## 18.06 - Spring 2005 - Problem Set 3

Solutions to the Challenge Problems

## Problem 1

a) The column space is the space of all vectors whose last m - r coordinates are zero. This is clear since the rank of the matrix R is r and the first r columns of R are independent.

Denote by  $f_{ij}$  the entry in the (i, j) position in F. The nullspace of R is the space of all linear combinations of the n - r vectors

$\begin{pmatrix} -f_{11} \\ -f_{21} \end{pmatrix}$		$\begin{pmatrix} -f_{12} \\ -f_{22} \end{pmatrix}$		$\begin{pmatrix} -f_{1(n-r)}\\ -f_{2(n-r)} \end{pmatrix}$
$\vdots$ $-f_{r1}$		$\vdots$ $-f_{r2}$		$\vdots$ $-f_{r(n-r)}$
	,		,,	$ \begin{bmatrix} 0 \\ 0 \end{bmatrix} $
0		0		
$\begin{pmatrix} \vdots \\ 0 \end{pmatrix}$		$\begin{pmatrix} \vdots \\ 0 \end{pmatrix}$		$\begin{pmatrix} 0\\ 1 \end{pmatrix}$

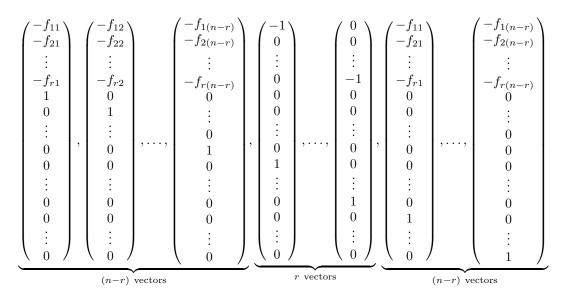
Clearly these vectors are linearly independent and therefore the dimension of the nullspace is n - r.

b) The column space of the matrix B is the same as the column space of R.

Denote by  $g_{ij}$  the entry in the (i, j) position in the  $r \times (2n - r)$  matrix  $G := (F \ I \ F)$ . Note that we have  $B = \begin{pmatrix} I & G \\ 0 & 0 \end{pmatrix}$ . The nullspace of B is the space of all linear combinations of the 2n - r vectors

$$\begin{pmatrix} -g_{11} \\ -g_{21} \\ \vdots \\ -g_{r1} \\ 1 \\ 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix}, \begin{pmatrix} -g_{12} \\ -g_{22} \\ \vdots \\ -g_{r2} \\ 0 \\ 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix}, \dots, \begin{pmatrix} -g_{1(2n-r)} \\ -g_{2(2n-r)} \\ \vdots \\ -g_{r(2n-r)} \\ 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{pmatrix}$$

In terms of the matrix F we may write the same vectors as



These vectors are clearly linearly independent, and therefore the nullspace of B has dimension 2n - r.

c) The column space of C is the space of vectors in 2m-dimensional space whose coordinates  $b_i$  satisfy the equations

$$\begin{array}{rcl} b_i &=& b_{i+m} & 1 \leq i \leq m \\ b_j &=& 0 & r+1 \leq j \leq m \end{array}$$

i.e. they are the vectors of the form

$$\begin{pmatrix}
b_1 \\
\vdots \\
b_r \\
0 \\
\vdots \\
0 \\
b_1 \\
\vdots \\
b_r \\
0 \\
\vdots \\
0
\end{pmatrix}$$

The nullspace of C is the same as the nullspace of R.

d) The column space of D is the same as the column space of C.

The nullspace of D is the same as the nullspace of B.

## Problem 2

a) The nullspace of A is contained in the nullspace of  $A^2$ . The reason is that if Ax = 0, i.e. if x is in the nullspace of A, then  $A^2x = A \cdot (Ax) = 0$ . Thus x is also in the nullspace of  $A^2$ . Similarly we have

$$N(A) \subset N(A^2) \subset N(A^3) \subset \dots$$

Note that one can prove that if A is an  $n \times n$  matrix, then one has  $N(A^n) = N(A^{n+1}) = \dots$ 

b) The nullspace is by definition the set of all vectors v such that  $\frac{d^2}{dx^2}v = 0$ . This means that the polynomial v must be linear: v = cx + d. Thus the nullspace is the space of polynomials of degree at most one.

The nullspace of  $\left(\frac{d^2}{dx^2}\right)^2$  is the nullspace of the composition of  $\frac{d^2}{dx^2}$  with itself: it is the nullspace of  $\frac{d^4}{dx^4}$ . Thus the nullspace of  $\frac{d^4}{dx^4}$  is the space of all polynomials of degree at most three:  $v = ax^3 + bx^2 + cx + d$ .