

# Math 235 Notes

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These are my 2nd year Linear Algebra 2 notes at the University of Waterloo (MATH 235). They are pretty similar to the content you may see in the course notes by D. Wolczuk.

You will find that these aren't very useful as notes, in the sense that they are not significantly shorter than the content in the course notes, they're really just a way for me to type down the content I am learning and absorb it.

Thanks to Prof. Dan Wolczuk for providing me with the macros to typeset this LaTeX document.

## 7. Fundamental Subspaces

Let  $A$  be an  $m \times n$  matrix. The **four fundamental subspaces** of  $A$  are

Definition  
Fundamental  
Subspaces

1.  $\text{Col}(A) = \{A\vec{x} \in \mathbb{R}^m | \vec{x} \in \mathbb{R}^n\}$ , called the **column space**

2.  $\text{Row}(A) = \{A^T\vec{x} \in \mathbb{R}^n | \vec{x} \in \mathbb{R}^m\}$ , called the **row space**

3.  $\text{Null}(A) = \{\vec{x} \in \mathbb{R}^n | A\vec{x} = \vec{0}\}$ , called the **null space**

4.  $\text{Null}(A^T) = \{\vec{x} \in \mathbb{R}^m | A^T\vec{x} = \vec{0}\}$ , called the **left nullspace**

If  $A$  is an  $m \times n$  matrix, then  $\text{Col}(A)$  and  $\text{Null}(A^T)$  are subspaces of  $\mathbb{R}^m$ , and  $\text{Row}(A)$  and  $\text{Null}(A)$  are subspaces of  $\mathbb{R}^n$

Theorem  
7.1.1

If  $A$  is an  $m \times n$  matrix, then the columns of  $A$  which correspond to leading ones in the RREF of  $A$  form a basis for  $\text{Col}(A)$ . Moreover,

Theorem  
7.1.2

$$\dim \text{Col}(A) = \text{rank } A$$

If  $R$  is an  $m \times n$  matrix and  $E$  is an  $n \times n$  invertible matrix, then

Theorem  
7.1.3

$$\{RE\vec{x} | \vec{x} \in \mathbb{R}^n\} = \{R\vec{y} | \vec{y} \in \mathbb{R}^n\}$$

If  $A$  is an  $m \times n$  matrix, then the non-zero rows in the reduced row echelon form of  $A$  form a basis for  $\text{Row}(A)$ . Hence,

Theorem  
7.1.4

$$\dim \text{Row}(A) = \text{rank } A$$

For any  $m \times n$  matrix  $A$  we have  $\text{rank } A = \text{rank } A^T$

Corollary  
7.1.5

If  $A$  is an  $m \times n$  matrix, then

Dimension  
Theorem

$$\text{rank } A + \dim \text{Null}(A) = n$$

# 8. Linear Mappings

Some review

A mapping  $L : \mathbb{R}^n \rightarrow \mathbb{R}^m$  is called **linear** if

$$L(s\vec{x} + t\vec{y}) = sL(\vec{x}) + tL(\vec{y})$$

for all  $\vec{x}, \vec{y} \in \mathbb{R}^n$  and  $s, t \in \mathbb{R}$

Two linear mappings  $L : \mathbb{R}^n \rightarrow \mathbb{R}^m$  and  $M : \mathbb{R}^n \rightarrow \mathbb{R}^m$  are said to be **equal** if  $L(\vec{v}) = M(\vec{v}), \forall \vec{v} \in \mathbb{R}^n$

Definition

Linear  
Mapping

The **range** of a linear mapping  $L : \mathbb{R}^n \rightarrow \mathbb{R}^m$  is defined by

$$\text{Range}(L) = \{L(\vec{x}) | \vec{x} \in \mathbb{R}^n\}$$

Definition

Range

The **kernel** of a linear mapping  $L : \mathbb{R}^n \rightarrow \mathbb{R}^m$  is defined by

$$\text{Ker}(L) = \{\vec{x} \in \mathbb{R}^n | L(\vec{x}) = \vec{0}\}$$

Definition

Kernel

The **standard matrix** of a linear mapping  $L : \mathbb{R}^n \rightarrow \mathbb{R}^m$  is defined by

$$[L] = [L(\vec{e}_1) \ \dots \ L(\vec{e}_n)]$$

Definition

Standard  
Matrix

It satisfies

$$L(\vec{x}) = [L]\vec{x}$$

for all  $\vec{x} \in \mathbb{R}^n$

If  $L : \mathbb{R}^n \rightarrow \mathbb{R}^m$  is a linear mapping, then  $\text{Range}(L) = \text{Col}([L])$

Theorem  
7.2.1

If  $L : \mathbb{R}^n \rightarrow \mathbb{R}^m$  is a linear mapping, then  $\text{Ker}(L) = \text{Null}([L])$

Theorem  
7.2.2

Let  $L : \mathbb{R}^n \rightarrow \mathbb{R}^m$  be a linear mapping. Then,

Theorem  
7.2.3

$$\dim(\text{Range}(L)) + \dim(\text{Ker}(L)) = \dim(\mathbb{R}^n)$$

## 8.1 General Linear Mappings

**Linear Mappings**  $L : \mathbb{V} \rightarrow \mathbb{W}$

We will extend our definition of a linear mapping to the case where the domain and codomain are general vector spaces instead of just  $\mathbb{R}^n$

Let  $\mathbb{V}$  and  $\mathbb{W}$  be vector spaces. A mapping  $L : \mathbb{V} \rightarrow \mathbb{W}$  is called **linear** if

$$L(s\vec{x} + t\vec{y}) = sL(\vec{x}) + tL(\vec{y})$$

for all  $\vec{x}, \vec{y} \in \mathbb{V}$  and  $s, t \in \mathbb{R}$

Two linear mappings  $L : \mathbb{V} \rightarrow \mathbb{W}$  and  $M : \mathbb{V} \rightarrow \mathbb{W}$  are said to be **equal** if  $L(\vec{v}) = M(\vec{v}), \forall \vec{v} \in \mathbb{V}$

**Note:** A linear mapping  $L : \mathbb{V} \rightarrow \mathbb{V}$  is called a **linear operator**

Definition

Linear  
Mapping

Let  $L : \mathbb{V} \rightarrow \mathbb{W}$  and  $M : \mathbb{V} \rightarrow \mathbb{W}$  be linear mappings. We define  $L + M : \mathbb{V} \rightarrow \mathbb{W}$  by

$$(L + M)(\vec{v}) = L(\vec{v}) + M(\vec{v})$$

and for any  $t \in \mathbb{R}$  we define  $tL : \mathbb{V} \rightarrow \mathbb{W}$  by

$$(tL)(\vec{v}) = tL(\vec{v})$$

Definition

Addition  
Scalar Multi-  
plication

Let  $\mathbb{V}$  and  $\mathbb{W}$  be vector spaces. The set  $\mathbb{L}$  of all linear mappings  $L : \mathbb{V} \rightarrow \mathbb{W}$  with standard addition and scalar multiplication of mappings is a vector space

Theorem  
8.1.1

Let  $L : \mathbb{V} \rightarrow \mathbb{W}$  and  $M : \mathbb{W} \rightarrow \mathbb{U}$  be linear mappings. We define  $M \circ L : \mathbb{V} \rightarrow \mathbb{U}$  by

$$(M \circ L)(\vec{v}) = M(L(\vec{v})), \forall \vec{v} \in \mathbb{V}$$

Definition  
Composition

If  $L : \mathbb{V} \rightarrow \mathbb{W}$  and  $M : \mathbb{W} \rightarrow \mathbb{U}$  are linear mappings, then  $M \circ L : \mathbb{V} \rightarrow \mathbb{U}$  is a linear mapping

Theorem  
8.1.2

Let  $L : \mathbb{V} \rightarrow \mathbb{W}$  and  $M : \mathbb{V} \rightarrow \mathbb{W}$  be linear mappings. If  $(M \circ L)(\vec{v}) = \vec{v}, \forall \vec{v} \in \mathbb{V}$  and  $(L \circ M)(\vec{w}) = \vec{w}, \forall \vec{w} \in \mathbb{W}$ , then  $L$  and  $M$  are said to be **invertible**. We write  $M = L^{-1}$  and  $L = M^{-1}$

Definition  
Invertible  
Mapping

## 8.2 Rank-Nullity Theorem

Let's extend the definitions of the range and kernel to general linear mappings.

For a linear mapping  $L : \mathbb{V} \rightarrow \mathbb{W}$  the **kernel** of  $L$  is defined to be

Definition

$$\text{Ker}(L) = \{\vec{v} \in \mathbb{V} | L(\vec{v}) = \vec{0}_{\mathbb{W}}\}$$

Range  
Kernel

and the **range** of  $L$  is defined to be

$$\text{Range}(L) = \{L(\vec{v}) \in \mathbb{W} | \vec{v} \in \mathbb{V}\}$$

If  $\mathbb{V}$  and  $\mathbb{W}$  are vector spaces and  $L : \mathbb{V} \rightarrow \mathbb{W}$  is a linear mapping, then

Theorem  
8.2.1

$$L(\vec{0}_{\mathbb{V}}) = \vec{0}_{\mathbb{W}}$$

If  $L : \mathbb{V} \rightarrow \mathbb{W}$  is a linear mapping, then  $\text{Ker}(L)$  is a subspace of  $\mathbb{V}$  and  $\text{Range}(L)$  is a subspace of  $\mathbb{W}$

Theorem  
8.2.2

Let  $L : \mathbb{V} \rightarrow \mathbb{W}$  be a linear mapping. We define the **rank** of  $L$  to be

Definition

$$\text{rank}(L) = \dim(\text{Range}(L))$$

Rank  
Nullity

We define the **nullity** of  $L$  to be

$$\text{nullity}(L) = \dim(\text{Ker}(L))$$

Let  $\mathbb{V}$  be an  $n$ -dimensional vector space and let  $\mathbb{W}$  be a vector space. If  $L : \mathbb{V} \rightarrow \mathbb{W}$  is linear, then

Rank-  
Nullity  
Theorem

$$\text{rank}(L) + \text{nullity}(L) = n$$

**Remark:** The proof for the Rank-Nullity Theorem is identical to the proof for the dimension theorem, only that this time it is a generalisation for general vector spaces. You could see the Rank-Nullity theorem as an analog of the Dimension theorem for general linear mappings.

### 8.3 Matrix of a Linear Mapping

We will now show that every linear mapping  $l : \mathbb{V} \rightarrow \mathbb{W}$  can also be represented as a matrix mapping. However, we must be careful when dealing with general vector spaces as our domain and codomain. For example, it is certainly impossible to represent a linear mapping that maps polynomials to matrices, since we cannot multiply a matrix by a polynomial.

Thus, if we are going to convert vectors in  $\mathbb{V}$  to vectors in  $\mathbb{R}^n$  in order to define matrix representations of general linear mappings. Recall the coordinate vector of  $\vec{x} \in \mathbb{V}$  with respect to a basis  $\mathcal{B}$  is a vector in  $\mathbb{R}^n$ . In particular, if  $\mathcal{B} = \{\vec{v}_1, \dots, \vec{v}_n\}$  and  $\vec{x} = b_1\vec{v}_1 + \dots + b_n\vec{v}_n$  then the coordinate vector of  $\vec{x}$  with respect to  $\mathcal{B}$  is defined to be

$$[\vec{x}]_{\mathcal{B}} = \begin{bmatrix} b_1 \\ \vdots \\ b_n \end{bmatrix}$$

Using coordinates, we can write a matrix mapping representation of a linear mapping  $L : \mathbb{V} \rightarrow \mathbb{W}$ . We want to find a matrix  $A$  such that

$$[L(\vec{x})]_{\mathcal{C}} = A[\vec{x}]_{\mathcal{B}}$$

for every  $\vec{x} \in \mathbb{V}$ , where  $\mathcal{B}$  is a basis for  $\mathbb{V}$  and  $\mathcal{C}$  is a basis for  $\mathbb{W}$

Considering  $[L(\vec{x})]_{\mathcal{C}}$  and using the properties of linear mappings and coordinates, we get

$$\begin{aligned} [L(\vec{x})]_{\mathcal{C}} &= [L(b_1\vec{v}_1 + \dots + b_n\vec{v}_n)]_{\mathcal{C}} = b_1[L(\vec{v}_1)]_{\mathcal{C}} + \dots + b_n[L(\vec{v}_n)]_{\mathcal{C}} \\ &= \begin{bmatrix} [L(\vec{v}_1)]_{\mathcal{C}} & \dots & [L(\vec{v}_n)]_{\mathcal{C}} \end{bmatrix} \begin{bmatrix} b_1 \\ \vdots \\ b_n \end{bmatrix} \end{aligned}$$

This, we have the matrix  $\begin{bmatrix} [L(\vec{v}_1)]_{\mathcal{C}} & \dots & [L(\vec{v}_n)]_{\mathcal{C}} \end{bmatrix}$  being matrix-vector multiplied by the vector  $[\vec{x}]_{\mathcal{B}}$  as desired.

Suppose  $\mathcal{B} = \{\vec{v}_1, \dots, \vec{v}_n\}$  is a basis for a vector space  $\mathbb{V}$  and  $\mathcal{C}$  is any basis for a finite dimensional vector space  $\mathbb{W}$ . For a linear mapping  $L : \mathbb{V} \rightarrow \mathbb{W}$ , the **matrix of  $L$  with respect to basis  $\mathcal{B}$  and  $\mathcal{C}$**  is defined by

$${}_c[L]_{\mathcal{B}} = \begin{bmatrix} [L(\vec{v}_1)]_{\mathcal{C}} & \dots & [L(\vec{v}_n)]_{\mathcal{C}} \end{bmatrix}$$

and satisfies

$$[L(\vec{x})]_{\mathcal{C}} = {}_c[L]_{\mathcal{B}}[\vec{x}]_{\mathcal{B}}$$

for all  $\vec{x} \in \mathbb{V}$  In the special case of a linear operator  $L$  acting on a finite dimensional vector space  $\mathbb{V}$  with basis  $\mathcal{B}$ , we often wish to find the matrix  ${}_B[L]_{\mathcal{B}}$

Suppose  $\mathcal{B} = \{\vec{v}_1, \dots, \vec{v}_n\}$  is any basis for an  $n$ -dimensional vector space  $\mathbb{V}$  and let  $L : \mathbb{V} \rightarrow \mathbb{V}$  be a linear operator. The  **$\mathcal{B}$ -matrix of  $L$**  (or the matrix of  $L$  with respect to the basis  $\mathcal{B}$ ) is defined by

$$[L]_{\mathcal{B}} = \begin{bmatrix} [L(\vec{v}_1)]_{\mathcal{B}} & \dots & [L(\vec{v}_n)]_{\mathcal{B}} \end{bmatrix}$$

and satisfies

$$[L(\vec{x})]_{\mathcal{B}} = [L]_{\mathcal{B}}[\vec{x}]_{\mathcal{B}}$$

for all  $\vec{x} \in \mathbb{V}$

(Makes more sense if you refer to the course notes) In example 4 we found that the matrix of  $L$  with respect to basis  $\mathcal{B}$  is diagonal since the vectors in  $\mathcal{B}$  are eigenvectors of  $L$ . Such a basis is called a **geometrically natural basis**

**Definition**  
Matrix of a  
Linear  
Mapping

**Definition**  
Matrix of a  
Linear  
Operator

## 8.4 Isomorphisms

The ten vector space axioms define a "structure" for the set based on the operations of addition and scalar multiplication. Since all vector spaces satisfy the same ten properties, we expect that all  $n$ -dimensional vector spaces should have the same structure, and they do as seen by the work done with coordinate vectors. Whatever basis we use for an  $n$ -dimensional vector space  $\mathbb{V}$ , we have a nice way of relating vectors in  $\mathbb{V}$  to vectors in  $\mathbb{R}^n$ . Moreover, we see that the operations of addition and scalar multiplication are preserved with respect to this basis.

No matter which vector space we are using and which basis for the vector space, any linear combination of vectors is really just performed on the coordinates of the vectors with respect to the defined basis.

Let's now look at how to use general linear mappings to mathematically prove these observations.

Let  $L : \mathbb{V} \rightarrow \mathbb{W}$  be a linear mapping.  $L$  is called **one-to-one** (injective) if for every  $\vec{u}, \vec{v} \in \mathbb{V}$  such that  $L(\vec{u}) = L(\vec{v})$ , we must have  $\vec{u} = \vec{v}$

**Definition**  
One-To-One  
Onto

$L$  is called **onto** (surjective) if for every  $\vec{w} \in \mathbb{W}$ , there exists  $\vec{v} \in \mathbb{V}$  such that  $L(\vec{v}) = \vec{w}$

We observe that for a linear mapping  $L : \mathbb{V} \rightarrow \mathbb{W}$  being onto means that  $\text{Range}(L) = \mathbb{W}$

And  $L$  being one-to-one means that for each  $\vec{w} \in \text{Range}(L)$  there exists exactly one  $\vec{v} \in \mathbb{V}$  such that  $L(\vec{v}) = \vec{w}$ . We now establish a relationship between a mapping being one-to-one and its kernel

Let  $L : \mathbb{V} \rightarrow \mathbb{W}$  be a linear mapping.  $L$  is one-to-one if and only if  $\text{Ker}(L) = \{\vec{0}_{\mathbb{V}}\}$

**Lemma**  
8.4.1

For two vector spaces  $\mathbb{V}$  and  $\mathbb{W}$  to have the same structure we need each vector  $\vec{v} \in \mathbb{V}$  to be identified with a unique vector  $\vec{w} \in \mathbb{W}$  such that linear combinations are preserved. So to do that we need to find a mapping  $L$  from  $\mathbb{V}$  to  $\mathbb{W}$  which is both one-to-one and onto, and for linear combinations to be preserved we need the linear mapping to be linear.

A vector space  $\mathbb{V}$  is said to be **isomorphic** to a vector space  $\mathbb{W}$  if there exists a linear mapping  $L : \mathbb{V} \rightarrow \mathbb{W}$  which is one-to-one and onto.  $L$  is called an **isomorphism** from  $\mathbb{V}$  to  $\mathbb{W}$

**Definition**  
Isomorphism  
Isomorphic

Looking at examples of isomorphisms will show that it is mapping basis vectors to basis vectors. And since it is that basis vectors are mapping to basis vectors, the dimensions of the two vector spaces should be the same

Let  $\mathbb{V}$  and  $\mathbb{W}$  be finite dimensional vector spaces.  $\mathbb{V}$  is isomorphic to  $\mathbb{W}$  if and only if  $\dim \mathbb{V} = \dim \mathbb{W}$

**Theorem**  
8.4.2

If  $\mathbb{V}$  and  $\mathbb{W}$  are both  $n$ -dimensional vector spaces and  $L : \mathbb{V} \rightarrow \mathbb{W}$  is linear, then  $L$  is one-to-one if and only if  $L$  is onto

**Theorem**  
8.4.3

Let  $\mathbb{V}$  and  $\mathbb{W}$  be isomorphic vector spaces and let  $\{\vec{v}_1, \dots, \vec{v}_n\}$  be a basis for  $\mathbb{V}$ . A linear mapping  $L : \mathbb{V} \rightarrow \mathbb{W}$  is an isomorphism if and only if  $\{L(\vec{v}_1), \dots, L(\vec{v}_n)\}$  is a basis for  $\mathbb{W}$  Theorem 8.4.4