The four fundamental subspaces

In this lecture we discuss the four fundamental spaces associated with a matrix and the relations between them.

Four subspaces

Any m by n matrix A determines four subspaces (possibly containing only the zero vector):

Column space, $C(A)$

$C(A)$ consists of all combinations of the columns of A and is a vector space in $\mathbb{R}^m$.

Nullspace, $N(A)$

This consists of all solutions $\mathbf{x}$ of the equation $A\mathbf{x} = \mathbf{0}$ and lies in $\mathbb{R}^n$.

Row space, $C(A^T)$

The combinations of the row vectors of A form a subspace of R^n. We equate this with $C(A^T)$, the column space of the transpose of A.

Left nullspace, $N(A^T)$

We call the nullspace of A^T the *left nullspace* of A. This is a subspace of $\mathbb{R}^m$.

Basis and Dimension

Column space

The r pivot columns form a basis for $C(A)$

$$\dim C(A) = r.$$

Nullspace

The special solutions to $A\mathbf{x} = \mathbf{0}$ correspond to free variables and form a basis for $N(A)$. An m by n matrix has $n - r$ free variables:

$$\dim N(A) = n - r.$$

Row space

We could perform row reduction on A^T, but instead we make use of R, the row reduced echelon form of A.

$$A = \begin{bmatrix} 1 & 2 & 3 & 1 \\ 1 & 1 & 2 & 1 \\ 1 & 2 & 3 & 1 \end{bmatrix} \to \cdots \to \begin{bmatrix} 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} I & F \\ 0 & 0 \end{bmatrix} = R$$

Although the column spaces of A and R are different, the row space of R is the same as the row space of A. The rows of R are combinations of the rows of A, and because reduction is reversible the rows of A are combinations of the rows of R.

The first r rows of R are the "echelon" basis for the row space of A:

$$\dim C(A^T) = r.$$

Left nullspace

The matrix A^T has m columns. We just saw that r is the rank of A^T, so the number of free columns of A^T must be $m - r$:

$$\dim N(A^T) = m - r.$$

The left nullspace is the collection of vectors y for which $A^T y = 0$. Equivalently, $y^T A = 0$; here y and 0 are row vectors. We say "left nullspace" because y^T is on the left of A in this equation.

To find a basis for the left nullspace we reduce an augmented version of A:

$$\begin{bmatrix} A_{m \times n} & I_{m \times n} \end{bmatrix} \longrightarrow \begin{bmatrix} R_{m \times n} & E_{m \times n} \end{bmatrix}.$$

From this we get the matrix E for which $EA = R$. (If A is a square, invertible matrix then $E = A^{-1}$.) In our example,

$$EA = \begin{bmatrix} -1 & 2 & 0 \\ 1 & -1 & 0 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 2 & 3 & 1 \\ 1 & 1 & 2 & 1 \\ 1 & 2 & 3 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} = R.$$

The bottom $m - r$ rows of E describe linear dependencies of rows of A, because the bottom $m - r$ rows of R are zero. Here $m - r = 1$ (one zero row in R).

The bottom $m - r$ rows of E satisfy the equation $\mathbf{y}^T A = \mathbf{0}$ and form a basis for the left nullspace of A.

New vector space

The collection of all 3×3 matrices forms a vector space; call it M. We can add matrices and multiply them by scalars and there's a zero matrix (additive identity). If we ignore the fact that we can multiply matrices by each other, they behave just like vectors.

Some subspaces of M include:

- all upper triangular matrices
- all symmetric matrices
- D, all diagonal matrices

D is the intersection of the first two spaces. Its dimension is 3; one basis for D is:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \begin{bmatrix} 1 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 7 \end{bmatrix}.$$