Diagonalization of Symmetric Real Matrices (from Handout)

Definition 1 Let
\[ \delta_{ij} = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases} \]
A basis \( V = \{v_1, \ldots, v_n\} \) of \( \mathbb{R}^n \) is orthonormal if \( v_i \cdot v_j = \delta_{ij} \).

In other words, a basis is orthonormal if each basis element has unit length (\( \|v_i\|^2 = v_i \cdot v_i = 1 \) for each \( i \)), and distinct basis elements are perpendicular (\( v_i \cdot v_j = 0 \) for \( i \neq j \)).

Remark: Suppose that \( x = \sum_{j=1}^{n} \alpha_j v_j \) where \( \{v_1, \ldots, v_n\} \) is an orthonormal basis of \( \mathbb{R}^n \). Then
\[
x \cdot v_k = \left( \sum_{j=1}^{n} \alpha_j v_j \right) \cdot v_k \\
= \sum_{j=1}^{n} \alpha_j (v_j \cdot v_k) \\
= \sum_{j=1}^{n} \alpha_j \delta_{jk} \\
= \alpha_k
\]
so
\[
x = \sum_{j=1}^{n} (x \cdot v_j) v_j
\]

Example: The standard basis of \( \mathbb{R}^n \) is orthonormal.

Recall that for a real \( n \times m \) matrix \( A \), \( A^\top \) denotes the transpose of \( A \): the \((i, j)\)th entry of \( A^\top \) is the \((j, i)\)th entry of \( A \). So the \( i \)th row of \( A^\top \) is the \( i \)th column of \( A \).

Definition 2 A real \( n \times n \) matrix \( A \) is unitary if \( A^\top = A^{-1} \).

Theorem 3 A real \( n \times n \) matrix \( A \) is unitary if and only if the columns of \( A \) are orthonormal.

Proof: Let \( v_j \) denote the \( j \)th column of \( A \).
\[
A^\top = A^{-1} \iff A^\top A = I \\
\iff v_i \cdot v_j = \delta_{ij} \forall i, j \\
\iff \{v_1, \ldots, v_n\} \text{ is orthonormal}
\]
If $A$ is unitary, let $V$ be the set of columns of $A$ and $W$ be the standard basis of $\mathbb{R}^n$. Since $A$ is unitary, it is invertible, so $V$ is a basis of $\mathbb{R}^n$.

$$A^\top = A^{-1} = Mtx_{V,W}(id)$$

Since $V$ is orthonormal, the transformation between bases $W$ and $V$ preserves all geometry, including lengths and angles.

**Theorem 4** Let $T \in L(\mathbb{R}^n, \mathbb{R}^n)$ and $W$ be the standard basis of $\mathbb{R}^n$. Suppose that $Mtx_W(T)$ is symmetric. Then the eigenvectors of $T$ are all real, and there is an orthonormal basis $V = \{v_1, \ldots, v_n\}$ of $\mathbb{R}^n$ consisting of eigenvectors of $T$, so that $Mtx_W(T)$ is diagonalizable:

$$Mtx_W(T) = Mtx_{W,V}(id) \cdot Mtx_V(T) \cdot Mtx_{V,W}(id)$$

where $Mtx_V T$ is diagonal and the change of basis matrices $Mtx_{V,W}(id)$ and $Mtx_{W,V}(id)$ are unitary.

**Proof:** *(Sketch)* The proof of the theorem requires a lengthy digression into the linear algebra of complex vector spaces. Here is a very brief outline.

1. Let $M = Mtx_W(T)$.
2. The inner product in $\mathbb{C}^n$ is defined as follows:

$$x \cdot y = \sum_{j=1}^{n} x_j \cdot \overline{y_j}$$

where $\overline{c}$ denotes the complex conjugate of any $c \in \mathbb{C}$; note that this implies that $x \cdot y = \overline{x \cdot y}$. The usual inner product in $\mathbb{R}^n$ is the restriction of this inner product on $\mathbb{C}^n$ to $\mathbb{R}^n$.

3. Given any complex matrix $A$, define $A^*$ to be the matrix whose $(i, j)^{th}$ entry is $\overline{a_{ji}}$, in other words, $A^*$ is formed by taking the complex conjugate of each element of the transpose of $A$. It is easy to verify that given $x, y \in \mathbb{C}^n$ and a complex $n \times n$ matrix $A$, $Ax \cdot y = x \cdot A^*y$. Since $M$ is real and symmetric, $M^* = M$.

4. If $M$ is real and symmetric, and $\lambda \in \mathbb{C}$ is an eigenvalue of $M$, with eigenvector $x \in \mathbb{C}^n$, then

$$\lambda |x|^2 = \lambda (x \cdot x) = \overline{(\lambda x) \cdot x} = \overline{(Mx) \cdot x} = x \cdot (M^*x)$$
\[
\begin{align*}
= \ x \cdot (M x) \\
= \ x \cdot (\lambda x) \\
= \ (\lambda x) \cdot x \\
= \ \bar{\lambda} (x \cdot x) \\
= \ \bar{\lambda} |x|^2 \\
= \ \bar{\lambda} |x|^2
\end{align*}
\]

which proves that \( \lambda = \bar{\lambda} \), hence \( \lambda \in \mathbb{R} \).

5. If \( M \) is real (not necessarily symmetric) and \( \lambda \in \mathbb{R} \) is an eigenvalue, then \( \det(M - \lambda I) = 0 \Rightarrow \exists v \in \mathbb{R}^n \) s.t. \( (M - \lambda I)v = 0 \), so there is at least one real eigenvector. Symmetry implies that, if \( \lambda \) has multiplicity \( m \), there are \( m \) independent real eigenvectors corresponding to \( \lambda \) (but unfortunately we don’t have time to show this). Thus, there is a basis of eigenvectors, hence \( M \) is diagonalizable over \( \mathbb{R} \).

6. If \( M \) is real and symmetric, eigenvectors corresponding to distinct eigenvalues are orthogonal: Suppose that \( Mx = \lambda x \) and \( My = \rho y \) with \( \rho \neq \lambda \). Then

\[
\lambda (x \cdot y) = (\lambda x) \cdot y = (M x) \cdot y = (M x)^T y = (x^T M)^T y = (x^T M) y = x^T (M y) = x^T (\rho y) = x \cdot (\rho y) = \rho (x \cdot y)
\]

so \( (\lambda - \rho)(x \cdot y) = 0 \); since \( \lambda - \rho \neq 0 \), we must have \( x \cdot y = 0 \).

7. Using the Gram-Schmidt method, we can get an orthonormal basis of eigenvectors:

- Let \( X_\lambda = \{ x \in \mathbb{R}^n : Mx = \lambda x \} \), the set of all eigenvectors corresponding to \( \lambda \). Notice that if \( Mx = \lambda x \) and \( My = \lambda y \), then

\[
M(\alpha x + \beta y) = \alpha M x + \beta M y = \alpha \lambda x + \beta \lambda y = \lambda (\alpha x + \beta y)
\]

so \( X_\lambda \) is a vector subspace. Thus, given any basis of \( X_\lambda \), we wish to find an orthonormal basis of \( X_\lambda \); all elements of this orthonormal basis will be eigenvectors corresponding to \( \lambda \).

- Suppose \( X_\lambda \) is \( m \)-dimensional and we are given independent vectors \( x_1, \ldots, x_m \in X_\lambda \). The Gram-Schmidt method finds an orthonormal basis \( \{ v_1, \ldots, v_m \} \) for \( X_\lambda \).

- Let \( v_1 = \frac{x_1}{|x_1|} \). Note that \( |v_1| = 1 \).
• Suppose we have found an orthonormal set \{v_1, \ldots, v_k\} such that span \{v_1, \ldots, v_k\} = span \{x_1, \ldots, x_k\}, with \(k < m\). Let

\[
y_{k+1} = x_{k+1} - \sum_{j=1}^{k} (x_{k+1} \cdot v_j)v_j, \quad v_{k+1} = \frac{y_{k+1}}{|y_{k+1}|}
\]

\[
\text{span \{v_1, \ldots, v_{k+1}\}} = \text{span \{v_1, \ldots, v_k, v_{k+1}\}}
\]

\[
= \text{span \{v_1, \ldots, v_k, y_{k+1}\}}
\]

\[
= \text{span \{v_1, \ldots, v_k, x_{k+1}\}}
\]

\[
= \text{span \{x_1, \ldots, x_k, x_{k+1}\}}
\]

• For \(i = 1, \ldots, k\),

\[
y_{k+1} \cdot v_i = \left( x_{k+1} - \sum_{j=1}^{k} (x_{k+1} \cdot v_j)v_j \right) \cdot v_i
\]

\[
= x_{k+1} \cdot v_i - \sum_{j=1}^{k} (x_{k+1} \cdot v_j)(v_j \cdot v_i)
\]

\[
= x_{k+1} \cdot v_i - \sum_{j=1}^{k} (x_{k+1} \cdot v_j)\delta_{ij}
\]

\[
= x_{k+1} \cdot v_i - x_{k+1} \cdot v_i
\]

\[
= 0
\]

\[
v_{k+1} \cdot v_i = \frac{y_{k+1} \cdot v_i}{|y_{k+1}|}
\]

\[
= \frac{0}{|y_{k+1}|}
\]

\[
= 0
\]

\[
|v_{k+1}| = \frac{|y_{k+1}|}{|y_{k+1}|}
\]

\[
= 1
\]

Application to Quadratic Forms

Consider a quadratic form

\[
f(x_1, \ldots, x_n) = \sum_{i=1}^{n} \alpha_{ii}x_i^2 + \sum_{i<j} \beta_{ij}x_ix_j \tag{1}
\]

Let

\[
\alpha_{ij} = \begin{cases} 
\frac{\beta_{ij}}{2} & \text{if } i < j \\
\frac{\beta_{ij}}{2} & \text{if } i > j 
\end{cases}
\]
Let

\[ A = \begin{pmatrix} \alpha_{11} & \cdots & \alpha_{1n} \\ \vdots & \ddots & \vdots \\ \alpha_{n1} & \cdots & \alpha_{nn} \end{pmatrix} \]

so

\[ f(x) = x^\top Ax \]

**Example:** Let

\[ f(x) = \alpha x_1^2 + \beta x_1 x_2 + \gamma x_2^2 \]

Let

\[ A = \begin{pmatrix} \alpha & \frac{\beta}{2} \\ \frac{\beta}{2} & \gamma \end{pmatrix} \]

so \( A \) is symmetric and

\[
\begin{align*}
(x_1, x_2) \begin{pmatrix} \alpha & \frac{\beta}{2} \\ \frac{\beta}{2} & \gamma \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} &= (x_1, x_2) \begin{pmatrix} \alpha x_1 + \frac{\beta}{2} x_2 \\ \frac{\beta}{2} x_1 + \gamma x_2 \end{pmatrix} \\
&= \alpha x_1^2 + \beta x_1 x_2 + \gamma x_2^2 \\
&= f(x)
\end{align*}
\]

Returning to the general quadratic form in Equation (1), \( A \) is symmetric, so let \( V = \{v_1, \ldots, v_n\} \) be an orthonormal basis of eigenvectors of \( A \) with corresponding eigenvalues \( \lambda_1, \ldots, \lambda_n \). Then

\[
A = U^\top D U
\]

where

\[
D = \begin{pmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_n \end{pmatrix}
\]

and \( U = Mt_{x_{V,W}}(id) \) is unitary.

The columns of \( U^\top \) (the rows of \( U \)) are the coordinates of \( v_1, \ldots, v_n \), expressed in terms of the standard basis \( W \).

Given \( x \in \mathbb{R}^n \), recall

\[
x = \sum_{i=1}^n \gamma_i v_i \text{ where } \gamma_i = x \cdot v_i
\]

Then

\[
f(x) = f\left( \sum \gamma_i v_i \right)
\]
\[
\begin{align*}
&= \left( \sum \gamma_i v_i \right)^T A \left( \sum \gamma_i v_i \right) \\
&= \left( \sum \gamma_i v_i \right)^T U^T D U \left( \sum \gamma_i v_i \right) \\
&= \left( U \sum \gamma_i v_i \right)^T D \left( U \sum \gamma_i v_i \right) \\
&= \left( \sum \gamma_i U v_i \right)^T D \left( \sum \gamma_i U v_i \right) \\
&= \left( \gamma_1, \ldots, \gamma_n \right) D \begin{pmatrix}
\gamma_1 \\
\vdots \\
\gamma_n
\end{pmatrix} \\
&= \sum \lambda_i \gamma_i^2
\end{align*}
\]

The equation for the level sets of \( f \) is
\[
\sum_{i=1}^{n} \lambda_i \gamma_i^2 = C
\]

- If \( \lambda_i \geq 0 \) for all \( i \), the level set is an ellipsoid, with principal axes in the directions \( v_1, \ldots, v_n \). The length of the principal axis along \( v_i \) is \( \sqrt{C/\lambda_i} \) if \( C \geq 0 \) (if \( \lambda_i = 0 \), the level set is a degenerate ellipsoid with principal axis of infinite length in that direction). The level set is empty if \( C < 0 \). See Figure 1.

- If \( \lambda_i \leq 0 \) for all \( i \), the level set is an ellipsoid, with principal axes in the directions \( v_1, \ldots, v_n \). The length of the principal axis along \( v_i \) is \( \sqrt{C/\lambda_i} \) if \( C \leq 0 \) (if \( \lambda_i = 0 \), the level set is a degenerate ellipsoid with principal axis of infinite length in that direction). The level set is empty if \( C > 0 \).

- If \( \lambda_i > 0 \) for some \( i \) and \( \lambda_j < 0 \) for some \( j \), the level set is a hyperboloid. For example, suppose \( n = 2 \), \( \lambda_1 > 0 \), \( \lambda_2 < 0 \). The equation is
\[
C = \lambda_1 \gamma_1^2 + \lambda_2 \gamma_2^2
\]

This is a hyperbola with asymptotes
\[
0 = \sqrt{\lambda_1 \gamma_1 + \sqrt{|\lambda_2| \gamma_2}} \\
\Rightarrow \gamma_1 = -\sqrt{\frac{|\lambda_2|}{\lambda_1}} \gamma_2 \\
0 = \left( \sqrt{\lambda_1 \gamma_1} - \sqrt{|\lambda_2| \gamma_2} \right) \\
\Rightarrow \gamma_1 = \sqrt{\frac{|\lambda_2|}{\lambda_1}} \gamma_2
\]

See Figure 2. This proves the following corollary of Theorem 4.
**Corollary 5** Consider the quadratic form (1).

1. $f$ has a global minimum at $0$ if and only if $\lambda_i \geq 0$ for all $i$; the level sets of $f$ are ellipsoids with principal axes aligned with the orthonormal eigenvectors $v_1, \ldots, v_n$.

2. $f$ has a global maximum at $0$ if and only if $\lambda_i \leq 0$ for all $i$; the level sets of $f$ are ellipsoids with principal axes aligned with the orthonormal eigenvectors $v_1, \ldots, v_n$.

3. If $\lambda_i < 0$ for some $i$ and $\lambda_j > 0$ for some $j$, then $f$ has a saddle point at $0$; the level sets of $f$ are hyperboloids with principal axes aligned with the orthonormal eigenvectors $v_1, \ldots, v_n$.

### Section 3.4. Linear Maps between Normed Spaces

**Definition 6** Suppose $X, Y$ are normed vector spaces and $T \in L(X, Y)$. We say $T$ is **bounded** if

$$\exists \beta \in \mathbb{R} \text{ s.t. } \|T(x)\|_Y \leq \beta \|x\|_X \quad \forall x \in X$$

Note this implies that $T$ is Lipschitz with constant $\beta$.

**Theorem 7** (Thms. 4.1, 4.3) Let $X, Y$ be normed vector spaces and $T \in L(X, Y)$. Then $T$ is continuous at some point $x_0 \in X$ if and only if $T$ is continuous at every $x \in X$ if and only if $T$ is uniformly continuous on $X$ if and only if $T$ is Lipschitz if and only if $T$ is bounded.

**Proof:** Suppose $T$ is continuous at $x_0$. Fix $\varepsilon > 0$. Then there exists $\delta > 0$ such that

$$\|z - x_0\| < \delta \implies \|T(z) - T(x_0)\| < \varepsilon$$

Now suppose $x$ is any element of $X$. If $\|y - x\| < \delta$, let $z = y - x + x_0$, so $\|z - x_0\| = \|y - x\| < \delta$.

$$\|T(y) - T(x)\| = \|T(y - x)\| = \|T(y - x + x_0 - x_0)\| = \|T(z) - T(x_0)\| < \varepsilon$$

which proves that $T$ is continuous at every $x$, and uniformly continuous.
We claim that $T$ is bounded if and only if $T$ is continuous at 0. Suppose $T$ is not bounded. Then

$$\exists \{x_n\} \text{ s.t. } \|T(x_n)\| > n\|x_n\| \quad \forall n$$

Note that $x_n \neq 0$. Let $\varepsilon = 1$. Fix $\delta > 0$ and choose $n$ such that $\frac{1}{n} < \delta$. Let

$$x'_n = \frac{x_n}{n\|x_n\|}$$
$$\|x'_n\| = \frac{\|x_n\|}{n\|x_n\|} = \frac{1}{n} < \delta$$
$$\|T(x'_n) - T(0)\| = \|T(x'_n)\|$$
$$= \frac{1}{n\|x_n\|} \|T(x_n)\|$$
$$> \frac{n\|x_n\|}{n\|x_n\|} = 1$$
$$= \varepsilon$$

Since this is true for every $\delta$, $T$ is not continuous at 0. Therefore, $T$ continuous at 0 implies $T$ is bounded. Now, suppose $T$ is bounded, so find $M$ such that $\|T(x)\| \leq M\|x\|$ for every $x \in X$. Given $\varepsilon > 0$, let $\delta = \varepsilon/M$. Then

$$\|x - 0\| < \delta \implies \|x\| < \delta$$
$$\implies \|T(x) - T(0)\| = \|T(x)\| < M\delta$$
$$\implies \|T(x) - T(0)\| < \varepsilon$$

so $T$ is continuous at 0.

Thus, we have shown that continuity at some point $x_0$ implies uniform continuity, which implies continuity at every point, which implies $T$ is continuous at 0, which implies that $T$ is bounded, which implies that $T$ is continuous at 0, which implies that $T$ is continuous at some $x_0$, so all of the statements except possibly the Lipschitz statement are equivalent.

Suppose $T$ is bounded, with constant $M$. Then

$$\|T(x) - T(y)\| = \|T(x - y)\| \leq M\|x - y\|$$

so $T$ is Lipschitz with constant $M$; conversely, if $T$ is Lipschitz with constant $M$, then $T$ is bounded with constant $M$. So all the statements are equivalent. ■

Every linear map on a finite-dimensional normed vector space is bounded (and thus continuous, uniformly continuous, and Lipschitz continuous).
Theorem 8 (Thm. 4.5) Let $X, Y$ be normed vector spaces with $\dim X = n$. Every $T \in L(X, Y)$ is bounded.

Proof: See de la Fuente. ■

Definition 9 A *topological isomorphism* between normed vector spaces $X$ and $Y$ is a linear transformation $T \in L(X, Y)$ that is invertible (one-to-one, onto), continuous, and has a continuous inverse.

Two normed vector spaces $X$ and $Y$ are *topologically isomorphic* if there is a topological isomorphism $T : X \to Y$.

Suppose $X$ and $Y$ are normed vector spaces. We define

$$B(X,Y) = \{ T \in L(X,Y) : T \text{ is bounded} \}$$

$$\|T\|_{B(X,Y)} = \sup \left\{ \frac{\|T(x)\|_Y}{\|x\|_X} : x \in X, x \neq 0 \right\}$$

$$= \sup \{ \|T(x)\|_Y : \|x\|_X = 1 \}$$

Theorem 10 (Thm. 4.8) Let $X, Y$ be normed vector spaces. Then

$$\left( B(X,Y), \| \cdot \|_{B(X,Y)} \right)$$

is a normed vector space.

Proof: See de la Fuente. ■

Theorem 11 (Thm. 4.9) Let $T \in L(R^n, R^m) (= B(R^n, R^m))$ with matrix $A = (a_{ij})$ with respect to the standard bases. Let

$$M = \max \{|a_{ij}| : 1 \leq i \leq m, 1 \leq j \leq n \}$$

Then

$$M \leq \|T\| \leq M\sqrt{mn}$$

Proof: See de la Fuente. ■

Theorem 12 (Thm. 4.10) Let $R \in L(R^m, R^n)$ and $S \in L(R^n, R^p)$. Then

$$\|S \circ R\| \leq \|S\|\|R\|$$
**Proof:** See de la Fuente. ■

Define

\[ \Omega(\mathbb{R}^n) = \{ T \in L(\mathbb{R}^n, \mathbb{R}^n) : T \text{ is invertible} \} \]

**Theorem 13 (Thm. 4.11’)** Suppose \( T \in L(\mathbb{R}^n, \mathbb{R}^n) \) and \( E \) is the standard basis of \( \mathbb{R}^n \). Then

\[ T \text{ is invertible} \iff \ker T = \{0\} \iff \det (Mt_x E(T)) \neq 0 \iff \det (Mt_{x,V}(T)) \neq 0 \text{ for every basis } V \iff \det (Mt_{x,W}(T)) \neq 0 \text{ for every pair of bases } V, W \]

**Theorem 14 (Thm. 4.12)** If \( S, T \in \Omega(\mathbb{R}^n) \), then \( S \circ T \in \Omega(\mathbb{R}^n) \) and

\[ (S \circ T)^{-1} = T^{-1} \circ S^{-1} \]

**Theorem 15 (Thm. 4.14)** Let \( S, T \in L(\mathbb{R}^n, \mathbb{R}^n) \). If \( T \) is invertible and

\[ \|T - S\| < \frac{1}{\|T^{-1}\|} \]

then \( S \) is invertible. In particular, \( \Omega(\mathbb{R}^n) \) is open in \( L(\mathbb{R}^n, \mathbb{R}^n) = B(\mathbb{R}^n, \mathbb{R}^n) \).

**Proof:** See de la Fuente. ■

**Theorem 16 (4.15)** The function \((\cdot)^{-1} : \Omega(\mathbb{R}^n) \to \Omega(\mathbb{R}^n)\) that assigns \( T^{-1} \) to each \( T \in \Omega(\mathbb{R}^n) \) is continuous.

**Proof:** See de la Fuente. ■
Figure 1: If $\lambda_1, \lambda_2 > 0$ and $C > 0$, the level set is an ellipsoid, with principal axes in the directions $v_1, v_2$. The length of the principal axis along $v_i$ is $\sqrt{C/\lambda_i}$. 
If $\lambda_1 > 0$ and $\lambda_2 < 0$, the level set is a hyperbola with asymptotes $\gamma_1 = \sqrt{\frac{\lambda_2}{\lambda_1}} \gamma_2$. 

Figure 2: If $\lambda_1 > 0$ and $\lambda_2 < 0$, the level set is a hyperbola with asymptotes $\gamma_1 = \sqrt{\frac{\lambda_2}{\lambda_1}} \gamma_2$. 