb{R}^{m \times n}$, its *Frobenius norm* is defined as

$$||A||_F = \sqrt{\sum_{i,j} A_{ij}^2} = \mathrm{tr}(A^T A).$$

We can compute $||A||_F$ as $||A||_F = \sqrt{\sigma_1(A)^2 + \cdots \sigma_q(A)^2}$, where $\sigma_i(A), i = 1, ..., q$ are singular values of A and $q = \min\{m, n\}$; see Section 3 for the definition of singular values. In particular, if A is a symmetric matrix in $\mathbb{R}^{n\times n}$, then $||A||_F = \sqrt{\sum_{i=1}^n \lambda_i^2}$ with $\lambda_1, ..., \lambda_n$ being the eigenvalues of A.

Maximum norm: The maximum norm (or ℓ_∞-norm) for $A \in \mathbb{R}^{m\times n}$ is defined as $||A||_{\max} = \max_{i,j} |A_{ij}|$. Strictly speaking, $||\cdot||_{\max}$ is not a matrix norm because it does not satisfy the submultiplicativity $||AB|| \leq ||A||\,||B||$. However, it is a vector norm when we consider $\mathbb{R}^{m\times n}$ as a mn-dimensional vector space; see Section 5.6 in Horn and Johnson (2012).

Operator norm: For any matrix $A \in \mathbb{R}^{m\times n}$ and ℓ_p-norm for vectors in $\mathbb{R}^m$ and $\mathbb{R}^n$, then the corresponding operator norm $||A||_p$ is defined as

$$||A||_p = \sup_{\boldsymbol{x}\neq \boldsymbol{0}} \frac{||A\boldsymbol{x}||_p}{||\boldsymbol{x}||_p}.$$

For the special cases when $p = 1, 2, \infty$, these (induced) operator norms can be computed as

- $||A||_1 = \max\limits_{1\leq j\leq n} \sum_{i=1}^m |A_{ij}|$, which is simply the maximum absolute column sum of the matrix.
- $||A||_\infty = \max\limits_{1\leq i\leq m} \sum_{j=1}^n |A_{ij}|$, which is simply the maximum absolute row sum of the matrix.
- $||A||_2 = \sqrt{\lambda_{\max}(AA^T)} = \sigma_{\max}(A)$, where $\lambda_{\max}(AA^T)$ is the maximum eigenvalue of AA^T and $\sigma_{\max}(A)$ is the maximum singular value of A.

There are several useful inequalities between these matrix norms. For any $A \in \mathbb{R}^{m\times n}$,

$$||A||_2 \leq ||A||_F \leq \sqrt{n}\,||A||_2\,,\ ||A||_{\max} \leq ||A||_2 \leq \sqrt{mn}\,||A||_{\max}\,, \quad \text{and} \quad ||A||_F \leq \sqrt{mn}\,||A||_{\max}\,.$$

3 Spectral Decomposition and Singular Value Decomposition (SVD)

Theorem 1 (Spectral Decomposition of a Real Symmetric Matrix)**.** *For a symmetric (square) matrix $A \in \mathbb{R}^{n\times n}$, there exists a real orthogonal matrix $U \in \mathbb{R}^{n\times n}$ such that*

$$A = U\Lambda U^T = \sum_{i=1}^n \lambda_i \boldsymbol{u}_i \boldsymbol{u}_i^T,$$

where $\Lambda = \mathrm{diag}(\lambda_1, ..., \lambda_n)$, $U = [\boldsymbol{u}_1, \boldsymbol{u}_2, ..., \boldsymbol{u}_n]$, and $\boldsymbol{u}_1, ..., \boldsymbol{u}_n$ are orthonormal eigenvectors of A associated with eigenvalues $\lambda_1, ..., \lambda_n$.

The spectral decomposition also provides us with a convenient method for computing the power $A^k = U\Lambda^k U^T$ and exponentiation $\exp(A) = U\exp(\Lambda)U^T$ of a real symmetric matrix $A \in \mathbb{R}^{n\times n}$.

While the spectral decomposition (Theorem 1) only works for symmetric (square) matrices, it is also feasible to diagonalize a rectangular matrix $A \in \mathbb{R}^{m\times n}$ through orthogonal matrices.

Theorem 2 (Singular Value Decomposition (SVD))**.** *Let $A \in \mathbb{R}^{m\times n}$ with $q = \min\{m, n\}$. There exist orthogonal matrices $\widetilde{U} = [\boldsymbol{u}_1, ..., \boldsymbol{u}_m] \in \mathbb{R}^{m\times m}$ and $\widetilde{V} = [\boldsymbol{v}_1, ..., \boldsymbol{v}_n] \in \mathbb{R}^{n\times n}$ as well as a (square) diagonal matrix $\Sigma_q = \mathrm{diag}(\sigma_1, ..., \sigma_q) \in \mathbb{R}^{q\times q}$ such that*

$$A = \widetilde{U}\Sigma\widetilde{V}^T = \sum_{i=1}^{q} \sigma_q \boldsymbol{u}_i \boldsymbol{v}_i^T = U\Sigma_q V^T,$$

where $U = [\boldsymbol{u}_1, ..., \boldsymbol{u}_q] \in \mathbb{R}^{m\times q}$, $V = [\boldsymbol{v}_1, ..., \boldsymbol{v}_q] \in \mathbb{R}^{n\times q}$, and

$$\Sigma = \Sigma_q \text{ if } m = n,$$
$$\Sigma = [\Sigma_q\ \mathbf{0}] \in \mathbb{R}^{m\times n} \text{ if } n > m,$$
$$\Sigma = \begin{bmatrix} \Sigma_q \\ \mathbf{0} \end{bmatrix} \in \mathbb{R}^{m\times n} \text{ if } m > n.$$

Here, $\sigma_1 \geq \cdots \geq \sigma_q \geq 0$ are called the ***singular values*** *of A, which are eigenvalues of AA^T when $m \leq n$ or A^TA when $m > n$.*

Notice that the number of nonzero singular values of A determines the rank of A. During the lecture (Lecture 6: Dimensionality Reduction), we will leverage the singular value decomposition to reduce the dimension (or matrix rank) of a user-movie rating matrix.

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