Economics 204 Summer/Fall 2025
Lecture 9–Thursday August 7, 2025
Revised: See Definition 5 and Footnote 2.

Section 3.3. Quotient Vector Spaces[1]

Given a vector space X over a field F and a vector subspace W of X, define an equivalence relation by

$$x \sim y \iff x - y \in W$$

Form a new vector space X/W: the set of elements of X/W is

$$\{[x] : x \in X\}$$

where $[x]$ denotes the equivalence class of x with respect to $\sim$. X/W is read "X mod W". Note that the vectors in X/W are *sets* of vectors in X: for $x \in X$,

$$[x] = \{x + w : w \in W\}$$

We claim that X/W can be viewed as a vector space over F. Define the vector space operations $+, \cdot$ in X/W as follows:

$$\begin{aligned} [x] + [y] &= [x + y] \\ \alpha[x] &= [\alpha x] \end{aligned}$$

The exercise below asks you to verify that these operations are well-defined. Then X/W is a vector space over F with these definitions for $+$ and $\cdot$.

[1]The first part of this material is not in de la Fuente.

Exercise: Verify that $\sim$ above is an equivalence relation and that vector addition and scalar multiplication are well-defined, i.e.

$$[x] = [x'], [y] = [y'] \Rightarrow [x + y] = [x' + y']$$
$$[x] = [x'], \alpha \in F \Rightarrow [\alpha x] = [\alpha x']$$

Example: Let $X = \mathbf{R}^3$ and let $W = \{x \in \mathbf{R}^3 : x_1 = x_2 = 0\}$. Then for $x, y \in \mathbf{R}^3$,

$$\begin{aligned} x \sim y &\iff x - y \in W \\ &\iff x_1 - y_1 = 0, x_2 - y_2 = 0 \\ &\iff x_1 = y_1, x_2 = y_2 \end{aligned}$$

and

$$[x] = \{x + w : w \in W\} = \{(x_1, x_2, z) : z \in \mathbf{R}\}$$

So the equivalence class corresponding to x is the line in $\mathbf{R}^3$ through x parallel to the axis of the third coordinate. See Figure 1. What is X/W? Intuitively this equivalence relation ignores the third coordinate, and we can identify the equivalence class $[x]$ with the vector $(x_1, x_2) \in \mathbf{R}^2$. The next two results show how to formalize this connection.

Theorem 1 *If X is a vector space with $\dim X = n$ for some $n \in \mathbf{N}$ and W is a vector subspace of X, then*

$$\dim(X/W) = \dim X - \dim W$$

Proof: (Sketch) Begin with a basis $\{w_1, \ldots, w_c\}$ for W, and a basis $\{[x_1], \ldots, [x_k]\}$ for X/W. Show that

$$\{w_1, \ldots, w_c\} \cup \{x_1, \ldots, x_k\}$$

is a basis for X. ∎

Theorem 2 *Let X and Y be vector spaces over the same field F and $T \in L(X, Y)$. Then* $\operatorname{Im} T$ *is isomorphic to* $X/\ker T$.

Proof: Notice that if X is finite-dimensional, then

$$\begin{aligned}
\dim(X/\ker T) &= \dim X - \dim \ker T \quad \text{(by the previous theorem} \\
&= \operatorname{Rank} T \quad \text{(by the Rank-Nullity Theorem)} \\
&= \dim \operatorname{Im} T
\end{aligned}$$

so $X/\ker T$ is isomorphic to $\operatorname{Im} T$.

We prove that this is true in general, and that the isomorphism is natural.

Define $\tilde{T} : X/\ker T \to \operatorname{Im} T$ by

$$\tilde{T}([x]) = T(x)$$

We first need to check that this is well-defined, that is, that if $[x] = [x']$ then $\tilde{T}([x]) = \tilde{T}([x'])$.

$$\begin{aligned}
[x] = [x'] &\Rightarrow x \sim x' \\
&\Rightarrow x - x' \in \ker T \\
&\Rightarrow T(x - x') = 0 \\
&\Rightarrow T(x) = T(x')
\end{aligned}$$

so $\tilde{T}$ is well-defined.

Clearly, $\tilde{T} : X/\ker T \to \operatorname{Im} T$. It is easy to check that $\tilde{T}$ is linear, so $\tilde{T} \in L(X/\ker T, \operatorname{Im} T)$. Next we show that $\tilde{T}$ is an isomorphism.

$$\begin{aligned} \tilde{T}([x]) = \tilde{T}([y]) &\Rightarrow T(x) = T(y) \\ &\Rightarrow T(x-y) = 0 \\ &\Rightarrow x - y \in \ker T \\ &\Rightarrow x \sim y \\ &\Rightarrow [x] = [y] \end{aligned}$$

so $\tilde{T}$ is one-to-one.

$$\begin{aligned} y \in \operatorname{Im} T &\Rightarrow \exists x \in X \text{ s.t. } T(x) = y \\ &\Rightarrow \tilde{T}([x]) = y \end{aligned}$$

so $\tilde{T}$ is onto, hence $\tilde{T}$ is an isomorphism. ∎

Example: Consider $T \in L(\mathbf{R}^3, \mathbf{R}^2)$ defined by

$$T(x_1, x_2, x_3) = (x_1, x_2)$$

Then $\ker T = \{x \in \mathbf{R}^3 : x_1 = x_2 = 0\}$ is the x_3-axis. (Also notice $\ker T = W$ from the previous example.)

Given x, the equivalence class $[(x_1, x_2, x_3)]$ is just the line through x parallel to the x_3-axis. $\tilde{T}([x]) = T(x_1, x_2, x_3) = (x_1, x_2)$.

$$\operatorname{Im} T = \mathbf{R}^2, \quad X/\ker T \cong \mathbf{R}^2 = \operatorname{Im} T$$

as we suggested intuitively above (here the symbol $\cong$ denotes isomorphism, that is, we write $Y \cong Z$ if Y and Z are isomorphic.)

Every real vector space X with dimension n is isomorphic to $\mathbf{R}^n$. What's the isomorphism?

Let X be a finite-dimensional vector space over $\mathbf{R}$ with $\dim X = n$. Fix any Hamel basis $V = \{v_1, \ldots, v_n\}$ of X. Any $x \in X$ has a unique representation

$$x = \sum_{j=1}^{n} \beta_j v_j$$

(here, we allow $\beta_j = 0$). (Generally, vectors are represented as column vectors, not row vectors.) Then given the representation of x above, we write

$$crd_V(x) = \begin{pmatrix} \beta_1 \\ \vdots \\ \beta_n \end{pmatrix} \in \mathbf{R}^n$$

That is, $crd_V(x)$ is the vector of coordinates of x with respect to the basis V.

$$crd_V(v_1) = \begin{pmatrix} 1 \\ 0 \\ \vdots \\ 0 \\ 0 \end{pmatrix} \quad crd_V(v_2) = \begin{pmatrix} 0 \\ 1 \\ \vdots \\ 0 \\ 0 \end{pmatrix} \quad crd_V(v_n) = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{pmatrix}$$

crd_V is an isomorphism from X to $\mathbf{R}^n$.

Matrix Representation of a Linear Transformation

Suppose $T \in L(X, Y)$, $\dim X = n$ and $\dim Y = m$. Fix bases

$$\begin{aligned} V &= \{v_1, \ldots, v_n\} \text{ of } X \\ W &= \{w_1, \ldots, w_m\} \text{ of } Y \end{aligned}$$

$T(v_j) \in Y$, so

$$T(v_j) = \sum_{i=1}^{m} \alpha_{ij} w_i$$

Define

$$Mtx_{W,V}(T) = \begin{pmatrix} \alpha_{11} & \cdots & \alpha_{1n} \\ \vdots & \ddots & \vdots \\ \alpha_{m1} & \cdots & \alpha_{mn} \end{pmatrix}$$

Notice that the columns are the coordinates (expressed with respect to W) of $T(v_1), \ldots, T(v_n)$.

Observe

$$\begin{pmatrix} \alpha_{11} & \cdots & \alpha_{1n} \\ \vdots & \ddots & \vdots \\ \alpha_{m1} & \cdots & \alpha_{mn} \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix} = \begin{pmatrix} \alpha_{11} \\ \vdots \\ \alpha_{m1} \end{pmatrix}$$

so

$$\begin{aligned} Mtx_{W,V}(T) \cdot crd_V(v_j) &= crd_W(T(v_j)) \\ Mtx_{W,V}(T) \cdot crd_V(x) &= crd_W(T(x)) \quad \forall x \in X \end{aligned}$$

Multiplying a vector by a matrix does two things:

- Computes the action of T
- Accounts for the change in basis

Example: $X = Y = \mathbf{R}^2$, $V = \{(1,0),(0,1)\}$, $W = \{(1,1),(-1,1)\}$, $T = id$, that is, $T(x) = x$ for all x.

$$Mtx_{W,V}(T) \neq \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$Mtx_{W,V}(T)$ is the matrix that *changes basis* from V to W. How do we compute it?

$$\begin{aligned}
v_1 = (1,0) &= \alpha_{11}(1,1) + \alpha_{21}(-1,1) \\
\alpha_{11} - \alpha_{21} &= 1 \\
\alpha_{11} + \alpha_{21} &= 0 \\
2\alpha_{11} &= 1, \alpha_{11} = \frac{1}{2} \\
\alpha_{21} &= -\frac{1}{2} \\
v_2 = (0,1) &= \alpha_{12}(1,1) + \alpha_{22}(-1,1) \\
\alpha_{12} - \alpha_{22} &= 0 \\
\alpha_{12} + \alpha_{22} &= 1 \\
2\alpha_{12} &= 1, \alpha_{12} = \frac{1}{2} \\
\alpha_{22} &= \frac{1}{2}
\end{aligned}$$

$$Mtx_{W,V}(id) = \begin{pmatrix} 1/2 & 1/2 \\ -1/2 & 1/2 \end{pmatrix}$$

Theorem 3 (Thm. 3.5') *Let X and Y be vector spaces over the same field F, with $\dim X = n$, $\dim Y = m$. Then $L(X,Y)$, the space of linear transformations from X to Y, is isomorphic to $F_{m\times n}$, the vector space of $m \times n$ matrices over F. If $V = \{v_1, \ldots, v_n\}$ is a basis for X and $W = \{w_1, \ldots, w_m\}$ is a basis for Y, then*

$$Mtx_{W,V} \in L(L(X,Y), F_{m\times n})$$

and $Mtx_{W,V}$ is an isomorphism from $L(X,Y)$ to $F_{m\times n}$.

Theorem 4 (From Handout) *Let X, Y, Z be finite-dimensional vector spaces over the same field F with bases U, V, W respectively. Let $S \in L(X,Y)$ and $T \in L(Y,Z)$. Then*

$$Mtx_{W,V}(T) \cdot Mtx_{V,U}(S) = Mtx_{W,U}(T \circ S)$$

i.e. matrix multiplication corresponds via the matrix representation isomorphism to composition of linear transformations.

Proof: See handout. ∎

Note that $Mtx_{W,V}$ is a function from $L(X,Y)$ to the space $F_{m\times n}$ of $m \times n$ matrices, while $Mtx_{W,V}(T)$ is an $m \times n$ matrix.

The theorem can be summarized by the following "Com-

mutative Diagram:"

$$\begin{array}{ccccccc} & & S & & & T & \\ & X & \to & Y & & \to & Z \\ crd_U & \updownarrow & & \updownarrow crd_V & & & \updownarrow crd_W \\ & \mathbf{R}^n & \to & \mathbf{R}^m & & \to & \mathbf{R}^r \\ & & Mtx_{V,U}(S) & & & Mtx_{W,V}(T) & \end{array}$$

We say the diagram commutes because you get the same answer any way you go around the diagram (in directions allowed by the arrows). The crd arrows go in both directions because crd is an isomorphism.

Section 3.5. Change of Basis and Similarity

Let X be a finite-dimensional vector space with basis V. If $T \in L(X, X)$ it is customary to use the same basis in the domain and range. In this case,

$$Mtx_V(T) \text{ denotes } Mtx_{V,V}(T)$$

Question: If W is another basis for X, how are $Mtx_V(T)$ and $Mtx_W(T)$ related?

$$\begin{aligned} & Mtx_{V,W}(id) \cdot Mtx_W(T) \cdot Mtx_{W,V}(id) \\ &= Mtx_{V,W}(id) \cdot Mtx_{W,V}(T \circ id) \\ &= Mtx_{V,V}(id \circ T \circ id) \\ &= Mtx_V(T) \end{aligned}$$

and

$$\begin{aligned} Mtx_{V,W}(id) \cdot Mtx_{W,V}(id) &= Mtx_{V,V}(id) \\ &= \begin{pmatrix} 1 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 1 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 0 & 1 \end{pmatrix} \end{aligned}$$

So this says that

$$Mtx_V(T) = P^{-1} Mtx_W(T) P$$

for the invertible matrix

$$P = Mtx_{W,V}(id)$$

that is the change of basis matrix. On the other hand, if P is any invertible matrix, then P is also a change of basis matrix for appropriate corresponding bases (see handout).

Definition 5 Two $n \times n$ matrices A and B are *similar* if

$$A = P^{-1} B P$$

for some invertible $n \times n$ matrix P.

Theorem 6 *Suppose that X is a finite-dimensional vector space.*

1. *If $T \in L(X, X)$ then any two matrix representations of T are similar. That is, if U, W are any*

two bases of X, then $Mtx_W(T)$ and $Mtx_U(T)$ are similar.

2. *Conversely, two similar matrices represent the same linear transformation T, relative to suitable bases. That is, given similar matrices A, B with $A = P^{-1}BP$ and any basis U, there is a basis W and $T \in L(X, X)$ such that*

$$\begin{aligned} B &= Mtx_U(T) \\ A &= Mtx_W(T) \\ P &= Mtx_{U,W}(id) \\ P^{-1} &= Mtx_{W,U}(id) \end{aligned}$$

Proof: See Handout on Diagonalization and Quadratic Forms. ∎

Section 3.6. Eigenvalues and Eigenvectors

Here, we define eigenvalues and eigenvectors of a linear transformation and show that λ is an eigenvalue of T if and only if λ is an eigenvalue for some matrix representation of T if and only if λ is an eigenvalue for every matrix representation of T.

Definition 7 Let X be a vector space and $T \in L(X, X)$. We say that λ is an *eigenvalue* of T and $v \neq 0$ is an *eigenvector corresponding to* λ if $T(v) = \lambda v$.

Theorem 8 (Theorem 4 in Handout) *Let X be a finite-dimensional vector space, and U a basis. Then λ is an eigenvalue of T if and only if λ is an eigenvalue of $Mtx_U(T)$. v is an eigenvector of T corresponding to λ if and only if $crd_U(v)$ is an eigenvector of $Mtx_U(T)$ corresponding to λ.*

Proof: By the Commutative Diagram Theorem,

$$\begin{aligned} T(v) = \lambda v &\Leftrightarrow crd_U(T(v)) = crd_U(\lambda v) \\ &\Leftrightarrow Mtx_U(T)(crd_U(v)) = \lambda(crd_U(v)) \end{aligned}$$

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Computing eigenvalues and eigenvectors:

Suppose $\dim X = n$; let I be the $n \times n$ identity matrix. Given $T \in L(X, X)$, fix a basis U and let

$$A = Mtx_U(T)$$

Find the eigenvalues of T by computing the eigenvalues of A:

$$\begin{aligned} Av = \lambda v &\iff (A - \lambda I)v = 0 \\ &\iff (A - \lambda I) \text{ is not invertible} \\ &\iff \det(A - \lambda I) = 0 \end{aligned}$$

We have the following facts:

- If $A \in \mathbf{R}_{n\times n}$,

$$f(\lambda) = \det(A - \lambda I)$$

is an n^{th} degree polynomial in λ with real coefficients; it is called the *characteristic polynomial* of A.

- f has n roots in $\mathbf{C}$, counting multiplicity:

$$f(\lambda) = (c_1 - \lambda)(c_2 - \lambda)\cdots(c_n - \lambda)$$

where $c_1, \ldots, c_n \in \mathbf{C}$ are the eigenvalues; the c_j's are not necessarily distinct. Notice that $f(\lambda) = 0$ if and only if $\lambda \in \{c_1, \ldots, c_n\}$, so the roots are the solutions of the equation $f(\lambda) = 0$.

- the roots that are not real come in conjugate pairs:

$$f(a + bi) = 0 \Leftrightarrow f(a - bi) = 0$$

- if $\lambda = c_j \in \mathbf{R}$, there is a corresponding eigenvector in $\mathbf{R}^n$.

- if $\lambda = c_j \notin \mathbf{R}$, the corresponding eigenvectors are in $\mathbf{C}^n \setminus \mathbf{R}^n$.

Diagonalization

Definition 9 Suppose X is a finite-dimensional vector space with basis U. Given a linear transformation $T \in L(X, X)$, let

$$A = Mtx_U(T)$$

We say that *A can be diagonalized* (or is *diagonalizable*) if there is a basis W for X such that $Mtx_W(T)$ is diagonal, i.e.

$$Mtx_W(T) = \begin{pmatrix} \lambda_1 & 0 & 0 & \cdots & 0 & 0 \\ 0 & \lambda_2 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 0 & \lambda_n \end{pmatrix}$$

Notice that the **standard basis vectors of $\mathbf{R}^n$ are eigenvectors of $Mtx_W(T)$.**[2] But w_j is an eigenvector of T corresponding to λ_j if and only if $crd_W(w_j)$ is an eigenvector of $Mtx_W(T)$, and $crd_W(w_j)$ is the j^{th} standard basis vector of $\mathbf{R}^n$, so $W = \{w_1, \ldots, w_n\}$ where w_j is an eigenvector corresponding to λ_j.

Then the action of T is clear: it stretches each basis element w_i by the factor λ_i.

Theorem 10 (Thm. 6.7') *Let X be an n-dimensional vector space, $T \in L(X, X)$, U any basis of X, and $A = Mtx_U(T)$. Then the following are equivalent:*

1. *A can be diagonalized*
2. *there is a basis W for X consisting of eigenvectors of T*

[2] **If the eigenvalues are distinct, they are the only eigenvectors up to scalar multiples.**

3. *there is a basis V for $\mathbf{R}^n$ consisting of eigenvectors of A*

Proof: Follows from Theorem 6.7 in de la Fuente and Theorem 4 from the Handout. ∎

Theorem 11 (Thm. 6.8') *Let X be a vector space and $T \in L(X, X)$.*

1. *If $\lambda_1, \ldots, \lambda_m$ are distinct eigenvalues of T with corresponding eigenvectors $v_1, \ldots, v_m$, then $\{v_1, \ldots, v_m\}$ is linearly independent.*
2. *If $\dim X = n$ and T has n distinct eigenvalues, then X has a basis consisting of eigenvectors of T; consequently, if U is any basis of X, then $Mtx_U(T)$ is diagonalizable.*

Proof: This is an adaptation of the proof of Theorem 6.8 in de la Fuente. ∎

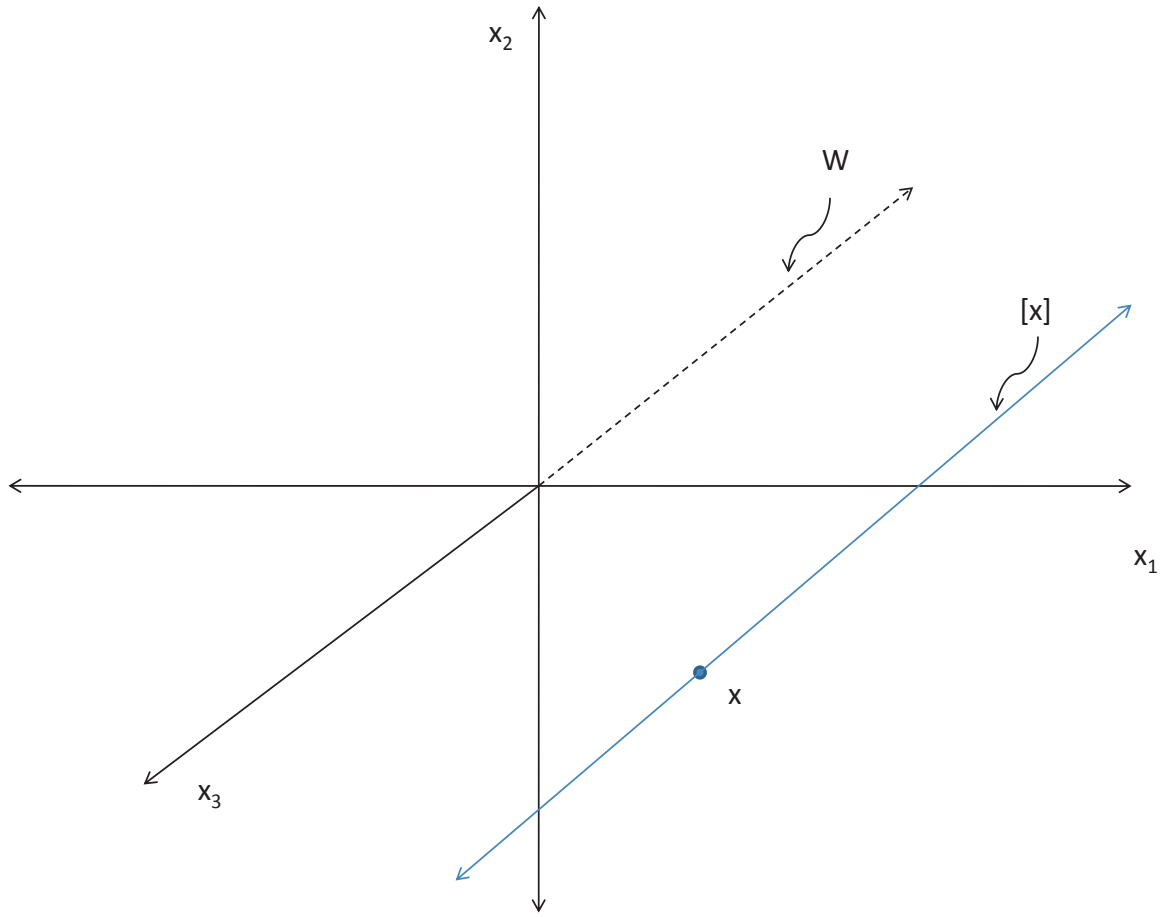

Figure 1: An illustration of X/W where $X = \mathbf{R}^3$ and $W = \{x \in \mathbf{R}^3 : x_1 = x_2 = 0\}$. Here $[x] = \{(x_1, x_2, z) : z \in \mathbf{R}\}$ is the line through x parallel to the axis of the third coordinate.