

Fundamentals of Linear Algebra and Optimization

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Homework 4

October 21, 2015; Due November 3, 2015, beginning of class

Problem B1 (50 pts). (1) Prove that the dimension of the subspace of 2×2 matrices A , such that the sum of the entries of every row is the same (say c_1) and the sum of entries of every column is the same (say c_2) is 2.

(2) Prove that the dimension of the subspace of 2×2 matrices A , such that the sum of the entries of every row is the same (say c_1), the sum of entries of every column is the same (say c_2), and $c_1 = c_2$, is also 2. Prove that every such matrix is of the form

$$\begin{pmatrix} a & b \\ b & a \end{pmatrix},$$

and give a basis for this subspace.

(3) Prove that the dimension of the subspace of 3×3 matrices A , such that the sum of the entries of every row is the same (say c_1), the sum of entries of every column is the same (say c_2), and $c_1 = c_2$, is 5. Begin by showing that the above constraints are given by the set of equations

$$\begin{pmatrix} 1 & 1 & 1 & -1 & -1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & -1 & -1 & -1 \\ 1 & -1 & 0 & 1 & -1 & 0 & 1 & -1 & 0 \\ 0 & 1 & -1 & 0 & 1 & -1 & 0 & 1 & -1 \\ 0 & 1 & 1 & -1 & 0 & 0 & -1 & 0 & 0 \end{pmatrix} \begin{pmatrix} a_{11} \\ a_{12} \\ a_{13} \\ a_{21} \\ a_{22} \\ a_{23} \\ a_{31} \\ a_{32} \\ a_{33} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}.$$

Prove that every matrix satisfying the above constraints is of the form

$$\begin{pmatrix} a+b-c & -a+c+e & -b+c+d \\ -a-b+c+d+e & a & b \\ c & d & e \end{pmatrix},$$

with $a, b, c, d, e \in \mathbb{R}$. Find a basis for this subspace. (Use the method to find a basis for the kernel of a matrix).

Problem B2 (10 pts). If A is an $n \times n$ symmetric matrix and B is any $n \times n$ invertible matrix, prove that A is positive definite iff $B^T A B$ is positive definite.

Problem B3 (100 pts). (1) Let A be any invertible 2×2 matrix

$$A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}.$$

Prove that there is an invertible matrix S such that

$$SA = \begin{pmatrix} 1 & 0 \\ 0 & ad - bc \end{pmatrix},$$

where S is the product of at most four elementary matrices of the form $E_{i,j;\beta}$.

Conclude that every matrix A in $\mathbf{SL}(2)$ (the group of invertible 2×2 matrices A with $\det(A) = +1$) is the product of at most four elementary matrices of the form $E_{i,j;\beta}$.

For any $a \neq 0, 1$, give an explicit factorization as above for

$$A = \begin{pmatrix} a & 0 \\ 0 & a^{-1} \end{pmatrix}.$$

What is this decomposition for $a = -1$?

(2) Recall that a rotation matrix R (a member of the group $\mathbf{SO}(2)$) is a matrix of the form

$$R = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}.$$

Prove that if $\theta \neq k\pi$ (with $k \in \mathbb{Z}$), any rotation matrix can be written as a product

$$R = ULU,$$

where U is upper triangular and L is lower triangular of the form

$$U = \begin{pmatrix} 1 & u \\ 0 & 1 \end{pmatrix}, \quad L = \begin{pmatrix} 1 & 0 \\ v & 1 \end{pmatrix}.$$

Therefore, every plane rotation (except a flip about the origin when $\theta = \pi$) can be written as the composition of three shear transformations!

(3) Recall that $E_{i,d}$ is the diagonal matrix

$$E_{i,d} = \text{diag}(1, \dots, 1, d, 1, \dots, 1),$$

whose diagonal entries are all $+1$, except the (i, i) th entry which is equal to d .

Given any $n \times n$ matrix A , for any pair (i, j) of distinct row indices ($1 \leq i, j \leq n$), prove that there exist two elementary matrices $E_1(i, j)$ and $E_2(i, j)$ of the form $E_{k,\ell;\beta}$, such that

$$E_{j,-1}E_1(i, j)E_2(i, j)E_1(i, j)A = P(i, j)A,$$

the matrix obtained from the matrix A by permuting row i and row j . Equivalently, we have

$$E_1(i, j)E_2(i, j)E_1(i, j)A = E_{j,-1}P(i, j)A,$$

the matrix obtained from A by permuting row i and row j and multiplying row j by -1 .

Prove that for every $i = 2, \dots, n$, there exist four elementary matrices $E_3(i, d), E_4(i, d), E_5(i, d), E_6(i, d)$ of the form $E_{k,\ell;\beta}$, such that

$$E_6(i, d)E_5(i, d)E_4(i, d)E_3(i, d)E_{n,d} = E_{i,d}.$$

What happens when $d = -1$, that is, what kind of simplifications occur?

Prove that all permutation matrices can be written as products of elementary operations of the form $E_{k,\ell;\beta}$ and the operation $E_{n,-1}$.

(4) Prove that for every invertible $n \times n$ matrix A , there is a matrix S such that

$$SA = \begin{pmatrix} I_{n-1} & 0 \\ 0 & d \end{pmatrix} = E_{n,d},$$

with $d = \det(A)$, and where S is a product of elementary matrices of the form $E_{k,\ell;\beta}$.

In particular, every matrix in $\mathbf{SL}(n)$ (the group of invertible $n \times n$ matrices A with $\det(A) = +1$) can be written as a product of elementary matrices of the form $E_{k,\ell;\beta}$. Prove that at most $n(n+1) - 2$ such transformations are needed.

Extra Credit (20 points). Prove that every matrix in $\mathbf{SL}(n)$ can be written as a product of at most $(n-1)(\max\{n, 3\} + 1)$ elementary matrices of the form $E_{k,\ell;\beta}$.

Problem B4 (50 pts). A matrix, A , is called *strictly column diagonally dominant* iff

$$|a_{jj}| > \sum_{i=1, i \neq j}^n |a_{ij}|, \quad \text{for } j = 1, \dots, n$$

Prove that if A is strictly column diagonally dominant, then Gaussian elimination with partial pivoting does not require pivoting, and A is invertible.

Problem B5 (40 pts). Let $(\alpha_1, \dots, \alpha_{m+1})$ be a sequence of pairwise distinct scalars in \mathbb{R} and let $(\beta_1, \dots, \beta_{m+1})$ be any sequence of scalars in \mathbb{R} , not necessarily distinct.

(1) Prove that there is a unique polynomial P of degree at most m such that

$$P(\alpha_i) = \beta_i, \quad 1 \leq i \leq m+1.$$

Hint. Remember Vandermonde!

(2) Let $L_i(X)$ be the polynomial of degree m given by

$$L_i(X) = \frac{(X - \alpha_1) \cdots (X - \alpha_{i-1})(X - \alpha_{i+1}) \cdots (X - \alpha_{m+1})}{(\alpha_i - \alpha_1) \cdots (\alpha_i - \alpha_{i-1})(\alpha_i - \alpha_{i+1}) \cdots (\alpha_i - \alpha_{m+1})}, \quad 1 \leq i \leq m + 1.$$

The polynomials $L_i(X)$ are known as *Lagrange polynomial interpolants*. Prove that

$$L_i(\alpha_j) = \delta_{ij} \quad 1 \leq i, j \leq m + 1.$$

Prove that

$$P(X) = \beta_1 L_1(X) + \cdots + \beta_{m+1} L_{m+1}(X)$$

is the unique polynomial of degree at most m such that

$$P(\alpha_i) = \beta_i, \quad 1 \leq i \leq m + 1.$$

(3) Prove that $L_1(X), \dots, L_{m+1}(X)$ are linearly independent, and that they form a basis of all polynomials of degree at most m .

How is 1 (the constant polynomial 1) expressed over the basis $(L_1(X), \dots, L_{m+1}(X))$?

Give the expression of every polynomial $P(X)$ of degree at most m over the basis $(L_1(X), \dots, L_{m+1}(X))$.

(4) Prove that the dual basis $(L_1^*, \dots, L_{m+1}^*)$ of the basis $(L_1(X), \dots, L_{m+1}(X))$ consists of the linear forms L_i^* given by

$$L_i^*(P) = P(\alpha_i),$$

for every polynomial P of degree at most m ; this is simply *evaluation at α_i* .

Problem B6 (60 pts). (a) Find a lower triangular matrix E such that

$$E \begin{pmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 2 & 1 & 0 \\ 1 & 3 & 3 & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 2 & 1 \end{pmatrix}.$$

(b) What is the effect of the product (on the left) with

$$E_{4,3;-1} E_{3,2;-1} E_{4,3;-1} E_{2,1;-1} E_{3,2;-1} E_{4,3;-1}$$

on the matrix

$$Pa_3 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 2 & 1 & 0 \\ 1 & 3 & 3 & 1 \end{pmatrix}.$$

(c) Find the inverse of the matrix Pa_3 .

(d) Consider the $(n + 1) \times (n + 1)$ Pascal matrix Pa_n whose i th row is given by the binomial coefficients

$$\binom{i-1}{j-1},$$

with $1 \leq i \leq n + 1$, $1 \leq j \leq n + 1$, and with the usual convention that

$$\binom{0}{0} = 1, \quad \binom{i}{j} = 0 \quad \text{if } j > i.$$

The matrix Pa_3 is shown in question (c) and Pa_4 is shown below:

$$Pa_4 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 2 & 1 & 0 & 0 \\ 1 & 3 & 3 & 1 & 0 \\ 1 & 4 & 6 & 4 & 1 \end{pmatrix}.$$

Find n elementary matrices $E_{i_k, j_k; \beta_k}$ such that

$$E_{i_n, j_n; \beta_n} \cdots E_{i_1, j_1; \beta_1} Pa_n = \begin{pmatrix} 1 & 0 \\ 0 & Pa_{n-1} \end{pmatrix}.$$

Use the above to prove that the inverse of Pa_n is the lower triangular matrix whose i th row is given by the signed binomial coefficients

$$(-1)^{i+j-2} \binom{i-1}{j-1},$$

with $1 \leq i \leq n + 1$, $1 \leq j \leq n + 1$. For example,

$$Pa_4^{-1} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 \\ 1 & -2 & 1 & 0 & 0 \\ -1 & 3 & -3 & 1 & 0 \\ 1 & -4 & 6 & -4 & 1 \end{pmatrix}.$$

Hint. Given any $n \times n$ matrix A , multiplying A by the elementary matrix $E_{i,j;\beta}$ on the right yields the matrix $AE_{i,j;\beta}$ in which β times the i th column is added to the j th column.

Problem B7 (30 pts). Given any two subspaces V_1, V_2 of a finite-dimensional vector space E , prove that

$$\begin{aligned} (V_1 + V_2)^0 &= V_1^0 \cap V_2^0 \\ (V_1 \cap V_2)^0 &= V_1^0 + V_2^0. \end{aligned}$$

Beware that in the second equation, V_1 and V_2 are subspaces of E , not E^* .

Hint. To prove the second equation, prove the inclusions $V_1^0 + V_2^0 \subseteq (V_1 \cap V_2)^0$ and $(V_1 \cap V_2)^0 \subseteq V_1^0 + V_2^0$. Proving the second inclusion is a little tricky. First, prove that we can pick a subspace W_1 of V_1 and a subspace W_2 of V_2 such that

1. V_1 is the direct sum $V_1 = (V_1 \cap V_2) \oplus W_1$.
2. V_2 is the direct sum $V_2 = (V_1 \cap V_2) \oplus W_2$.
3. $V_1 + V_2$ is the direct sum $V_1 + V_2 = (V_1 \cap V_2) \oplus W_1 \oplus W_2$.

TOTAL: 340 + 20 points.