DSC 210 Numerical Linear Algebra, Fall 2025

Homework problems for Topic 1: *Linear Algebra Basics*

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Write your solutions to the following problems by typing them in LaTeX. Unless otherwise noted by the problem's instructions, show your work and provide justification for your answer. Homework is due via Gradescope at **23rd October 2025, 11:59 PM**.
Late Policy: If you submit your homework after the deadline we will apply a late penalty of 10% per day.

Guidelines for Homework Related Questions:

(a) As a general rule, we can help you understand the homework problems and explain the material from the corresponding lectures, but we cannot give you the entire solution.

(b) Regarding debugging programming questions: We ask you to do some debugging on your own first, including printing out intermediate values in your algorithms, trying a simpler version of the problem, etc.

(c) We will not be pre-grading the homework, i.e. we won't confirm if the answer you have is correct.

AI Usage Policy:

(a) Code: You may use LLMs to debug your code; however, you may not use LLMs to generate your entire code, and code must be reviewed and tested.

(b) Writing: You may use LLMs to correct grammar, style and latex issues; however, you may not use LLMs to generate entire solutions, sentences or paragraphs. All writing must be in your own voice.

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You can access the Homework Template using the following link: `https://www.overleaf.com/read/vfhcmsppvskp`

Question 1: Property of triangular matrices (20 points)

Given L_1 and L_2 are two lower triangular matrices of size $n \times n$, prove that $L_1 L_2$ is also a lower triangular matrix. Further, prove by induction that multiplication of $m\,(m > 2)$ lower triangular matrices $(L_1, L_2, ..., L_m)$ is also a lower triangular matrix.

Solution:

Base Case: Suppose that for two matricies A, B of size m = 2, they are defined as

$$\mathbf{A} = \begin{bmatrix} a_{11} & 0 \\ a_{21} & a_{22} \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} b_{11} & 0 \\ b_{21} & b_{22} \end{bmatrix}$$

The matrix product C is calcuated as follows:

$$\begin{aligned} C &= AB \\ &= \begin{bmatrix} a_{11} & 0 \\ a_{21} & a_{22} \end{bmatrix} \cdot \begin{bmatrix} b_{11} & 0 \\ b_{21} & b_{22} \end{bmatrix} \\ &= \begin{bmatrix} a_{11}b_{11} & 0 \\ a_{21}b_{11} + a_{22}b_{21} & a_{22}b_{22} \end{bmatrix} \end{aligned}$$

which indicates that C is also a lower triangular matrix.

We can then generalize this to $L_1, L_2 \in \mathbb{R}^{n \times n}$ where the ij-th entry of L_1, L_2 is

$$(L_1 L_2)_{ij} = \sum_{k=1}^{n} (L_1)_{ik} (L_2)_{kj}$$

where $i \geq k \geq j$, $\therefore i \geq j$. Should there by any term where $i < j$, it implies that there is no k that satisfies the previous statement, so every term in the sum is 0. This is what defines a lower triangular matrix.

Induction Hypothesis: Assume that for some m = k, consider the product of a combination of lower triangular matricies $P = L_1, L_2, \ldots, L_k$ is also a lower triangular matrix, as proven by the result of a product off two lower triangular matricies of size $n \times n$. Now consider the lower triangular matricies $Q = L_1, L_2, \ldots, L_k, L_{k+1}$, again a lower triangular matrix. The product of P and Q (two lower triangular matricies) will result in another lower triangular matrix, as proven in the base case. Therefore, by induction, the product of any $m \geq 2$ lower triangular matricies is lower triangular.

■

Question 2: Matrix operations (20 points)

Let $\mathbf{B}$ be a 4×4 matrix to which we apply the following 7 operations sequentially and get a final matrix $\mathbf{D}$:

(i) double column 1,

(ii) halve row 3,

(iii) add row 1 to row 4,

(iv) interchange columns 2 and 3,

(v) subtract row 2 from each of the other rows,

(vi) replace column 4 by column 1,

(vii) delete column 2 (so that the column dimension is reduced by 1).

(a) Express each operation (i) to (vii) as a matrix and the final matrix $\mathbf{D}$ as a product of 8 matrices. (10 points)

(b) Write the final result again as a product of $\mathbf{ABC}$, i.e. write matrix $\mathbf{D} = \mathbf{ABC}$ and find $\mathbf{A}, \mathbf{C}$. (5 points)

(c) Write Python code to verify your answers in parts a, and b. Show the answers and code. (5 points) Let

$$\mathbf{B} = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 5 & 6 & 7 & 8 \\ 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 \end{bmatrix}$$

Hint: You can use NumPy for matrix operations.

Solution:

(a) (i) double column 1

$$\mathbf{B_i} = \begin{bmatrix} 2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(ii) halve row 3

$$\mathbf{B_{ii}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0.5 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(iii) add row 1 to row 4

$$\mathbf{B_{iii}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix}$$

(iv) interchange columns 2 and 3

$$\mathbf{B_{iv}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(v) subtract row 2 from each of the other rows

$$\mathbf{B_v} = \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & -1 & 0 & 1 \end{bmatrix}$$

(vi) replace column 4 by column 1

$$\mathbf{B_{vi}} = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

(vii) delete column 2 (so that the column dimension is reduced by 1)

$$\mathbf{B_{vii}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

(viii) matrix D, a result of multiplying all 8 previous matricies

$$\mathbf{D} = \begin{bmatrix} -8 & -4 & -8 \\ 10 & 6 & 10 \\ -1 & -1 & -1 \\ 18 & 10 & 18 \end{bmatrix}$$

(b) A is the product of all row elementary operations, which are given below.

i.

$$\mathbf{B_v} \cdot \mathbf{B_{iii}} \cdot \mathbf{Bii} = \mathbf{A} = \begin{bmatrix} -1 & -1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & -1 & 0.5 & 0 \\ 1 & -1 & 0 & 1 \end{bmatrix}$$

C is the product of all column elementary operations, which then has the second column removed, the result is given below.

i. Note: Column 2 is removed

$$\mathbf{B_i} \cdot \mathbf{B_{iv}} \cdot \mathbf{B_{vi}} = \mathbf{C} = \begin{bmatrix} 2 & 0 & 2 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Therefore,

$$\begin{aligned} D &= ABC \\ &= \begin{bmatrix} -1 & -1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & -1 & 0.5 & 0 \\ 1 & -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 2 & 3 & 4 \\ 5 & 6 & 7 & 8 \\ 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 \end{bmatrix} \begin{bmatrix} 2 & 0 & 2 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \\ &= \begin{bmatrix} -8 & -4 & -8 \\ 10 & 6 & 10 \\ -1 & -1 & -1 \\ 18 & 10 & 18 \end{bmatrix} \end{aligned}$$

(c) For code you may use:

```python
import numpy as np

# original matrix
B = np.array([
    [1, 2, 3, 4],
    [5, 6, 7, 8],
    [9, 10, 11, 12],
    [13, 14, 15, 16]], dtype=float)

B_copy = B.copy()

# (i) double column 1
B1 = np.eye(4)
B1[0, 0] = 2
B_copy = B_copy @ B1

# (ii) halve row 3
B2 = np.eye(4)
B2[2, 2] = 0.5
B_copy = B2 @ B_copy

# (iii) add row 1 to row 4
B3 = np.eye(4)
B3[3, 0] = 1
B_copy = B3 @ B_copy

# (iv) interchange columns 2 and 3
B4 = np.eye(4)
B4[:, [1, 2]] = B4[:, [2, 1]]
B_copy = B_copy @ B4

# (v) subtract row 2 from each of the other rows
B5 = np.eye(4)
B5[0, 1] = -1
B5[2, 1] = -1
B5[3, 1] = -1
B_copy = B5 @ B_copy

# (vi) replace column 4 by column 1
B6 = np.eye(4)
B6[:, 3] = B6[:, 0]
B_copy = B_copy @ B6

# (vii) delete column 2
B7 = np.delete(np.eye(4), 1, axis=1)
D = B_copy @ B7

print("Final Matrix D:\n", D)

# row operations

## (ii) halve row 3
R_2 = np.eye(4)
R_2[2, 2] = 0.5

## (iii) add row 1 to row 4
R_3 = np.eye(4)
R_3[3, 0] = 1

## (v) subtract row 2 from each of the other rows
```

```python
    R_5 = np.eye(4)
    R_5[0, 1] -= 1
    R_5[2, 1] -= 1
    R_5[3, 1] -= 1

    ## combine all row operations
    A = R_5 @ R_3 @ R_2

    # column operations

    ## (i) double column 1
    C_1 = np.eye(4)
    C_1[0, 0] = 2

    ## (iv) interchange columns 2 and 3
    C_4 = np.eye(4)
    C_4[:, [1, 2]] = C_4[:, [2, 1]]

    ## (vi) replace column 4 by column 1
    C_6 = np.eye(4)
    C_6[:, 3] = C_6[:, 0]

    ## (vii) delete column 2
    C_7 = np.delete(np.eye(4), 1, axis=1)

    ## combine all column operations
    C = C_1 @ C_4 @ C_6 @ C_7

    # resulting matrix D
    D = A @ B @ C

    print("A =\n", A)
    print("C =\n", C)
    print("Final Matrix D = A @ B @ C =\n", D)

```

Question 3: Matrix properties (20 points)

Prove that if a matrix $\mathbf{A}$ is triangular (upper or lower) then $\mathbf{A}^{-1}$ is also triangular. Further, use the result to show that if $\mathbf{A}$ is both triangular and orthogonal, then it is diagonal.

Solution:

Theorem. The product of two more more lower triangular matricies also is a lower triangular matrix. (Proved in Question 1)

Proof. Given that a matrix $\mathbf{A}$ is a lower triangular matrix, there exists a possible sequence of elementary row operations that transforms A into an identity matrix I_n, given that $A \in \mathbb{R}^{n \times n}$. This sequence of elementary row operations can be defined as:

$$E_p E_{p-1} \dots E_2 E_1 A = I_n$$

This is known as forward substitution. Because $\mathbf{A}$ is lower triangular, forward substitution only uses triangular elementary operations, so each E_i term is lower triangular. By the theorem proven in question 1, the product of these E_i matricies is also lower triangular. To get the inverse, that is to say get $\mathbf{A}^{-1}$, multiply both sides by $\mathbf{A}^{-1}$.

$$\therefore \mathbf{A}^{-1} = E_p E_{p-1} \dots E_2 E_1$$

∎

Corollary. This proof was done for a lower triangular matrix, however due to the properties of triangular matricies having 0 values on either side of the diagonal, the reasoning is valid for upper triangular matricies as well when back substitution is used.

Proof. If a matrix $\mathbf{A}$ is lower triangular, then matrix $\mathbf{A}^\top$ is upper triangular (and vice versa). Additionally, if a matrix $\mathbf{A}$ is orthogonal, then $\mathbf{A}^{-1} = \mathbf{A}^\top$.

By the first proof in this section, $\mathbf{A}^{-1}$ is also lower triangular. COmbined with the definiton of orthogonality, $\mathbf{A}^{-1} = \mathbf{A}^\top$ is both lower and upper triangular. By definiton, a matrix that is both lower and upper triangular must be diagonal. Therefore, if a matrix is both triangular and orthogonal, it must be diagonal.

∎

Question 4: p-norm inequalities (20 points)

Let $\mathbf{x}$ be a real m-vector, the vector p-norms $\|\mathbf{x}\|_p$ are related by various inequalities, often involving the dimension of the vector, i.e. m. For each of the following, prove the inequality and give an example of a nonzero vector $\mathbf{x}$ for which *equality* is satisfied.

(a) $\|\mathbf{x}\|_\infty \leq \|\mathbf{x}\|_2$. (7 points)

(b) $\|\mathbf{x}\|_2 \leq \sqrt{m} \cdot \|\mathbf{x}\|_\infty$. (7 points)

(c) Plot a 2D contour of $\|\mathbf{x}\|_\infty = 1$, on the same chart also highlight regions where $\|\mathbf{x}\|_2 < 1$, $\|\mathbf{x}\|_2 = 1$ and $\|\mathbf{x}\|_2 > 1$. (6 points)

Solution:

Proof 1. Let x be the m-vector norm $x = (x_1, x_2, \ldots, x_m)^\top \in \mathbb{R}^m$. By definition, a norm is a function $\|x\| \cdot \mathbb{R}^m \to \mathbb{R}$ that assigns a real-valued length to each vector, measuring the value of x. Also by definition, let

$$\|\mathbf{x}\|_\infty = \max_{1 \leq i \leq m} |x_i|, \quad \text{and} \quad \|\mathbf{x}\|_2 = \sqrt{\sum_{i=1}^{m} x_i^2}.$$

Now, let p represent the norm where $|x_p| = \|\mathbf{x}\|_\infty$. Thus by comparing the two terms we see that

$$\|\mathbf{x}\|_2^2 = \sum_{i=1}^{m} x_i^2 > x_p^2 = \|\mathbf{x}\|_\infty^2$$

When p = 2 (the Euclidean norm),

$$\|\mathbf{x}\|_2 > \|\mathbf{x}\|_\infty$$

$$\|\mathbf{x}\|_\infty = \max_i |x_i|^p$$

■

Proof 2. Building off of proof 1, let $\|\mathbf{x}\|_\infty = \max_i |x_i|_p$. Assume then that $|x_i| \leq \|\mathbf{x}\|_\infty$.

$$\Sigma_{i=1}^{m} x_i \leq m\|\mathbf{x}\|_\infty = \Sigma_{i=1}^{m}\|\mathbf{x}\|_\infty$$

$$\therefore \Sigma_{i=1}^{m} x_i^2 \leq m\|\mathbf{x}\|_\infty^2 = \Sigma_{i=1}^{m}\|\mathbf{x}\|_\infty^2$$

$$\therefore \|\mathbf{x}\|_2 \leq \sqrt{m}\|\mathbf{x}\|_\infty$$

■

Code

```python
import numpy as np
import matplotlib.pyplot as plt

# setup mesh
x = np.linspace(-1.5, 1.5, 400)
X, Y = np.meshgrid(x, x)

# compute norms
norm_inf = np.maximum(np.abs(X), np.abs(Y))
norm2 = np.sqrt(X**2 + Y**2)

# plot contours
plt.figure(figsize=(6,6))
plt.contour(X, Y, norm_inf, levels=[1], colors='red', linewidths=2, linestyles='--', label=r'$\|x\|_\infty=1$')
plt.contour(X, Y, norm2, levels=[1], colors='blue', linewidths=2, label=r'$\|x\|_2=1$')
# plt.contourf(X, Y, norm2, levels=[0, 1], colors=['#a8dadc'], alpha=0.5) # fill inside unit 2-norm circle
# plt.contourf(X, Y, norm2 > 1, levels=[0.5, 1.5], colors=['#e63946'], alpha=0.3) # fill outside unit 2-norm circle

# pretty plot
plt.gca().set_aspect('equal', adjustable='box')
plt.title(r"Contours of $\|x\|_\infty=1$ and $\|x\|_2=1$")
plt.xlabel("$x_1$")
plt.ylabel("$x_2$")
plt.grid(True)
plt.show()
```

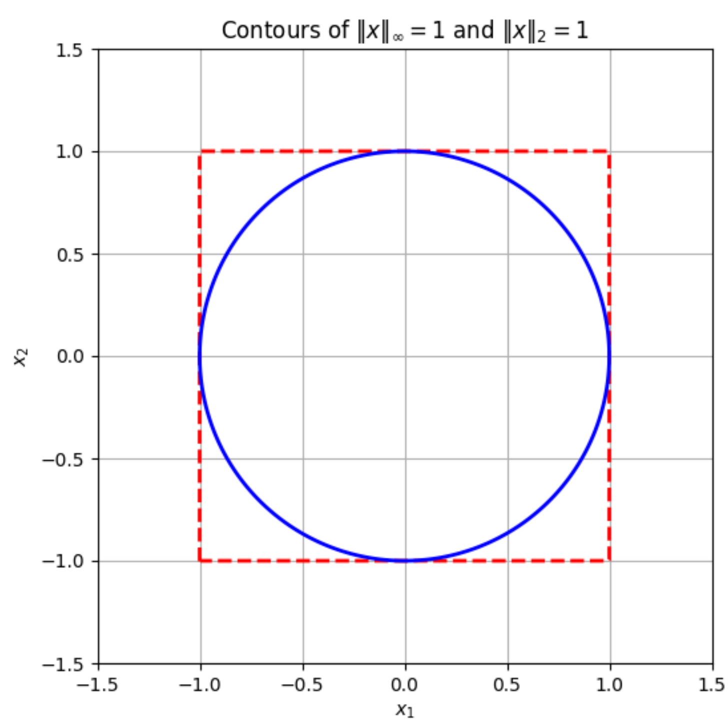

Figure 1: Contours of $\|x\|_\infty = 1$ (red) and $\|x\|_2 = 1$ (blue).

Question 5: Basic vector operations (20 points)

Given two 3-dimensional vectors $\mathbf{a}, \mathbf{b}$, and three matrices $A \in \mathbb{R}^{2\times 3}, B \in \mathbb{R}^{3\times 2}, C \in \mathbb{R}^{2\times 3}$, scalars β_1, β_2 with the values below:

$$\mathbf{a} = \begin{bmatrix}1\\3\\5\end{bmatrix} \mathbf{b} = \begin{bmatrix}2\\4\\6\end{bmatrix} \mathbf{A} = \begin{bmatrix}1 & 2 & 3\\2 & 4 & 6\end{bmatrix} \mathbf{B} = \begin{bmatrix}7 & 8\\9 & 10\\11 & 12\end{bmatrix} \mathbf{C} = \begin{bmatrix}1 & 0 & 0\\0 & 0 & 1\end{bmatrix}$$
$$\beta_{\mathbf{1}} = 4, \beta_{\mathbf{2}} = 5$$

(a) Compute the following operations by hand and show your work: (15 points)

(i) Vector operations: $\mathbf{a}+\mathbf{b}$, $\beta_1\mathbf{a}$, $\mathbf{a}\circ\mathbf{b}$, $\beta_1\mathbf{a}+\beta_2\mathbf{b}$ where $\circ$ denotes component-wise multiplication. (3 points)

(ii) Matrix operations: $\beta_1\mathbf{A}$, $\mathbf{A}+\mathbf{B}$, $\mathbf{A}+\mathbf{C}$. (3 points)

(iii) Transpose operations: $(\mathbf{AB})^\top$, $\mathbf{B}^\top\mathbf{A}^\top$, $(\mathbf{A}^\top)^\top$, $(\mathbf{A}+\mathbf{C})^\top$. (3 points)

(iv) Inner products and outer product: $\langle\mathbf{a},\mathbf{b}\rangle$, $\langle\mathbf{b},\mathbf{a}\rangle$, $\langle\mathbf{a},\mathbf{a}\rangle$, $\langle\mathbf{b},\mathbf{b}\rangle$, $\beta_1\langle\mathbf{a},\mathbf{b}\rangle$, $\langle\beta_1\mathbf{a},\mathbf{b}\rangle$, $\mathbf{b}\mathbf{a}^\top$. (3 points)

(v) Determinants: $\det(\mathbf{AB})$, $\det(\mathbf{BC})$. (3 points)

(b) Implement all the parts above using python (any programming language of your choice) and show the answers and code. (5 points)

Solution:

1. (a) **I: Vector Operations**

i.

$$\mathbf{a}+\mathbf{b} = \begin{bmatrix}1\\3\\5\end{bmatrix} + \begin{bmatrix}2\\4\\6\end{bmatrix}$$
$$= \boxed{\begin{bmatrix}3\\7\\11\end{bmatrix}}$$

ii.

$$\beta_1\mathbf{a} = 4 * \begin{bmatrix}1\\3\\5\end{bmatrix}$$
$$= \boxed{\begin{bmatrix}4\\12\\20\end{bmatrix}}$$

iii.

$$
\begin{aligned}
\mathbf{a} \circ \mathbf{b} &= \begin{bmatrix} 1 \cdot 2 \\ 3 \cdot 4 \\ 5 \cdot 6 \end{bmatrix} \\
&= \boxed{\begin{bmatrix} 2 \\ 12 \\ 30 \end{bmatrix}}
\end{aligned}
$$

iv.

$$
\begin{aligned}
\beta_1 \mathbf{a} + \beta_2 \mathbf{b} &= 4 * \begin{bmatrix} 1 \\ 3 \\ 5 \end{bmatrix} + 5 \cdot \begin{bmatrix} 2 \\ 4 \\ 6 \end{bmatrix} \\
&= \begin{bmatrix} 4 \\ 12 \\ 20 \end{bmatrix} + \begin{bmatrix} 10 \\ 20 \\ 30 \end{bmatrix} \\
&= \boxed{\begin{bmatrix} 14 \\ 32 \\ 50 \end{bmatrix}}
\end{aligned}
$$

(b) **II: Matrix Operations**

i.

$$
\begin{aligned}
\beta_1 \mathbf{A} &= 4 * \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix} \\
&= \boxed{\begin{bmatrix} 4 & 8 & 12 \\ 16 & 20 & 30 \end{bmatrix}}
\end{aligned}
$$

ii.

$$
\mathbf{A} + \mathbf{B} = \boxed{NotPossible, sizeA \neq sizeB}
$$

iii.

$$
\begin{aligned}
\mathbf{A} + \mathbf{C} &= \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
&= \boxed{\begin{bmatrix} 2 & 2 & 3 \\ 2 & 4 & 7 \end{bmatrix}}
\end{aligned}
$$

(c) **III: Transpose Operations**

i.

$$
\begin{aligned}
(\mathbf{AB})^\top &= \begin{bmatrix} 1 \cdot 7 + 2 \cdot 9 + 3 \cdot 11 & 1 \cdot 8 + 2 \cdot 10 + 3 \cdot 12 \\ 4 \cdot 7 + 5 \cdot 9 + 6 \cdot 11 & 4 \cdot 8 + 5 \cdot 10 + 6 \cdot 12 \end{bmatrix}^\top \\
&= \begin{bmatrix} 58 & 64 \\ 116 & 128 \end{bmatrix}^\top \\
&= \boxed{\begin{bmatrix} 58 & 116 \\ 64 & 128 \end{bmatrix}}
\end{aligned}
$$

ii.

$$
\begin{aligned}
\mathbf{B}^\top \mathbf{A}^\top &= \begin{bmatrix} 7 & 8 \\ 9 & 10 \\ 11 & 12 \end{bmatrix}^\top \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix}^\top \\
&= \begin{bmatrix} 7 & 8 & 9 \\ 10 & 11 & 12 \end{bmatrix} \begin{bmatrix} 1 & 2 \\ 3 & 4 \\ 5 & 6 \end{bmatrix} \\
&= \begin{bmatrix} 7 \cdot 1 + 8 \cdot 3 + 9 \cdot 5 & 7 \cdot 2 + 8 \cdot 4 + 9 \cdot 6 \\ 4 \cdot 1 + 11 \cdot 3 + 12 \cdot 5 & 10 \cdot 2 + 11 \cdot 4 + 12 \cdot 6 \end{bmatrix} \\
&= \boxed{\begin{bmatrix} 58 & 116 \\ 64 & 128 \end{bmatrix}}
\end{aligned}
$$

iii.

$$
\begin{aligned}
(\mathbf{A}^\top)^\top &= (\begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix}^\top)^\top \\
&= \begin{bmatrix} 1 & 2 \\ 3 & 4 \\ 5 & 6 \end{bmatrix}^\top \\
&= \boxed{\begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix}}
\end{aligned}
$$

iv.

$$
\begin{aligned}
(\mathbf{A} + \mathbf{C})^\top &= (\begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix})^\top \\
&= (\begin{bmatrix} 2 & 2 & 3 \\ 4 & 5 & 7 \end{bmatrix})^\top \\
&= \boxed{\begin{bmatrix} 2 & 2 \\ 3 & 4 \\ 5 & 7 \end{bmatrix}}
\end{aligned}
$$

(d) **IV: Inner Products and Outer Product**

i.

$$
\begin{aligned}
\langle \mathbf{a}, \mathbf{b} \rangle &= 1 \cdot 2 + 3 \cdot 4 + 5 \cdot 6 \\
&= \boxed{44}
\end{aligned}
$$

ii.

$$
\begin{aligned}
\langle \mathbf{b}, \mathbf{a} \rangle &= 2 \cdot 1 + 4 \cdot 3 + 6 \cdot 5 \\
&= \boxed{44}
\end{aligned}
$$

iii.

$$
\begin{aligned}
\langle \mathbf{a}, \mathbf{a} \rangle &= 1^2 + 3^2 + 5^2 \\
&= \boxed{35}
\end{aligned}
$$

iv.

$$\begin{aligned}\langle \mathbf{b}, \mathbf{b} \rangle &= 2^2 + 4^2 + 6^2 \\ &= \boxed{56}\end{aligned}$$

v.

$$\begin{aligned}\beta_1 \langle \mathbf{a}, \mathbf{b} \rangle &= 4 \cdot (1 \cdot 2 + 3 \cdot 4 + 5 \cdot 6) \\ &= \boxed{176}\end{aligned}$$

vi.

$$\begin{aligned}\langle \beta_1 \mathbf{a}, \mathbf{b} \rangle & 4 \cdot 1 \cdot 2 + 4 \cdot 3 \cdot 4 + 4 \cdot 5 \cdot 6 \\ &= \boxed{176}\end{aligned}$$

vii.

$$\begin{aligned}\mathbf{b}\mathbf{a}^\top &= \begin{bmatrix} 2 \\ 4 \\ 6 \end{bmatrix} \begin{bmatrix} 1 & 3 & 5 \end{bmatrix} \\ &= \boxed{\begin{bmatrix} 2 & 6 & 10 \\ 4 & 12 & 20 \\ 6 & 18 & 30 \end{bmatrix}}\end{aligned}$$

(e) **V: Determinants**

i.

$$\begin{aligned}\det(\mathbf{AB}) &= \det(\begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix} \begin{bmatrix} 7 & 8 \\ 9 & 10 \\ 11 & 12 \end{bmatrix}) \\ &= \det(\begin{bmatrix} 1 \cdot 7 + 2 \cdot 9 + 3 \cdot 11 & 1 \cdot 8 + 2 \cdot 10 + 3 \cdot 12 \\ 4 \cdot 7 + 5 \cdot 9 + 6 \cdot 11 & 4 \cdot 8 + 5 \cdot 10 + 6 \cdot 12 \end{bmatrix}) \\ &= \det(\begin{bmatrix} 58 & 64 \\ 139 & 154 \end{bmatrix}) \\ &= 58 \cdot 154 - 64 \cdot 139 \\ &= \boxed{36}\end{aligned}$$

ii.

$$\begin{aligned}\det(\mathbf{BC}) &= \det(\begin{bmatrix} 7 & 8 \\ 9 & 10 \\ 11 & 12 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}) \\ &= \det(\begin{bmatrix} 7 \cdot 1 + 9 \cdot 0 + 11 \cdot 0 & 8 \cdot 1 + 10 \cdot 0 + 12 \cdot 0 \\ 7 \cdot 0 + 9 \cdot 0 + 11 \cdot 1 & 8 \cdot 0 + 10 \cdot 0 + 12 \cdot 1 \end{bmatrix}) \\ &= \det(\begin{bmatrix} 7 & 0 & 8 \\ 9 & 0 & 10 \\ 11 & 0 & 12 \end{bmatrix}) \\ &= \boxed{0}\end{aligned}$$

2

```python
# imports
import numpy as np

# variable initialization
vector_a = np.array([[1],
                     [3],
                     [5]])

vector_b = np.array([[2],
                     [4],
                     [6]])

matrix_a = np.array([[1, 2, 3],
                     [4, 5, 6]])

matrix_b = np.array([[7, 8],
                     [9, 10],
                     [11, 12]])

matrix_c = np.array([[1, 0 , 0],
                     [0, 0, 1]])

beta_a, beta_b = 4, 5

## verify part (i), vector operations
vector_add = vector_a + vector_b
vector_scalar = beta_a * vector_a
dot_prod = np.dot(vector_a.T, vector_b)
linear_combo = (vector_scalar) + (beta_b * vector_b)
vector_operations_dict = {
    "vector_add": vector_add,
    "vector_scalar": vector_scalar,
    "dot_prod": dot_prod,
    "linear_combo": linear_combo
}

for k, v in vector_operations_dict.items():
    print(f"{k}:\n{v}\n")

## verify part (ii), matrix operations
matrix_scalar = beta_a * matrix_a
# matrix_add_b = matrix_a + matrix_b # incompatible matrix
matrix_add_ac = matrix_a + matrix_c
matrix_operations_dict = {
    "matrix_scalar": matrix_scalar,
    "matrix_add_ac": matrix_add_ac
}

for k, v in matrix_operations_dict.items():
    print(f"{k}:\n{v}\n")

## verify part (iii), transpose operations
transpose_prod = np.transpose(matrix_a @ matrix_b)
transpose_prod_new = transpose_prod
transpose_transpose = np.transpose(np.transpose(matrix_a))
transpose_sum = np.transpose(matrix_a + matrix_c)
transpose_dict = {
    "transpose_prod": transpose_prod,
    "transpose_prod_new": transpose_prod_new,
    "transpose_transpose": transpose_transpose,
    "transpose_sum": transpose_sum
```

```
    }
    for k, v in transpose_dict.items():
        print(f"{k}:\n{v}\n")

    ## verify part (iv), inner and outer products
    vec_a_flat = vector_a.flatten()
    vec_b_flat = vector_b.flatten()
    inner_ab = np.dot(vec_a_flat, vec_b_flat)
    inner_ba = np.dot(vec_b_flat, vec_a_flat)
    inner_aa = np.dot(vec_a_flat, vec_a_flat)
    inner_bb = np.dot(vec_b_flat, vec_b_flat)
    scalar_out = beta_a * inner_ab
    scalar_in = np.dot(beta_a * vec_a_flat, vec_b_flat)
    outer_prod = np.outer(vec_b_flat, vec_a_flat)

    inner_prod_dict = {
        "inner_ab": inner_ab,
        "inner_ba": inner_ba,
        "inner_aa": inner_aa,
        "inner_bb": inner_bb,
        "scalar_out": scalar_out,
        "scalar_in": scalar_in,
        "outer_prod": outer_prod
    }

    for k, v in inner_prod_dict.items():
        print(f"{k}:\n{v}\n")

    # verify part (v), determinants
    det_ab = np.linalg.det(matrix_a @ matrix_b)
    det_bc = np.linalg.det(matrix_b @ matrix_c)
    det_dict = {
        "det_ab": det_ab,
        "det_bc": det_bc
    }

    for k, v in det_dict.items():
        print(f"{k}:\n{v}\n")
```