Linear Algebra and Vector Calculus
Notes and Exercises

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Chapter 1

Linear Algebra Basics

1.1 Linear Functions

A function $L\colon \boldsymbol{R}^m \to \boldsymbol{R}^n$ is a linear function if for all $\boldsymbol{x}, \boldsymbol{y} \in \boldsymbol{R}^m$ and for all $a, b \in \boldsymbol{R}$

$$L(a\boldsymbol{x} + b\boldsymbol{y}) = aL(\boldsymbol{x}) + bL(\boldsymbol{y}).$$

It follows (by induction) that for all $\boldsymbol{x}_1, \ldots, \boldsymbol{x}_r \in \boldsymbol{R}^m$ and all $a_1, \ldots, a_r \in \boldsymbol{R}$

$$L(a_1\boldsymbol{x}_1 + \cdots + a_r\boldsymbol{x}_r) = a_1 L(\boldsymbol{x}_1) + \cdots + a_r L(\boldsymbol{x}_r).$$

Theorem 1.1. *A linear function $L\colon \boldsymbol{R}^m \to \boldsymbol{R}^n$ is completely determined by its effect on the standard basis vectors $\boldsymbol{e}_1, \ldots, \boldsymbol{e}_m$ of $\boldsymbol{R}^m$. An arbitrary choice of vectors $L(\boldsymbol{e}_1), \ldots, L(\boldsymbol{e}_m)$ of $\boldsymbol{R}^n$ determines a linear function from $\boldsymbol{R}^m$ to $\boldsymbol{R}^n$.*

Proof. Given any vector $\boldsymbol{x} \in \boldsymbol{R}^m$, we can express it as a unique linear combination $\sum_{i=1}^m \alpha_i \boldsymbol{e}_i$ of the basis vectors. By the linearity of L, $L(\boldsymbol{x}) = \sum_i \alpha_i L(\boldsymbol{e}_i)$ which is completely specified by $L(\boldsymbol{e}_1), \ldots, L(\boldsymbol{e}_m)$.

Let $\boldsymbol{b}_1, \ldots, \boldsymbol{b}_m$ be any vectors in $\boldsymbol{R}^n$. Define a map L from $\boldsymbol{R}^m$ to $\boldsymbol{R}^n$ as follows: for $\boldsymbol{x} = \sum_{i=1}^m \alpha_i \boldsymbol{e}_i \in \boldsymbol{R}^m$, $L(\boldsymbol{x}) = \sum_{i=1}^m \alpha_i \boldsymbol{b}_i$. Then $L(\boldsymbol{e}_i) = \boldsymbol{b}_i$ for all $1 \le i \le m$ and for all $\boldsymbol{x}, \boldsymbol{y} \in \boldsymbol{R}^m$ and all $a, b \in \boldsymbol{R}$:

$$L(a\boldsymbol{x} + b\boldsymbol{y}) = \sum_{i=1}^m (ax_i + by_i)\boldsymbol{b}_i = a\sum_i x_i \boldsymbol{b}_i + b\sum_i y_i \boldsymbol{b}_i = aL(\boldsymbol{x}) + bL(\boldsymbol{y})$$

$\square$

Note that the domain of definition of a linear function must be a vector space. An non-linear function can be defined on a subset of a vector space.

1.2 Image and Kernel of a Linear Function

The image $\mathrm{Im}(L)$ of a linear function $L\colon \boldsymbol{R}^m \to \boldsymbol{R}^n$ is the set of vectors in $\boldsymbol{R}^n$ that L maps $\boldsymbol{R}^m$ to. In symbols, $\mathrm{Im}(L) := \{L(\boldsymbol{x}) \in \boldsymbol{R}^n : \boldsymbol{x} \in \boldsymbol{R}^m\}$. The kernel $\mathrm{Ker}(L)$ of L is the set of vectors in $\boldsymbol{R}^m$ that L maps to the zero vector in $\boldsymbol{R}^n$: $\mathrm{Ker}(L) := \{\boldsymbol{x} \in \boldsymbol{R}^m : L(\boldsymbol{x}) = 0_n\}$.

Theorem 1.2. *Let $L\colon \boldsymbol{R}^m \to \boldsymbol{R}^n$ be a linear function. Then the following hold:*

1. $\mathrm{Im}(L)$ *is a subspace of* $\boldsymbol{R}^n$*;*

2. $\mathrm{Ker}(L)$ *is a subspace of* $\boldsymbol{R}^m$*;*

3. $\dim(\mathrm{Im}(L)) + \dim(\mathrm{Ker}(L)) = \dim(\boldsymbol{R}^m) = m$*.*

Proof. The proof of (1) and (2) are similar. For proving (1), let $\boldsymbol{z}_1, \boldsymbol{z}_2 \in \mathrm{Im}(L)$ and $\alpha, \beta \in \boldsymbol{R}$. Then there exist $\boldsymbol{x}_1, \boldsymbol{x}_2 \in \boldsymbol{R}^m$ such that

$$L(\alpha\boldsymbol{x}_1 + \beta\boldsymbol{x}_2) = \alpha\boldsymbol{z}_1 + \beta\boldsymbol{z}_2,$$

implying that $\alpha\boldsymbol{z}_1 + \beta\boldsymbol{z}_2 \in \mathrm{Im}(L)$. Since $\mathrm{Im}(L)$ is closed under vector addition and multiplication by scalars, it is a vector space. Since it is a subset of $\boldsymbol{R}^n$, it must be a subspace of $\boldsymbol{R}^n$.

To prove (3), let us assume that $\dim(\mathrm{Ker}(L)) = k$ and that $\boldsymbol{b}_1, \ldots, \boldsymbol{b}_k$ is a basis of $\mathrm{Ker}(L)$. Extend this basis to a basis $\boldsymbol{b}_1, \ldots, \boldsymbol{b}_k, \boldsymbol{b}_{k+1}, \ldots, \boldsymbol{b}_m$ for $\boldsymbol{R}^m$. Then for every vector $\boldsymbol{x} \in \boldsymbol{R}^m$ there exist scalars $\beta_1, \ldots, \beta_m$ such that $\boldsymbol{x} = \sum_{i=1}^{k} \beta_i \boldsymbol{b}_i$. Moreover since L is linear,

$$\begin{aligned} L(\boldsymbol{x}) &= \sum_{i=1}^{m} \beta_i L(\boldsymbol{b}_i) \\ &= \sum_{i=k+1}^{m} \beta_i L(\boldsymbol{b}_i). \end{aligned}$$

This shows that every vector in $\mathrm{Im}(L)$ can be expressed as a linear combination of the vectors $L(\boldsymbol{b}_{k+1}), \ldots, L(\boldsymbol{b}_m)$. To show that they form a basis of $\mathrm{Im}(L)$, it is sufficient to show that they are linearly independent. Suppose not. Then there exist scalars $\beta_{k+1}, \ldots, \beta_m$, not all zero, such that $\sum_{i=k+1}^{m} \beta_i L(\boldsymbol{b}_i) = \boldsymbol{0}_n$. By the linearity of L, we have $L(\sum_{i=k+1}^{m} \beta_i \boldsymbol{b}_i) = \boldsymbol{0}_n$ and hence $\boldsymbol{0}_m \neq \sum_{i=k+1}^{m} \beta_i \boldsymbol{b}_i \in \mathrm{Ker}(L)$. This is a contradiction since the vectors $\boldsymbol{b}_{k+1}, \ldots, \boldsymbol{b}_m$ are not in the space spanned by the vectors $\boldsymbol{b}_1, \ldots, \boldsymbol{b}_k$. Thus the vectors $\beta_{k+1}, \ldots, \beta_m$ must be independent and form a basis of $\mathrm{Im}(L)$. This proves (3). $\square$

1.3 Quadratic Forms

A function $q\colon \boldsymbol{R}^m \to \boldsymbol{R}$ is called a *quadratic form* if there exists a real symmetric $m \times m$ matrix A such that for all $\boldsymbol{x} \in \boldsymbol{R}^m$ such that

$$q(\boldsymbol{x}) = \boldsymbol{x}^\intercal A \boldsymbol{x}.$$

The right-hand side of the equation may be written as:

$$\begin{aligned} (x_1, \ldots, x_m) \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{m1} \\ \vdots & \vdots & \cdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mm} \end{pmatrix} \begin{pmatrix} x_1 \\ \vdots \\ x_m \end{pmatrix} &= (x_1, \ldots, x_m)[x_1 A_{*1} + \cdots + x_m A_{*m}] \\ &= \sum_{i=1}^{m} \sum_{j=1}^{m} x_i a_{ij} x_j. \end{aligned}$$

The symbol A_{*j} denotes the jth column of A. The name "quadratic" form arises from the last expression which is what a quadratic expression in m variables looks like.

Example 1.1. The function

$$q(h_1, h_2, h_3) = h_1^2 + h_2^2 + h_3^2 + 2h_1h_2 + 2h_2h_3 + 2h_1h_3 = (h_1 + h_2 + h_3)^2$$

can be expressed as $\boldsymbol{h}^{\intercal} A \boldsymbol{h}$, where A is the all-ones 3×3 matrix.

1.3.1 Definiteness

A quadratic form $q\colon \boldsymbol{R}^m \to \boldsymbol{R}$ is

1. *positive definite* if for all non-zero $\boldsymbol{x} \in \boldsymbol{R}^m$, $q(\boldsymbol{x}) > 0$;
2. *negative definite* if for all non-zero $\boldsymbol{x} \in \boldsymbol{R}^m$, $q(\boldsymbol{x}) > 0$;
3. *indefinite* if $q(\boldsymbol{x})$ takes on both positive and negative values.

Example 1.2. Let $q(\boldsymbol{h}) = -h_1^2 + 2h_2^2 - h_3^2$ such that the matrix associated with q is

$$\begin{pmatrix} -1 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & -1 \end{pmatrix}.$$

The $q(0,1,0) = 2$ and $q(1,0,1) = -2$. Thus the quardatic form q is indefinite.

Example 1.3. The quadratic form $q(h_1, h_2, h_3) = h_1^2 + h_2^2 + 4h_3^2 + 2h_1h_2 - 4h_2h_3 - 4h_1h_3$ is positive definite, since we may re-write $q(h_1, h_2, h_3)$ as $(h_1 + h_2 - 2h_3)^2$ which is strictly positive for all $(h_1, h_2, h_3) \in \boldsymbol{R}^3 \setminus \{0\}$.

To characterize the definiteness of quadratic forms, we make use of the following properties of real symmetric matrices.

Lemma 1.1. *The eigenvectors of a real symmetric matrix A are real.*

Proof. Suppose that A is an $m \times m$ matrix and suppose that some eigenvalue λ is complex. Let $\boldsymbol{x}$ be a eigenvector corresponding to it, which can be a complex vector. Then

$$A\boldsymbol{x} = \lambda \boldsymbol{x}. \tag{1.1}$$

Taking complex conjugates on each side, we get:

$$A\bar{\boldsymbol{x}} = \bar{\lambda}\bar{\boldsymbol{x}}. \tag{1.2}$$

Pre-multiply (1.1) by $\bar{\boldsymbol{x}}^{\intercal}$ and (1.2) by $\boldsymbol{x}^{\intercal}$ to obtain:

$$\bar{\boldsymbol{x}}^{\intercal} A \boldsymbol{x} = \bar{\boldsymbol{x}}^{\intercal} \lambda \boldsymbol{x} \tag{1.3}$$

$$\boldsymbol{x}^{\intercal} A \bar{\boldsymbol{x}} = \boldsymbol{x}^{\intercal} \bar{\lambda} \bar{\boldsymbol{x}}. \tag{1.4}$$

Take the transpose of equation (1.4), we obtain: $\bar{\boldsymbol{x}}^\intercal A\boldsymbol{x} = \bar{\boldsymbol{x}}^\intercal \bar{\lambda}\boldsymbol{x}$, where we made use of the fact that A is symmetric. Now subtracting this equation from (1.3), we obtain:

$$\boldsymbol{x}^\intercal(\lambda - \bar{\lambda})\bar{\boldsymbol{x}} = 0.$$

Since $\boldsymbol{x}^\intercal\bar{\boldsymbol{x}}$ is the sum of products of complex conjugates, it is not zero unless each component of $\boldsymbol{x}$ is zero. Since this is not the case ($\boldsymbol{x}$ is an eigenvector), we must have $\lambda = \bar{\lambda}$ and hence λ is real. □

Example 1.4. Consider the unit matrix

$$I_2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}.$$

This has as eigenvalues 1 and 1, which are clearly not distinct. In general, I_m has m eigenvalues all of which are 1. Note that I_m has rank m. On the other hand, the matrix

$$\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

has rank one and has two distinct eigenvalues $0, 2$ which are the roots of the equation: $(1-\lambda)^2 - 1 = 0$. Thus the rank of a matrix has nothing to do with the number of distinct eigenvalues.

Now that we know that a real symmetric matrix has only real eigenvalues, what can we say about the corresponding eigenvectors? It turns out that the eigenvectors corresponding to the eigenvalues of a real symmetric matrix form an orthonormal basis for $\boldsymbol{R}^m$. We show this using a sequence of lemmas.

Lemma 1.2. *The eigenvectors of a real symmetric matrix corresponding to distinct eigenvalues are mutually orthogonal.*

Proof. Let λ_i and λ_j be two distinct eigenvalues of a real symmetric matrix A. Let $\boldsymbol{x}_i$ and $\boldsymbol{x}_j$ be eigenvectors corresponding to these eigenvalues. Then $A\boldsymbol{x}_i = \lambda_i\boldsymbol{x}_i$ and $A\boldsymbol{x}_j = \lambda_j\boldsymbol{x}_j$. Pre-multiplying the first of these equations by $\boldsymbol{x}_j^\intercal$ and the second by $\boldsymbol{x}_i^\intercal$, we obtain:

$$\boldsymbol{x}_j^\intercal A\boldsymbol{x}_i = \boldsymbol{x}_j^\intercal \lambda_i \boldsymbol{x}_i \tag{1.5}$$

$$\boldsymbol{x}_i^\intercal A\boldsymbol{x}_j = \boldsymbol{x}_i^\intercal \lambda_j \boldsymbol{x}_j \tag{1.6}$$

Taking the transpose of the second of these equations, we obtain:

$$\boldsymbol{x}_j^\intercal A\boldsymbol{x}_i = \boldsymbol{x}_j^\intercal \lambda_j \boldsymbol{x}_i. \tag{1.7}$$

Now the right-hand sides of equations (1.5) and (1.6) are identical. Hence $\boldsymbol{x}_j^\intercal(\lambda_i - \lambda_j)\boldsymbol{x}_i = 0$ and since $\lambda_i \neq \lambda_j$, it must be that the vectors $\boldsymbol{x}_i$ and $\boldsymbol{x}_j$ are orthogonal. □

Lemma 1.3. *Let $A \in \boldsymbol{R}^{m\times m}$ and let λ be an eigenvalue. The eigenvectors belonging to λ form a subspace $\mathscr{E}_A(\lambda)$ of $\boldsymbol{R}^m$.*

Proof. Let $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$ are two eigenvectors belonging to λ. Then

$$A(a\boldsymbol{x}_1 + b\boldsymbol{x}_2) = aA\boldsymbol{x}_1 + bA\boldsymbol{x}_2 = \lambda(a\boldsymbol{x}_1 + b\boldsymbol{x}_2).$$

Thus any linear combination of the eigenvectors is also an eigenvector of λ, showing that this set of vectors is indeed a subspace. $\square$

Lemma 1.4. *Let $A \in \boldsymbol{R}^{m\times m}$ be a symmetric matrix. Then the algebraic multiplicity of each eigenvalue of A equals its geometric multiplicity.*

Proof. Let λ_i be an eigenvalue with algebraic multiplicity k. Suppose that $\dim(\mathscr{E}_A(\lambda_i)) = r$ and let $\{\boldsymbol{v}_1, \ldots, \boldsymbol{v}_r\}$ be an orthonormal basis for $\mathscr{E}_A(\lambda_i)$. Extend this to an orthonormal basis $\{\boldsymbol{v}_1, \ldots, \boldsymbol{v}_r, \boldsymbol{v}_{r+1}, \ldots, \boldsymbol{v}_m\}$ for $\boldsymbol{R}^m$.

Define $S = [\boldsymbol{v}_1, \ldots, \boldsymbol{v}_r, \boldsymbol{v}_{r+1}, \ldots, \boldsymbol{v}_m]$ to be the $m \times m$ matrix whose columns are the basis vectors. Then S is an orthonormal matrix and $S^{-1} = S^\intercal$. Consider the matrix $S^{-1}AS$. This is similar to A and therefore has the same eigenvalues as A including the same multiplicities.

We may write $S^{-1}AS$ as:

$$\begin{aligned}
S^{-1}AS &= \begin{pmatrix} -\boldsymbol{v}_1^\intercal- \\ \vdots \\ -\boldsymbol{v}_m^\intercal- \end{pmatrix} A \begin{pmatrix} \boldsymbol{v}_1 & \boldsymbol{v}_2 & \cdots & \boldsymbol{v}_m \\ | & | & & | \end{pmatrix} \\
&= \begin{pmatrix} -\boldsymbol{v}_1^\intercal- \\ \vdots \\ -\boldsymbol{v}_m^\intercal- \end{pmatrix} \begin{pmatrix} \lambda_i\boldsymbol{v}_1 & \cdots & \lambda_i\boldsymbol{v}_r & A\boldsymbol{v}_{r+1} & \cdots & A\boldsymbol{v}_m \\ | & & | & | & & | \end{pmatrix} \\
&= \left(\begin{array}{c|c} \lambda_i I_r & \boldsymbol{0}_{r,m-r} \\ \hline \boldsymbol{0}_{m-r,r} & C^\intercal AC \end{array}\right),
\end{aligned}$$

where $C = [\boldsymbol{v}_{r+1}, \ldots, \boldsymbol{v}_m]$. The characteristic polynomials $\det(S^{-1}AS - \lambda I_m)$ and $\det(A - \lambda I_m)$ are identical and

$$\det(S^{-1}AS - \lambda I_m) = (\lambda_i - \lambda)^r \det(C^\intercal AC - \lambda I_{m-r}).$$

Since we know that in the RHS, the term $\lambda_i - \lambda$ is raised to the mth power, we must have $r \leq m$. $\square$