Basis, Dimension, Kernel, Image

- Definitions: Pivot, Basis, Rank and Nullity
- Main Results: Dimension, Pivot Theorem
- Main Results: Rank-Nullity, Row Rank, Pivot Method
- Definitions: Kernel, Image, `rowspace`, `colspace`
- How to Compute: Nullspace, Rowspace, Colspace
- Dimension, Kernel and Image
- Testing Bases for Equivalence
- Equivalent Bases: Computer Illustration
- A False Test for Equivalent Bases

Definitions: Pivot and Basis

Pivot of A	A column in matrix A is called a **pivot column of A** provided the corresponding column in $\mathrm{rref}(A)$ contains a leading one.
Basis of V	It is an independent set $\mathbf{v}_1, \ldots, \mathbf{v}_k$ from data set V whose linear combinations generate all data items in V. Briefly: the vectors $\mathbf{v}_1, \ldots, \mathbf{v}_k$ are independent and span V.

Definitions: Rank and Nullity

$\mathrm{rank}(A)$	The number of leading ones in $\mathrm{rref}(A)$
$\mathrm{nullity}(A)$	The number of columns of A minus $\mathrm{rank}(A)$

Main Results: Dimension, Pivot Theorem

Theorem 1 (Dimension)
If a vector space V has an independent spanning set $\mathbf{v}_1, \ldots, \mathbf{v}_p$ and another independent spanning set $\mathbf{u}_1, \ldots, \mathbf{u}_q$, then $p = q$. The **dimension** of V is this unique number p. We write $p = \dim(V)$.

Theorem 2 (The Pivot Theorem)

- The pivot columns of a matrix A are linearly independent.
- A non-pivot column of A is a linear combination of the pivot columns of A.

The proofs can be found in web documents and also in the textbook by E & P. Self-contained proofs of the statements of the pivot theorem appear in these slides.

Lemma 1 Let B be invertible and $\mathbf{v}_1, \ldots, \mathbf{v}_p$ independent. Then $B\mathbf{v}_1, \ldots, B\mathbf{v}_p$ are independent.

Proof of Independence of the Pivot Columns

Consider the fundamental frame sequence identity $\mathbf{rref}(A) = EA$ where $E = E_k \cdots E_2 E_1$ is a product of elementary matrices. Let $B = E^{-1}$. Then

$$\mathbf{col}(\mathbf{rref}(A), j) = E\,\mathbf{col}(A, j)$$

implies that a pivot column j of A satisfies

$$\mathbf{col}(A, j) = B\,\mathbf{col}(I, j).$$

Because the columns of I are independent, then also the pivot columns of A are independent, by the Lemma.

Proof of Non-Pivot Column Dependence

Using matrix $\boldsymbol{B}$ from the previous proof, $\vec{\mathbf{u}} = \boldsymbol{B}\vec{\mathbf{v}}$ holds for a non-pivot column $\vec{\mathbf{u}}$ of $\boldsymbol{A}$ and its corresponding non-pivot column $\vec{\mathbf{v}}$ in $\boldsymbol{C} = \mathbf{rref}(\boldsymbol{A})$. Because each nonzero row of $\boldsymbol{C}$ has a leading one, if a component $\boldsymbol{v_i} \neq \mathbf{0}$, then row $\boldsymbol{i}$ of $\boldsymbol{C}$ has a leading one in column $\boldsymbol{j_i} < \boldsymbol{i}$. Then $\mathbf{col}(\boldsymbol{C}, \boldsymbol{j_i})$ is a column of the identity $\boldsymbol{I}$ and

$$\vec{\mathbf{v}} = \sum_{v_i \neq 0} v_i \,\mathbf{col}(C, j_i).$$

Multiply the preceding display by $\boldsymbol{B}$ to give

$$\begin{aligned} \vec{\mathbf{u}} &= B\vec{\mathbf{v}} \\ &= \sum_{v_i \neq 0} v_i B \,\mathbf{col}(C, j_i) \\ &= \sum_{v_i \neq 0} v_i \,\mathbf{col}(A, j_i). \end{aligned}$$

Then $\vec{\mathbf{u}}$ is a linear combination of pivot columns of $\boldsymbol{A}$.

Main Results: Rank-Nullity, Row Rank, Pivot Method

Theorem 3 (Rank-Nullity Equation)
$\mathbf{rank}(A) + \mathbf{nullity}(A) =$ column dimension of A

Theorem 4 (Row Rank Equals Column Rank)
The number of independent rows of a matrix A equals the number of independent columns of A. Equivalently, $\mathbf{rank}(A) = \mathbf{rank}(A^T)$.

Theorem 5 (Pivot Method)
Let A be the augmented matrix of $\mathbf{v}_1, \ldots, \mathbf{v}_k$. Let the leading ones in $\mathbf{rref}(A)$ occur in columns $i_1, \ldots, i_p$. Then a largest independent subset of the k vectors $\mathbf{v}_1, \ldots, \mathbf{v}_k$ is the set

$$\mathbf{v}_{i_1}, \mathbf{v}_{i_2}, \ldots, \mathbf{v}_{i_p}.$$

Proof that $\mathbf{rank}(\boldsymbol{A}) = \mathbf{rank}(\boldsymbol{A}^T)$

Let $\boldsymbol{S}$ denote the set of all linear combinations of the rows of $\boldsymbol{A}$. Then $\boldsymbol{S}$ is a subspace, known as the row space of $\boldsymbol{A}$. A frame sequence from $\boldsymbol{A}$ to $\mathbf{rref}(\boldsymbol{A})$ consists of combination, swap and multiply operations on the rows of $\boldsymbol{A}$. Therefore, each nonzero row of $\mathbf{rref}(\boldsymbol{A})$ is a linear combination of the rows of $\boldsymbol{A}$. Because these rows are independent and span $\boldsymbol{S}$, then they are a basis for $\boldsymbol{S}$. The size of the basis is $\mathbf{rank}(\boldsymbol{A})$.

The pivot theorem applied to $\boldsymbol{A}^T$ implies that each vector in $\boldsymbol{S}$ is a linear combination of the pivot columns of $\boldsymbol{A}^T$. Because the pivot columns of $\boldsymbol{A}^T$ are independent and span $\boldsymbol{S}$, then they are a basis for $\boldsymbol{S}$. The size of the basis is $\mathbf{rank}(\boldsymbol{A}^T)$.

The two competing bases for $\boldsymbol{S}$ have sizes $\mathbf{rank}(\boldsymbol{A})$ and $\mathbf{rank}(\boldsymbol{A}^T)$, respectively. But the size of a basis is unique, called the dimension of the subspace $\boldsymbol{S}$, hence the equality

$$\mathbf{rank}(\boldsymbol{A}) = \mathbf{rank}(\boldsymbol{A}^T).$$

Definitions: Kernel, Image, rowspace, colspace

$\text{kernel}(A) = \text{nullspace}(A) = \{\mathbf{x} \;:\; A\mathbf{x} = 0\}$.

$\text{Image}(A) = \text{colspace}(A) = \{\mathbf{y} \;:\; \mathbf{y} = A\mathbf{x}$ for some $\mathbf{x}\}$.

$\text{rowspace}(A) = \text{colspace}(A^T) = \{\mathbf{w} \;:\; \mathbf{w} = A^T\mathbf{y}$ for some $\mathbf{y}\}$.

How to Compute Nullspace, Rowspace and Colspace

Null Space. Compute $\mathbf{rref}(A)$. Write out the general solution $\mathbf{x}$ to $A\mathbf{x} = \mathbf{0}$, where the free variables are assigned parameter names $t_1, \ldots, t_k$. Report the basis for $\mathbf{nullspace}(A)$ as the list $\partial_{t_1}\mathbf{x}, \ldots, \partial_{t_k}\mathbf{x}$.

Column Space. Compute $\mathbf{rref}(A)$. Identify the pivot columns $i_1, \ldots, i_k$. Report the basis for $\mathbf{colspace}(A)$ as the list of columns $i_1, \ldots, i_k$ of A.

Row Space. Compute $\mathbf{rref}(A^T)$. Identify the pivot columns $j_1, \ldots, j_\ell$ of A^T. Report the basis for $\mathbf{rowspace}(A)$ as the list of rows $j_1, \ldots, j_\ell$ of A.

Alternatively, compute $\mathbf{rref}(A)$, then $\mathbf{rowspace}(A)$ has a *different* basis consisting of the list of nonzero rows of $\mathbf{rref}(A)$.

Dimension, Kernel and Image

Symbol $\dim(V)$ equals the number of elements in a basis for $\boldsymbol{V}$.

Theorem 6 (Dimension Identities)

(a) $\dim(\text{nullspace}(A)) = \dim(\text{kernel}(A)) = \text{nullity}(A)$

(b) $\dim(\text{colspace}(A)) = \dim(\text{Image}(A)) = \text{rank}(A)$

(c) $\dim(\text{rowspace}(A)) = \text{rank}(A)$

(d) $\dim(\text{kernel}(A)) + \dim(\text{Image}(A)) =$ column dimension of A

(e) $\dim(\text{kernel}(A)) + \dim(\text{kernel}(A^T)) =$ column dimension of A

Testing Bases for Equivalence

Theorem 7 (Equivalence Test for Bases)
Define augmented matrices

$$B = \mathbf{aug}(\mathbf{v}_1, \ldots, \mathbf{v}_k), \quad C = \mathbf{aug}(\mathbf{u}_1, \ldots, \mathbf{u}_\ell), \quad W = \mathbf{aug}(B, C).$$

Then relation $k = \ell = \mathbf{rank}(B) = \mathbf{rank}(C) = \mathbf{rank}(W)$ implies

1. $\mathbf{v}_1, \ldots, \mathbf{v}_k$ is an independent set.
2. $\mathbf{u}_1, \ldots, \mathbf{u}_\ell$ is an independent set.
3. $\mathbf{span}\{\mathbf{v}_1, \ldots, \mathbf{v}_k\} = \mathbf{span}\{\mathbf{u}_1, \ldots, \mathbf{u}_\ell\}$

In particular, $\mathbf{colspace}(B) = \mathbf{colspace}(C)$ and each set of vectors is an equivalent basis for this vector space.

Proof: Because $\mathbf{rank}(B) = k$, then the first k columns of W are independent. If some column of C is independent of the columns of B, then W would have $k + 1$ independent columns, which violates $k = \mathbf{rank}(W)$. Therefore, the columns of C are linear combinations of the columns of B. Then vector space $\mathbf{colspace}(C)$ is a subspace of vector space $\mathbf{colspace}(B)$. Because both vector spaces have dimension k, then $\mathbf{colspace}(B) = \mathbf{colspace}(C)$. The proof is complete.

Equivalent Bases: Computer Illustration

The following `maple` code applies the theorem to verify that two bases are equivalent:

1. The basis is determined from the `colspace` command in `maple`.

2. The basis is determined from the pivot columns of $\boldsymbol{A}$.

In `maple`, the report of the column space basis is identical to the nonzero rows of $\mathbf{rref}(\boldsymbol{A}^T)$.

```
with(linalg):
A:=matrix([[1,0,3],[3,0,1],[4,0,0]]);
colspace(A);             # Solve Ax=0, basis v1,v2 below
v1:=vector([2,0,-1]);v2:=vector([0,2,3]);
rref(A);                 # Find the pivot cols=1,3
u1:=col(A,1); u2:=col(A,3); # pivot col basis
B:=augment(v1,v2); C:=augment(u1,u2);
W:=augment(B,C);
rank(B),rank(C),rank(W); # Test requires all equal 2
```

A False Test for Equivalent Bases

The relation

$$\mathbf{rref}(\boldsymbol{B}) = \mathbf{rref}(\boldsymbol{C})$$

holds for a substantial number of matrices $\boldsymbol{B}$ and $\boldsymbol{C}$. However, it does not imply that each column of $\boldsymbol{C}$ is a linear combination of the columns of $\boldsymbol{B}$.

For example, define

$$\boldsymbol{B} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 1 \end{pmatrix}, \quad \boldsymbol{C} = \begin{pmatrix} 1 & 1 \\ 0 & 1 \\ 1 & 0 \end{pmatrix}.$$

Then

$$\mathbf{rref}(\boldsymbol{B}) = \mathbf{rref}(\boldsymbol{C}) = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{pmatrix},$$

but $\mathbf{col}(\boldsymbol{C}, 2)$ is not a linear combination of the columns of $\boldsymbol{B}$. This means $\mathbf{colspace}(\boldsymbol{B}) \neq \mathbf{colspace}(\boldsymbol{C})$.

Geometrically, the column spaces are planes in $\boldsymbol{R}^3$ which intersect only along the line $\boldsymbol{L}$ through the two points $(0, 0, 0)$ and $(1, 0, 1)$.