1 Inner Products

An **inner product** $\langle \cdot, \cdot \rangle$ on a vector space V over $\mathbb{R}$ is a function that takes in two vectors and outputs a scalar, such that $\langle \cdot, \cdot \rangle$ is symmetric, linear, and positive-definite.

- Symmetry: $\langle \vec{u}, \vec{v} \rangle = \langle \vec{v}, \vec{u} \rangle$
- Scaling: $\langle c\vec{u}, \vec{v} \rangle = c\langle \vec{u}, \vec{v} \rangle$ and $\langle \vec{u}, c\vec{v} \rangle = c\langle \vec{u}, \vec{v} \rangle$
- Additivity: $\langle \vec{u} + \vec{v}, \vec{w} \rangle = \langle \vec{u}, \vec{w} \rangle + \langle \vec{v}, \vec{w} \rangle$ and $\langle \vec{u}, \vec{v} + \vec{w} \rangle = \langle \vec{u}, \vec{v} \rangle + \langle \vec{u}, \vec{w} \rangle$
- Positive-definite: $\langle \vec{u}, \vec{u} \rangle \geq 0$ with $\langle \vec{u}, \vec{u} \rangle = 0$ if and only if $\vec{u} = \vec{0}$

$\|u\| > 0$ unless $u = 0$ in which case $\|u\| = 0$

For two vectors, $\vec{u}, \vec{v} \in \mathbb{R}^n$, the standard inner product is $\langle \vec{u}, \vec{v} \rangle = \vec{u}^T\vec{v}$. We define the **norm**, or the magnitude, of a vector $\vec{v}$ to be $\|\vec{v}\| = \sqrt{\langle \vec{v}, \vec{v} \rangle} = \sqrt{\vec{v}^T\vec{v}}$. For any non-zero vector, we can *normalize*, i.e., set its magnitude to 1 while preserving its direction, by dividing the vector by its norm $\frac{\vec{v}}{\|\vec{v}\|}$.

Orthogonality and Orthonormality

The inner product lets us define the angle between two vectors through the equation

$$\langle \vec{u}, \vec{v} \rangle = \|\vec{u}\|\|\vec{v}\| \cos\theta \tag{1}$$

Notice that if the angle θ between two vectors is $\pm 90°$, the inner product $\langle \vec{u}, \vec{v} \rangle = 0$.

Therefore, we define two vectors $\vec{u}$ and $\vec{v}$ to be **orthogonal** to each other if $\langle \vec{u}, \vec{v} \rangle = \vec{u}^T\vec{v} = 0$. A set of vectors is orthogonal if any two vectors in this set are orthogonal to each other.

Furthermore, we define two vectors $\vec{u}$ and $\vec{v}$ to be **orthonormal** to each other if they are orthogonal to each other and their norms are 1. A set of vectors is orthonormal if any two vectors in this set are orthogonal to each other and every vector has a norm of 1. In fact, for any two vectors $\vec{u}$ and $\vec{v}$ in an orthonormal set,

$$\langle \vec{u}, \vec{v} \rangle = \vec{u}^T\vec{v} = \begin{cases} 1, & \text{if } \vec{u} = \vec{v} \\ 0, & \text{otherwise} \end{cases}.$$

Unitary Matrices

An **orthogonal** or **unitary** matrix is a square matrix whose columns are orthonormal with respect to the inner product. To avoid any confusion, we will often refer to these matrices as **orthonormal matrices.**

$$U = \begin{bmatrix} \vec{u}_1 & \cdots & \vec{u}_n \end{bmatrix}, \qquad \vec{u}_i^T\vec{u}_j = \begin{cases} 1, & \text{if } i = j \\ 0, & \text{otherwise} \end{cases}$$

Note that $U^TU = UU^T = I$, so the inverse of a unitary matrix is its transpose $U^{-1} = U^T$.

Since the columns of a unitary matrix are orthonormal vectors, we can interpret these matrices as "rotation" and "reflection" matrices of the standard axes. This also implies that $\|U\vec{v}\| = \|\vec{v}\|$ for any vector $\vec{v}$.

2 Spectral Theorem

Let A be an $n \times n$ **symmetric** matrix with real entries. Then the following statements will be true.

1. All eigenvalues of A are real.
2. A has n linearly independent eigenvectors $\in \mathbb{R}^n$.
3. A has orthogonal eigenvectors, i.e., $A = V\Lambda V^{-1} = V\Lambda V^T$, where Λ is a diagonal matrix and V is an orthonormal matrix. We say that A is orthogonally diagonalizable.

Ex: $A = \begin{bmatrix} 1 & 1+j \\ 2 & 3-2j \end{bmatrix}$ $\bar{A} = \begin{bmatrix} 1 & 1-j \\ 2 & 3+2j \end{bmatrix}$

$A \cdot \vec{0} = \lambda \cdot \vec{0}$

Recall that a matrix A is symmetric if $A = A^T$. Furthermore, if A is of the form $B^T B$ for some arbitrary matrix B, then all of the eigenvalues of A are non-negative, i.e., $\lambda \geq 0$.

a) Prove the following: All eigenvalues of a real symmetric matrix A are real.

$v \neq 0$

Hint: Let $(\lambda, \vec{v})$ be an eigenvalue/vector pair. Then $A\vec{v} = \lambda\vec{v}$ and take the complex conjugate and transpose of both sides. Try to show that $\bar{\lambda} = \lambda$.

Show: $\lambda = \bar{\lambda}$

$Av = \lambda v$

$A\bar{v} = \bar{A}\bar{v} = \bar{\lambda}\bar{v}$

$\bar{v}^T A^T = \bar{\lambda}\bar{v}^T$

Know: A is symmetric, $A = A^T$

$\bar{v}^T A v = \bar{\lambda}\bar{v}^T v$

$\bar{v}^T \lambda v = \bar{\lambda}\bar{v}^T v$

$\lambda \cancel{\bar{v}^T v} = \bar{\lambda}\cancel{\bar{v}^T v}$

If $\bar{v}^T v \neq 0$

$v = \begin{bmatrix} v_1 \\ \vdots \\ v_n \end{bmatrix}$ $\bar{v} = \begin{bmatrix} \bar{v}_1 \\ \vdots \\ \bar{v}_n \end{bmatrix}$

$\bar{v}^T v = \bar{v}_1 v_1 + \ldots + \bar{v}_n v_n$

claim: $\bar{v}v > 0$

$v = re^{j\theta}$ $\bar{v} = re^{-j\theta}$

$\bar{v}v = r^2$ $\bar{v}^T v > 0$

b) Prove the following: For any symmetric matrix A, any two eigenvectors corresponding to distinct eigenvalues of A are orthogonal.

Hint: Let $\vec{v}_1$ and $\vec{v}_2$ be eigenvectors of A with eigenvalues $\lambda_1 \neq \lambda_2$.

$$A\vec{v}_1 = \lambda_1\vec{v}_1$$
$$A\vec{v}_2 = \lambda_2\vec{v}_2$$

$(Av)^T = v^T A^T$

Take the transpose of the second equation and show that $\lambda_1\langle\vec{v}_1, \vec{v}_2\rangle = \lambda_2\langle\vec{v}_1, \vec{v}_2\rangle$.

show: $\langle v_1, v_2 \rangle = v_1^T v_2 = 0$

$Av_1 = \lambda_1 v_1$

$v_2^T A^T = \lambda_2 v_2^T$

$\downarrow$

$v_2^T A v_1 = \lambda_2 v_2^T v_1$

$v_2^T A v_1 = \lambda_1 v_2^T v_1$

$\lambda_2 v_2^T v_1 = \lambda_1 v_2^T v_1$

$\lambda_2 \langle v_2, v_1 \rangle = \lambda_1 \langle v_2, v_1 \rangle$

$\lambda_2 \langle v_1, v_2 \rangle = \lambda_1 \langle v_1, v_2 \rangle$

$\lambda_2 \langle v_1, v_2 \rangle - \lambda_1 \langle v_1, v_2 \rangle$

$= \underbrace{(\lambda_2 - \lambda_1)}_{\neq 0} \underbrace{\langle v_1, v_2 \rangle}_{= 0} = 0$

$v_1 \perp v_2$

$\lambda_1 \neq \lambda_2$

doesn't have to be square

c) Prove the following: For any matrix A, $A^T A$ is symmetric and only has non-negative eigenvalues.
Hint: Consider the quantity $\|A\vec{v}\|^2$. Remember that norms are positive-definite.

1. $A^T A$ is symmetric

$$(A^T A)^T = A^T (A^T)^T = A^T A$$

$$(AB)^T = B^T A^T$$

2. λ of $A^T A$ are ≥ 0

$$\|Av\|^2 = \langle Av, Av \rangle = (Av)^T (Av) = v^T A^T A v$$

Let v be an eigenvec. of $A^T A$ with eigenvalue λ

$$\|Av\|^2 = v^T A^T A v = v^T \lambda v = \lambda v^T v = \underline{\lambda \|v\|^2}$$

$$\lambda = \frac{\|Av\|^2}{\|v\|^2} \geq 0$$

$\|v\|$ is nonzero since v is an eigenvector of $A^T A$
$v \neq 0$

Rank 1 matrices

3 Outer Products

$A = \sigma_1 u_1 v_1^T + \dots + \sigma_n u_n v_n^T$

An **outer product** $\otimes$ is a function that takes two vectors and outputs a **matrix**. We define $\vec{x} \otimes \vec{y} = \vec{x}\vec{y}^T$.

a) Let $\vec{x} = \begin{bmatrix} 1 \\ 3 \\ -2 \end{bmatrix}$ and $\vec{y} = \begin{bmatrix} 4 \\ 2 \\ -1 \end{bmatrix}$.

$\underset{m \times 1}{\vec{x}} \otimes \underset{n \times 1}{\vec{y}} = \underset{m \times 1 \cdot 1 \times n}{\vec{x}\vec{y}^T}$

$m \times n$ matrix

(i) Compute the outer-product $A = \vec{x}\vec{y}^T$.

(ii) What is the shape of the matrix A?

(iii) What is the rank of A?

(i) $\begin{bmatrix} 1 \\ 3 \\ -2 \end{bmatrix} \begin{bmatrix} 4 & 2 & -1 \end{bmatrix} = \begin{bmatrix} 4 & 2 & -1 \\ 12 & 6 & -3 \\ -8 & -4 & 2 \end{bmatrix}$

(ii) 3×3 matrix

(iii) Cols are all lin. dependent, Rank $(A) = 1$

b) Let $B = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$.

(i) Write B as an outer-product of two vectors $\vec{x}$ and $\vec{y}$.

(ii) What is the rank of B?

(i) $\underset{\vec{x}}{\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}} \underset{\vec{y}}{\begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}}$

(ii) Rank (B)

$\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$ is a basis for Col B

c) Let $C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix}$.

(i) Write C as a sum of outer-products: $\vec{x}\vec{y}^T + \vec{u}\vec{w}^T$.

(ii) What is the rank of C?

$C = xy^T + uw^T$

where x, u are L.I.

$\{x, u\}$ would form a basis for Col C

C is rank 2

d) Let $D = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$.

(i) Write D as a sum of outer-products.

(ii) What is the rank of D?