

MATH 311

Topics in Applied Mathematics I

Lecture 27:
Review for Test 2.

Topics for Test 2

Vector spaces (Leon/Colley 3.4–3.6)

- Basis and dimension
- Rank and nullity of a matrix
- Coordinates relative to a basis
- Change of basis, transition matrix

Linear transformations (Leon/Colley 4.1–4.3)

- Linear transformations
- Range and kernel
- Matrix transformations
- Matrix of a linear transformation
- Change of basis for a linear operator
- Similar matrices

Topics for Test 2

Eigenvalues and eigenvectors (Leon/Colley 6.1, 6.3)

- Eigenvalues, eigenvectors, eigenspaces
- Characteristic polynomial
- Diagonalization

Orthogonality (Leon/Colley 5.1–5.3, 5.5–5.6)

- Orthogonal complement
- Orthogonal projection
- Least squares problems
- The Gram-Schmidt orthogonalization process

Sample problems for Test 2

Problem 1 Let $A = \begin{pmatrix} 0 & -1 & 4 & 1 \\ 1 & 1 & 2 & -1 \\ -3 & 0 & -1 & 0 \\ 2 & -1 & 0 & 1 \end{pmatrix}$.

- (i) Find the rank and the nullity of the matrix A .
- (ii) Find a basis for the row space of A , then extend this basis to a basis for \mathbb{R}^4 .
- (iii) Find a basis for the nullspace of A .

Problem 2 Let V be a subspace of $F(\mathbb{R})$ spanned by functions e^x and e^{-x} . Let L be a linear operator on V such that $\begin{pmatrix} 2 & -1 \\ -3 & 2 \end{pmatrix}$ is the matrix of L relative to the basis e^x, e^{-x} . Find the matrix of L relative to the basis $\cosh x = \frac{1}{2}(e^x + e^{-x}), \sinh x = \frac{1}{2}(e^x - e^{-x})$.

Sample problems for Test 2

Problem 3 Let $L : V \rightarrow W$ be a linear mapping of a finite-dimensional vector space V to a vector space W . Show that

$$\dim \text{Range}(L) + \dim \ker(L) = \dim V.$$

Problem 4 Let $A = \begin{pmatrix} 1 & 2 & 0 \\ 1 & 1 & 1 \\ 0 & 2 & 1 \end{pmatrix}$.

- (i) Find all eigenvalues of the matrix A .
- (ii) For each eigenvalue of A , find an associated eigenvector.
- (iii) Is the matrix A diagonalizable? Explain.
- (iv) Find all eigenvalues of the matrix A^2 .

Sample problems for Test 2

Problem 5 Find a linear polynomial which is the best least squares fit to the following data:

| | | | | | |
|--------|------|------|-----|-----|-----|
| x | -2 | -1 | 0 | 1 | 2 |
| $f(x)$ | -3 | -2 | 1 | 2 | 5 |

Problem 6 Let V be a subspace of \mathbb{R}^4 spanned by the vectors $\mathbf{x}_1 = (1, 1, 1, 1)$ and $\mathbf{x}_2 = (1, 0, 3, 0)$.

(i) Find an orthonormal basis for V .

(ii) Find an orthonormal basis for the orthogonal complement V^\perp .

Problem 1. Let $A = \begin{pmatrix} 0 & -1 & 4 & 1 \\ 1 & 1 & 2 & -1 \\ -3 & 0 & -1 & 0 \\ 2 & -1 & 0 & 1 \end{pmatrix}$.

(i) Find the rank and the nullity of the matrix A .

The rank (= dimension of the row space) and the nullity (= dimension of the nullspace) of a matrix are preserved under elementary row operations. We apply such operations to convert the matrix A into row echelon form.

Interchange the 1st row with the 2nd row:

$$\rightarrow \begin{pmatrix} 1 & 1 & 2 & -1 \\ 0 & -1 & 4 & 1 \\ -3 & 0 & -1 & 0 \\ 2 & -1 & 0 & 1 \end{pmatrix}$$

Add 3 times the 1st row to the 3rd row, then subtract 2 times the 1st row from the 4th row:

$$\rightarrow \begin{pmatrix} 1 & 1 & 2 & -1 \\ 0 & -1 & 4 & 1 \\ 0 & 3 & 5 & -3 \\ 2 & -1 & 0 & 1 \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 1 & 2 & -1 \\ 0 & -1 & 4 & 1 \\ 0 & 3 & 5 & -3 \\ 0 & -3 & -4 & 3 \end{pmatrix}$$

Multiply the 2nd row by -1 :

$$\rightarrow \begin{pmatrix} 1 & 1 & 2 & -1 \\ 0 & 1 & -4 & -1 \\ 0 & 3 & 5 & -3 \\ 0 & -3 & -4 & 3 \end{pmatrix}$$

Add the 4th row to the 3rd row:

$$\rightarrow \begin{pmatrix} 1 & 1 & 2 & -1 \\ 0 & 1 & -4 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & -3 & -4 & 3 \end{pmatrix}$$

Add 3 times the 2nd row to the 4th row:

$$\rightarrow \begin{pmatrix} 1 & 1 & 2 & -1 \\ 0 & 1 & -4 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -16 & 0 \end{pmatrix}$$

Add 16 times the 3rd row to the 4th row:

$$\rightarrow \begin{pmatrix} 1 & 1 & 2 & -1 \\ 0 & 1 & -4 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Now that the matrix is in row echelon form, its rank equals the number of nonzero rows, which is 3. Since

$(\text{rank of } A) + (\text{nullity of } A) = (\text{the number of columns of } A) = 4$,
it follows that the nullity of A equals 1.

Problem 1. Let $A = \begin{pmatrix} 0 & -1 & 4 & 1 \\ 1 & 1 & 2 & -1 \\ -3 & 0 & -1 & 0 \\ 2 & -1 & 0 & 1 \end{pmatrix}$.

(ii) Find a basis for the row space of A , then extend this basis to a basis for \mathbb{R}^4 .

The row space of a matrix is invariant under elementary row operations. Therefore the row space of the matrix A is the same as the row space of its row echelon form:

$$\begin{pmatrix} 0 & -1 & 4 & 1 \\ 1 & 1 & 2 & -1 \\ -3 & 0 & -1 & 0 \\ 2 & -1 & 0 & 1 \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 1 & 2 & -1 \\ 0 & 1 & -4 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}.$$

The nonzero rows of the latter matrix are linearly independent so that they form a basis for its row space:

$$\mathbf{v}_1 = (1, 1, 2, -1), \quad \mathbf{v}_2 = (0, 1, -4, -1), \quad \mathbf{v}_3 = (0, 0, 1, 0).$$

To extend the basis $\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3$ to a basis for \mathbb{R}^4 , we need a vector $\mathbf{v}_4 \in \mathbb{R}^4$ that is not a linear combination of $\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3$.

It is known that at least one of the vectors $\mathbf{e}_1 = (1, 0, 0, 0)$, $\mathbf{e}_2 = (0, 1, 0, 0)$, $\mathbf{e}_3 = (0, 0, 1, 0)$, and $\mathbf{e}_4 = (0, 0, 0, 1)$ can be chosen as \mathbf{v}_4 .

In particular, the vectors $\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3, \mathbf{e}_4$ form a basis for \mathbb{R}^4 .

This follows from the fact that the 4×4 matrix whose rows are these vectors is not singular:

$$\begin{vmatrix} 1 & 1 & 2 & -1 \\ 0 & 1 & -4 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} = 1 \neq 0.$$

Problem 1. Let $A = \begin{pmatrix} 0 & -1 & 4 & 1 \\ 1 & 1 & 2 & -1 \\ -3 & 0 & -1 & 0 \\ 2 & -1 & 0 & 1 \end{pmatrix}$.

(iii) Find a basis for the nullspace of A .

The nullspace of A is the solution set of the system of linear homogeneous equations with A as the coefficient matrix. To solve the system, we convert A to reduced row echelon form:

$$\rightarrow \begin{pmatrix} 1 & 1 & 2 & -1 \\ 0 & 1 & -4 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\implies x_1 = x_2 - x_4 = x_3 = 0$$

General solution: $(x_1, x_2, x_3, x_4) = (0, t, 0, t) = t(0, 1, 0, 1)$.

Thus the vector $(0, 1, 0, 1)$ forms a basis for the nullspace of A .

Problem 2. Let V be a subspace of $F(\mathbb{R})$ spanned by functions e^x and e^{-x} . Let L be a linear operator on V such that $\begin{pmatrix} 2 & -1 \\ -3 & 2 \end{pmatrix}$ is the matrix of L relative to the basis e^x, e^{-x} . Find the matrix of L relative to the basis $\cosh x = \frac{1}{2}(e^x + e^{-x}), \sinh x = \frac{1}{2}(e^x - e^{-x})$.

Let A denote the matrix of the operator L relative to the basis e^x, e^{-x} (which is given) and B denote the matrix of L relative to the basis $\cosh x, \sinh x$ (which is to be found). By definition of the functions $\cosh x$ and $\sinh x$, the transition matrix from $\cosh x, \sinh x$ to e^x, e^{-x} is $U = \frac{1}{2} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$.

It follows that $B = U^{-1}AU$. We obtain that

$$B = \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} 2 & -1 \\ -3 & 2 \end{pmatrix} \cdot \frac{1}{2} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} = \begin{pmatrix} 0 & -1 \\ 1 & 4 \end{pmatrix}.$$

Problem 3. Let $L : V \rightarrow W$ be a linear mapping of a finite-dimensional vector space V to a vector space W . Show that $\dim \text{Range}(L) + \dim \ker(L) = \dim V$.

The kernel $\ker(L)$ is a subspace of V . It is finite-dimensional since the vector space V is.

Take a basis $\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_k$ for the subspace $\ker(L)$, then extend it to a basis $\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_k, \mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_m$ for the entire space V .

Claim Vectors $L(\mathbf{u}_1), L(\mathbf{u}_2), \dots, L(\mathbf{u}_m)$ form a basis for the range of L .

Assuming the claim is proved, we obtain

$$\dim \text{Range}(L) = m, \quad \dim \ker(L) = k, \quad \dim V = k + m.$$

Claim Vectors $L(\mathbf{u}_1), L(\mathbf{u}_2), \dots, L(\mathbf{u}_m)$ form a basis for the range of L .

Proof (spanning): Any vector $\mathbf{w} \in \text{Range}(L)$ is represented as $\mathbf{w} = L(\mathbf{v})$, where $\mathbf{v} \in V$. Then

$$\mathbf{v} = \alpha_1 \mathbf{v}_1 + \alpha_2 \mathbf{v}_2 + \cdots + \alpha_k \mathbf{v}_k + \beta_1 \mathbf{u}_1 + \beta_2 \mathbf{u}_2 + \cdots + \beta_m \mathbf{u}_m$$

for some $\alpha_i, \beta_j \in \mathbb{R}$. It follows that

$$\begin{aligned} \mathbf{w} = L(\mathbf{v}) &= \alpha_1 L(\mathbf{v}_1) + \cdots + \alpha_k L(\mathbf{v}_k) + \beta_1 L(\mathbf{u}_1) + \cdots + \beta_m L(\mathbf{u}_m) \\ &= \beta_1 L(\mathbf{u}_1) + \cdots + \beta_m L(\mathbf{u}_m). \end{aligned}$$

Note that $L(\mathbf{v}_i) = \mathbf{0}$ since $\mathbf{v}_i \in \ker(L)$.

Thus $\text{Range}(L)$ is spanned by the vectors $L(\mathbf{u}_1), \dots, L(\mathbf{u}_m)$.

Claim Vectors $L(\mathbf{u}_1), L(\mathbf{u}_2), \dots, L(\mathbf{u}_m)$ form a basis for the range of L .

Proof (linear independence): Suppose that

$$t_1L(\mathbf{u}_1) + t_2L(\mathbf{u}_2) + \cdots + t_mL(\mathbf{u}_m) = \mathbf{0}$$

for some $t_i \in \mathbb{R}$. Let $\mathbf{u} = t_1\mathbf{u}_1 + t_2\mathbf{u}_2 + \cdots + t_m\mathbf{u}_m$. Since

$$L(\mathbf{u}) = t_1L(\mathbf{u}_1) + t_2L(\mathbf{u}_2) + \cdots + t_mL(\mathbf{u}_m) = \mathbf{0},$$

the vector \mathbf{u} belongs to the kernel of L . Therefore $\mathbf{u} = s_1\mathbf{v}_1 + s_2\mathbf{v}_2 + \cdots + s_k\mathbf{v}_k$ for some $s_j \in \mathbb{R}$. It follows that

$$t_1\mathbf{u}_1 + t_2\mathbf{u}_2 + \cdots + t_m\mathbf{u}_m - s_1\mathbf{v}_1 - s_2\mathbf{v}_2 - \cdots - s_k\mathbf{v}_k = \mathbf{u} - \mathbf{u} = \mathbf{0}.$$

Linear independence of vectors $\mathbf{v}_1, \dots, \mathbf{v}_k, \mathbf{u}_1, \dots, \mathbf{u}_m$ implies that $t_1 = \cdots = t_m = 0$ (as well as $s_1 = \cdots = s_k = 0$).

Thus the vectors $L(\mathbf{u}_1), L(\mathbf{u}_2), \dots, L(\mathbf{u}_m)$ are linearly independent.

Problem 4. Let $A = \begin{pmatrix} 1 & 2 & 0 \\ 1 & 1 & 1 \\ 0 & 2 & 1 \end{pmatrix}$.

(i) Find all eigenvalues of the matrix A .

The eigenvalues of A are roots of the characteristic equation $\det(A - \lambda I) = 0$. We obtain that

$$\det(A - \lambda I) = \begin{vmatrix} 1 - \lambda & 2 & 0 \\ 1 & 1 - \lambda & 1 \\ 0 & 2 & 1 - \lambda \end{vmatrix}$$

$$\begin{aligned} &= (1 - \lambda)^3 - 2(1 - \lambda) - 2(1 - \lambda) = (1 - \lambda)((1 - \lambda)^2 - 4) \\ &= (1 - \lambda)((1 - \lambda) - 2)((1 - \lambda) + 2) = -(\lambda - 1)(\lambda + 1)(\lambda - 3). \end{aligned}$$

Hence the matrix A has three eigenvalues: -1 , 1 , and 3 .

Problem 4. Let $A = \begin{pmatrix} 1 & 2 & 0 \\ 1 & 1 & 1 \\ 0 & 2 & 1 \end{pmatrix}$.

(ii) For each eigenvalue of A , find an associated eigenvector.

An eigenvector $\mathbf{v} = (x, y, z)$ of the matrix A associated with an eigenvalue λ is a nonzero solution of the vector equation

$$(A - \lambda I)\mathbf{v} = \mathbf{0} \iff \begin{pmatrix} 1 - \lambda & 2 & 0 \\ 1 & 1 - \lambda & 1 \\ 0 & 2 & 1 - \lambda \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}.$$

To solve the equation, we convert the matrix $A - \lambda I$ to reduced row echelon form.

First consider the case $\lambda = -1$. The row reduction yields

$$A + I = \begin{pmatrix} 2 & 2 & 0 \\ 1 & 2 & 1 \\ 0 & 2 & 2 \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 1 & 0 \\ 1 & 2 & 1 \\ 0 & 2 & 2 \end{pmatrix}$$

$$\rightarrow \begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 0 & 2 & 2 \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 0 \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 0 & -1 \\ 0 & 1 & 1 \\ 0 & 0 & 0 \end{pmatrix}.$$

Hence

$$(A + I)\mathbf{v} = \mathbf{0} \iff \begin{cases} x - z = 0, \\ y + z = 0. \end{cases}$$

The general solution is $x = t$, $y = -t$, $z = t$, where $t \in \mathbb{R}$. In particular, $\mathbf{v}_1 = (1, -1, 1)$ is an eigenvector of A associated with the eigenvalue -1 .

Secondly, consider the case $\lambda = 1$. The row reduction yields

$$A - I = \begin{pmatrix} 0 & 2 & 0 \\ 1 & 0 & 1 \\ 0 & 2 & 0 \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 0 & 1 \\ 0 & 2 & 0 \\ 0 & 2 & 0 \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 2 & 0 \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}.$$

Hence

$$(A - I)\mathbf{v} = \mathbf{0} \iff \begin{cases} x + z = 0, \\ y = 0. \end{cases}$$

The general solution is $x = -t$, $y = 0$, $z = t$, where $t \in \mathbb{R}$. In particular, $\mathbf{v}_2 = (-1, 0, 1)$ is an eigenvector of A associated with the eigenvalue 1.

Finally, consider the case $\lambda = 3$. The row reduction yields

$$\begin{aligned} A-3I &= \begin{pmatrix} -2 & 2 & 0 \\ 1 & -2 & 1 \\ 0 & 2 & -2 \end{pmatrix} \rightarrow \begin{pmatrix} 1 & -1 & 0 \\ 1 & -2 & 1 \\ 0 & 2 & -2 \end{pmatrix} \rightarrow \begin{pmatrix} 1 & -1 & 0 \\ 0 & -1 & 1 \\ 0 & 2 & -2 \end{pmatrix} \\ &\rightarrow \begin{pmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ 0 & 2 & -2 \end{pmatrix} \rightarrow \begin{pmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & 0 \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 0 & -1 \\ 0 & 1 & -1 \\ 0 & 0 & 0 \end{pmatrix}. \end{aligned}$$

Hence

$$(A - 3I)\mathbf{v} = \mathbf{0} \iff \begin{cases} x - z = 0, \\ y - z = 0. \end{cases}$$

The general solution is $x = t$, $y = t$, $z = t$, where $t \in \mathbb{R}$. In particular, $\mathbf{v}_3 = (1, 1, 1)$ is an eigenvector of A associated with the eigenvalue 3.

Problem 4. Let $A = \begin{pmatrix} 1 & 2 & 0 \\ 1 & 1 & 1 \\ 0 & 2 & 1 \end{pmatrix}$.

(iii) Is the matrix A diagonalizable? Explain.

The matrix A is diagonalizable, i.e., there exists a basis for \mathbb{R}^3 formed by its eigenvectors.

Namely, the vectors $\mathbf{v}_1 = (1, -1, 1)$, $\mathbf{v}_2 = (-1, 0, 1)$, and $\mathbf{v}_3 = (1, 1, 1)$ are eigenvectors of the matrix A belonging to distinct eigenvalues. Therefore these vectors are linearly independent. It follows that $\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3$ is a basis for \mathbb{R}^3 .

Alternatively, the existence of a basis for \mathbb{R}^3 consisting of eigenvectors of A already follows from the fact that the matrix A has three distinct eigenvalues.

Problem 4. Let $A = \begin{pmatrix} 1 & 2 & 0 \\ 1 & 1 & 1 \\ 0 & 2 & 1 \end{pmatrix}$.

(iv) Find all eigenvalues of the matrix A^2 .

Suppose that \mathbf{v} is an eigenvector of the matrix A associated with an eigenvalue λ , that is, $\mathbf{v} \neq \mathbf{0}$ and $A\mathbf{v} = \lambda\mathbf{v}$. Then

$$A^2\mathbf{v} = A(A\mathbf{v}) = A(\lambda\mathbf{v}) = \lambda(A\mathbf{v}) = \lambda(\lambda\mathbf{v}) = \lambda^2\mathbf{v}.$$

Therefore \mathbf{v} is also an eigenvector of the matrix A^2 and the associated eigenvalue is λ^2 . We already know that the matrix A has eigenvalues -1 , 1 , and 3 . It follows that A^2 has eigenvalues 1 and 9 .

Since a 3×3 matrix can have up to 3 eigenvalues, we need an additional argument to show that 1 and 9 are the only eigenvalues of A^2 . One reason is that the eigenvalue 1 has multiplicity 2.

Problem 5. Find a linear polynomial which is the best least squares fit to the following data:

| | | | | | |
|--------|------|------|-----|-----|-----|
| x | -2 | -1 | 0 | 1 | 2 |
| $f(x)$ | -3 | -2 | 1 | 2 | 5 |

We are looking for a function $f(x) = c_1 + c_2x$, where c_1, c_2 are unknown coefficients. The data of the problem give rise to an overdetermined system of linear equations in variables c_1 and c_2 :

$$\begin{cases} c_1 - 2c_2 = -3, \\ c_1 - c_2 = -2, \\ c_1 = 1, \\ c_1 + c_2 = 2, \\ c_1 + 2c_2 = 5. \end{cases}$$

This system is inconsistent.

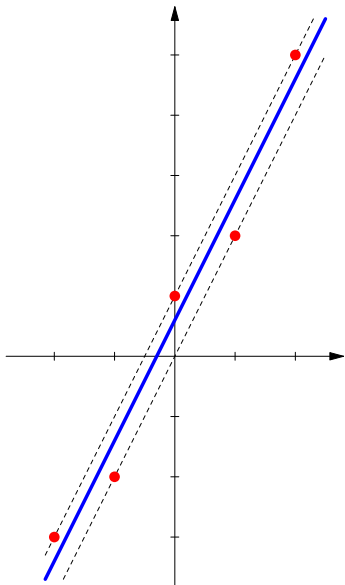
We can represent the system as a matrix equation $A\mathbf{c} = \mathbf{y}$, where

$$A = \begin{pmatrix} 1 & -2 \\ 1 & -1 \\ 1 & 0 \\ 1 & 1 \\ 1 & 2 \end{pmatrix}, \quad \mathbf{c} = \begin{pmatrix} c_1 \\ c_2 \end{pmatrix}, \quad \mathbf{y} = \begin{pmatrix} -3 \\ -2 \\ 1 \\ 2 \\ 5 \end{pmatrix}.$$

The least squares solution \mathbf{c} of the above system is a solution of the normal system $A^T A \mathbf{c} = A^T \mathbf{y}$:

$$\begin{pmatrix} 1 & 1 & 1 & 1 & 1 \\ -2 & -1 & 0 & 1 & 2 \end{pmatrix} \begin{pmatrix} 1 & -2 \\ 1 & -1 \\ 1 & 0 \\ 1 & 1 \\ 1 & 2 \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 \\ -2 & -1 & 0 & 1 & 2 \end{pmatrix} \begin{pmatrix} -3 \\ -2 \\ 1 \\ 2 \\ 5 \end{pmatrix}$$
$$\iff \begin{pmatrix} 5 & 0 \\ 0 & 10 \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \end{pmatrix} = \begin{pmatrix} 3 \\ 20 \end{pmatrix} \iff \begin{cases} c_1 = 3/5 \\ c_2 = 2 \end{cases}$$

Thus the function $f(x) = \frac{3}{5} + 2x$ is the best least squares fit to the above data among linear polynomials.



Problem 6. Let V be a subspace of \mathbb{R}^4 spanned by the vectors $\mathbf{x}_1 = (1, 1, 1, 1)$ and $\mathbf{x}_2 = (1, 0, 3, 0)$.

(i) Find an orthonormal basis for V .

First we apply the Gram-Schmidt orthogonalization process to vectors $\mathbf{x}_1, \mathbf{x}_2$ and obtain an orthogonal basis $\mathbf{v}_1, \mathbf{v}_2$ for the subspace V :

$$\mathbf{v}_1 = \mathbf{x}_1 = (1, 1, 1, 1),$$

$$\mathbf{v}_2 = \mathbf{x}_2 - \frac{\mathbf{x}_2 \cdot \mathbf{v}_1}{\mathbf{v}_1 \cdot \mathbf{v}_1} \mathbf{v}_1 = (1, 0, 3, 0) - \frac{4}{4}(1, 1, 1, 1) = (0, -1, 2, -1).$$

Then we normalize vectors $\mathbf{v}_1, \mathbf{v}_2$ to obtain an orthonormal basis $\mathbf{w}_1, \mathbf{w}_2$ for V :

$$\|\mathbf{v}_1\| = 2 \implies \mathbf{w}_1 = \frac{\mathbf{v}_1}{\|\mathbf{v}_1\|} = \frac{1}{2}(1, 1, 1, 1)$$

$$\|\mathbf{v}_2\| = \sqrt{6} \implies \mathbf{w}_2 = \frac{\mathbf{v}_2}{\|\mathbf{v}_2\|} = \frac{1}{\sqrt{6}}(0, -1, 2, -1)$$

Problem 6. Let V be a subspace of \mathbb{R}^4 spanned by the vectors $\mathbf{x}_1 = (1, 1, 1, 1)$ and $\mathbf{x}_2 = (1, 0, 3, 0)$.

(ii) Find an orthonormal basis for the orthogonal complement V^\perp .

Since the subspace V is spanned by vectors $(1, 1, 1, 1)$ and $(1, 0, 3, 0)$, it is the row space of the matrix

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

Then the orthogonal complement V^\perp is the nullspace of A . To find the nullspace, we convert the matrix A to reduced row echelon form:

$$\begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 0 & 3 & 0 \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 0 & 3 & 0 \\ 1 & 1 & 1 & 1 \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 0 & 3 & 0 \\ 0 & 1 & -2 & 1 \end{pmatrix}.$$

Hence a vector $(x_1, x_2, x_3, x_4) \in \mathbb{R}^4$ belongs to V^\perp if and only if

$$\begin{pmatrix} 1 & 0 & 3 & 0 \\ 0 & 1 & -2 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

$$\iff \begin{cases} x_1 + 3x_3 = 0 \\ x_2 - 2x_3 + x_4 = 0 \end{cases} \iff \begin{cases} x_1 = -3x_3 \\ x_2 = 2x_3 - x_4 \end{cases}$$

The general solution of the system is $(x_1, x_2, x_3, x_4) = (-3t, 2t - s, t, s) = t(-3, 2, 1, 0) + s(0, -1, 0, 1)$, where $t, s \in \mathbb{R}$.

It follows that V^\perp is spanned by vectors $\mathbf{x}_3 = (0, -1, 0, 1)$ and $\mathbf{x}_4 = (-3, 2, 1, 0)$.

The vectors $\mathbf{x}_3 = (0, -1, 0, 1)$ and $\mathbf{x}_4 = (-3, 2, 1, 0)$ form a basis for the subspace V^\perp .

It remains to orthogonalize and normalize this basis:

$$\mathbf{v}_3 = \mathbf{x}_3 = (0, -1, 0, 1),$$

$$\begin{aligned}\mathbf{v}_4 &= \mathbf{x}_4 - \frac{\mathbf{x}_4 \cdot \mathbf{v}_3}{\mathbf{v}_3 \cdot \mathbf{v}_3} \mathbf{v}_3 = (-3, 2, 1, 0) - \frac{-2}{2}(0, -1, 0, 1) \\ &= (-3, 1, 1, 1),\end{aligned}$$

$$\|\mathbf{v}_3\| = \sqrt{2} \implies \mathbf{w}_3 = \frac{\mathbf{v}_3}{\|\mathbf{v}_3\|} = \frac{1}{\sqrt{2}}(0, -1, 0, 1),$$

$$\|\mathbf{v}_4\| = \sqrt{12} = 2\sqrt{3} \implies \mathbf{w}_4 = \frac{\mathbf{v}_4}{\|\mathbf{v}_4\|} = \frac{1}{2\sqrt{3}}(-3, 1, 1, 1).$$

Thus the vectors $\mathbf{w}_3 = \frac{1}{\sqrt{2}}(0, -1, 0, 1)$ and $\mathbf{w}_4 = \frac{1}{2\sqrt{3}}(-3, 1, 1, 1)$ form an orthonormal basis for V^\perp .

Problem 6. Let V be a subspace of \mathbb{R}^4 spanned by the vectors $\mathbf{x}_1 = (1, 1, 1, 1)$ and $\mathbf{x}_2 = (1, 0, 3, 0)$.

(i) Find an orthonormal basis for V .

(ii) Find an orthonormal basis for the orthogonal complement V^\perp .

Alternative solution: First we extend the set $\mathbf{x}_1, \mathbf{x}_2$ to a basis $\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, \mathbf{x}_4$ for \mathbb{R}^4 . Then we orthogonalize and normalize the latter. This yields an orthonormal basis $\mathbf{w}_1, \mathbf{w}_2, \mathbf{w}_3, \mathbf{w}_4$ for \mathbb{R}^4 .

By construction, $\mathbf{w}_1, \mathbf{w}_2$ is an orthonormal basis for V . It follows that $\mathbf{w}_3, \mathbf{w}_4$ is an orthonormal basis for V^\perp .

The set $\mathbf{x}_1 = (1, 1, 1, 1)$, $\mathbf{x}_2 = (1, 0, 3, 0)$ can be extended to a basis for \mathbb{R}^4 by adding two vectors from the standard basis.

For example, we can add vectors $\mathbf{e}_3 = (0, 0, 1, 0)$ and $\mathbf{e}_4 = (0, 0, 0, 1)$. To show that $\mathbf{x}_1, \mathbf{x}_2, \mathbf{e}_3, \mathbf{e}_4$ is indeed a basis for \mathbb{R}^4 , we check that the matrix whose rows are these vectors is nonsingular:

$$\begin{vmatrix} 1 & 1 & 1 & 1 \\ 1 & 0 & 3 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} = - \begin{vmatrix} 1 & 3 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} = -1 \neq 0.$$

To orthogonalize the basis $\mathbf{x}_1, \mathbf{x}_2, \mathbf{e}_3, \mathbf{e}_4$, we apply the Gram-Schmidt process:

$$\mathbf{v}_1 = \mathbf{x}_1 = (1, 1, 1, 1),$$

$$\mathbf{v}_2 = \mathbf{x}_2 - \frac{\mathbf{x}_2 \cdot \mathbf{v}_1}{\mathbf{v}_1 \cdot \mathbf{v}_1} \mathbf{v}_1 = (1, 0, 3, 0) - \frac{4}{4}(1, 1, 1, 1) = (0, -1, 2, -1),$$

$$\begin{aligned} \mathbf{v}_3 &= \mathbf{e}_3 - \frac{\mathbf{e}_3 \cdot \mathbf{v}_1}{\mathbf{v}_1 \cdot \mathbf{v}_1} \mathbf{v}_1 - \frac{\mathbf{e}_3 \cdot \mathbf{v}_2}{\mathbf{v}_2 \cdot \mathbf{v}_2} \mathbf{v}_2 = (0, 0, 1, 0) - \frac{1}{4}(1, 1, 1, 1) - \\ &\quad - \frac{2}{6}(0, -1, 2, -1) = \left(-\frac{1}{4}, \frac{1}{12}, \frac{1}{12}, \frac{1}{12}\right) = \frac{1}{12}(-3, 1, 1, 1), \end{aligned}$$

$$\begin{aligned} \mathbf{v}_4 &= \mathbf{e}_4 - \frac{\mathbf{e}_4 \cdot \mathbf{v}_1}{\mathbf{v}_1 \cdot \mathbf{v}_1} \mathbf{v}_1 - \frac{\mathbf{e}_4 \cdot \mathbf{v}_2}{\mathbf{v}_2 \cdot \mathbf{v}_2} \mathbf{v}_2 - \frac{\mathbf{e}_4 \cdot \mathbf{v}_3}{\mathbf{v}_3 \cdot \mathbf{v}_3} \mathbf{v}_3 = (0, 0, 0, 1) - \\ &\quad - \frac{1}{4}(1, 1, 1, 1) - \frac{-1}{6}(0, -1, 2, -1) - \frac{1/12}{1/12} \cdot \frac{1}{12}(-3, 1, 1, 1) = \\ &\quad = \left(0, -\frac{1}{2}, 0, \frac{1}{2}\right) = \frac{1}{2}(0, -1, 0, 1). \end{aligned}$$

It remains to normalize vectors $\mathbf{v}_1 = (1, 1, 1, 1)$,
 $\mathbf{v}_2 = (0, -1, 2, -1)$, $\mathbf{v}_3 = \frac{1}{12}(-3, 1, 1, 1)$, $\mathbf{v}_4 = \frac{1}{2}(0, -1, 0, 1)$:

$$\|\mathbf{v}_1\| = 2 \implies \mathbf{w}_1 = \frac{\mathbf{v}_1}{\|\mathbf{v}_1\|} = \frac{1}{2}(1, 1, 1, 1)$$

$$\|\mathbf{v}_2\| = \sqrt{6} \implies \mathbf{w}_2 = \frac{\mathbf{v}_2}{\|\mathbf{v}_2\|} = \frac{1}{\sqrt{6}}(0, -1, 2, -1)$$

$$\|\mathbf{v}_3\| = \frac{1}{\sqrt{12}} = \frac{1}{2\sqrt{3}} \implies \mathbf{w}_3 = \frac{\mathbf{v}_3}{\|\mathbf{v}_3\|} = \frac{1}{2\sqrt{3}}(-3, 1, 1, 1)$$

$$\|\mathbf{v}_4\| = \frac{1}{\sqrt{2}} \implies \mathbf{w}_4 = \frac{\mathbf{v}_4}{\|\mathbf{v}_4\|} = \frac{1}{\sqrt{2}}(0, -1, 0, 1)$$

Thus $\mathbf{w}_1, \mathbf{w}_2$ is an orthonormal basis for V while $\mathbf{w}_3, \mathbf{w}_4$ is an orthonormal basis for V^\perp .

Thus for any vector $\mathbf{y} \in \mathbb{R}^4$ the orthogonal projection of \mathbf{y} onto the subspace V is

$$\mathbf{p} = (\mathbf{y} \cdot \mathbf{w}_1)\mathbf{w}_1 + (\mathbf{y} \cdot \mathbf{w}_2)\mathbf{w}_2$$

and the orthogonal projection of \mathbf{y} onto V^\perp is

$$\mathbf{o} = (\mathbf{y} \cdot \mathbf{w}_3)\mathbf{w}_3 + (\mathbf{y} \cdot \mathbf{w}_4)\mathbf{w}_4.$$

Also, the distance from \mathbf{y} to V is $\|\mathbf{y} - \mathbf{p}\| = \|\mathbf{o}\|$
and the distance from \mathbf{y} to V^\perp is $\|\mathbf{y} - \mathbf{o}\| = \|\mathbf{p}\|$.