Handwritten Homework Assignments - Exploration for MATH 1554

For each assignment, complete the questions by hand on a separate sheet of paper. Write neatly and use complete sentences where necessary. **You must submit original work**, but I'm okay with you all working together to share ideas. Handwritten homework assignments are due on Fridays in Gradescope, and no late submissions are accepted.

Week 1: *Practice sketching in 3D.* In $\mathbb{R}^3$, using the coordinates x, y, z, sketch the following making a new sketch for each part (a)-(d):

- **(a)** a horizontal plane,
- **(b)** the plane $y = 0$ and the plane $x = 0$ on the same axes, and sketch and label the intersection of these two planes,
- **(c)** a line passing through the origin which is not contained in any of the three coordinate planes, include and label at least three points on the line,
- **(d)** the plane defined by $x - y = 0$, include and label at least four points in this plane no three of which are colinear.

In each case, you are practicing drawing an accurate, representative graph of the plane of points which satisfy the given equation in the variables x, y, and z.

Week 2: *Practice with span, linear combination, and inconsistent systems.* ***(a)*** Choose two vectors v, w in $\mathbb{R}^2$ and a third vector b also in $\mathbb{R}^2$, and express b as a linear combination of v, w by finding scalars c_1, c_2 such that $c_1v+c_2w = b$. Sketch the situation in $\mathbb{R}^2$ with an illustration that uses the parallelogram rule. ***(b)*** Repeat part *(a)* with vectors in $\mathbb{R}^3$ such that the augmented matrix $[v\ w \mid b]$ gives a consistent system, again illustrating by graphing but this time in $\mathbb{R}^3$. ***(c)*** Why is it harder to find a consistent system for part *(b)* compared to part *(a)*? Explain your idea clearly using complete sentences.

Warning!

PLEASE NOTE: Your submissions for this and future exploration assignments need to contain vectors which are *general looking*. Choosing vectors which are scalar multiples of $\begin{bmatrix}1\\0\end{bmatrix}, \begin{bmatrix}0\\1\end{bmatrix}$, or $\begin{bmatrix}1\\0\\0\end{bmatrix}, \begin{bmatrix}0\\1\\0\end{bmatrix}, \begin{bmatrix}0\\0\\1\end{bmatrix}$, or have too many zeros or ones, or are otherwise too simple and miss the point of the exploration will receive a deduction of points.

Please, do not ask on Piazza if your vectors are general enough to get full credit. The explorations are assignments which require you to make a *judgement call*, to **explore** a particular concept of the course and NOT to come up with the simplest example which satisfies the minimum requirements of the assignment.

Week 3: *Learn some basics of MATLAB.* See Sal's personal website for links to the MATLAB #1 Exploration. (requires MATLAB installation)

Week 4: *Practice with transformations.* For each matrix A below, ***(a)*** state the domain and codomain of T_A, ***(b)*** find $T_A(e_1), T_A(e_2)$, ***(c)*** find $T_A(v), T_A(w)$, ***(d)*** describe in a few words what the transformation is doing, and ***(e)*** state whether the associated transformation is one-to-one/onto, and ***(f)*** give the matrix an appropriate "name" (fine to be silly name like, e.g., "the x-zero-er" for projection to y-axis"). For the problems below use

$$e_1 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad e_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, v = \begin{bmatrix} -1 \\ 2 \end{bmatrix}, \quad w = \begin{bmatrix} 2 \\ -3 \end{bmatrix}$$

(1i) $A = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}$

(1ii) $A = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$

(1iii) $A = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}$

(1iv) $A = \begin{bmatrix} 3 & 0 \\ 0 & 2 \end{bmatrix}$

(1v) $A = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}$

(1vi) $A = \begin{bmatrix} \sqrt{2}/2 & \sqrt{2}/2 \\ -\sqrt{2}/2 & \sqrt{2}/2 \end{bmatrix}$

(1vii) $A = \begin{bmatrix} 1 & 1 \\ 0 & 1 \\ 1 & 0 \end{bmatrix}$

(1viii) $A = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$

Next, for the problems below use

$$e_1 = \begin{bmatrix}1\\0\\0\end{bmatrix}, \quad e_2 = \begin{bmatrix}0\\1\\0\end{bmatrix}, \quad e_3 = \begin{bmatrix}0\\0\\1\end{bmatrix}, \quad v = \begin{bmatrix}3\\-1\\2\end{bmatrix}, \quad w = \begin{bmatrix}0\\1\\\text{-2}\end{bmatrix}$$

(2i) $A = \begin{bmatrix}1 & 0 & 0\\0 & 0 & 1\end{bmatrix}$

(2ii) $A = \begin{bmatrix}1 & 0 & 0\\0 & 0 & 0\\0 & 0 & 1\end{bmatrix}$

(2iii) $A = \begin{bmatrix}0 & 2 & 1\\0 & 3 & 0\\3 & 1 & 0\\1 & 1 & 2\end{bmatrix}$

(2iv) $A = \begin{bmatrix}0 & 0 & 0\\0 & 0 & 0\end{bmatrix}$

Sal says: For the "name your matrix" this is a bit silly, and that's ok. Just come up with a creative name that makes sense to you, and don't worry about it too much!

Hint: For part **(2iii)** above, an appropriate name could be 'the total mystery' or the 'crazy transformation', or maybe 'some kind of weird shear embedding'. It's not always easy to see what the matrix is doing! Don't overthink this one, please.

Week 5: *Practice matrix algebra "fake truths".* For full credit, correctly indicate which problem you are solving by writing the statement you are answering (like "$AB = 0$ and $A \neq 0$,$B \neq 0$"). For grading purposes, please try to write the problems in the same order as listed here. The matrix 0 is the zero matrix and the matrix I is the identity matrix.

For each problem find square matrices which satisfy the given conditions. You don't have to justify *how* you found the matrices for each problem, but you *must verify the equality with calculations* in each case. Just show the matrices A, B, C and the given products.

The following restrictions are required for each problem:
No matrix A, B, or C can be diagonal, none can be equal or a scalar multiple of each other, and no product can be the zero matrix (except **(e)**) or scalar multiple of the identity matrix (except **(c)**). All of the below are possible with these restrictions.

(a) $AB \neq BA$.

(b) $AB = BA$ but neither A nor B is 0 nor I, $A \neq B$ and A, B are not inverses.

(c) $AB = I$ but neither A nor B is I.

(d) $AB = AC$ but $B \neq C$, and the matrix A has *no zeros entries.*

(e) $AB = 0$ but neither A nor B is 0.

Week 6: *Walkthrough Nul(A) is a subspace.*

Step 1: Pick a matrix and find Nul(A)**.** Pick a matrix A of size no smaller than 3×5 (to get a good feel for the problem). Choose entries not all positive, and not too many zeros, and your matrix shouldn't be rref (ideally, but it's ok to pick a matrix in rref if you want - or just start with a matrix in rref and do some row operations to jumble it up). Find the null space Nul(A) by finding the parametric vector form of the general solution x to $A\mathrm{x} = 0$, and write Nul(A) = span$\{v_1, v_2, \ldots, v_k\}$ where $v_1, v_2, \ldots, v_k$ are the vectors appearing in parametric vector form.

Step 2: An example that Nul(A) **is closed under vector addition.** Choose two vectors $\mathrm{w}_1, \mathrm{w}_2$ in the span Nul(A) = span$\{v_1, \ldots, v_k\}$ from step 1. Do this by taking two or more vectors in the basis from step 1 and adding them to each other using some scalars, *i.e.* chose a random linear combination of the vectors $v_1, \ldots, v_k$ from step 1. Do this twice with different weights each time, once to get w_1 and once to get w_2. Add these vectors together to get $\mathrm{z} = \mathrm{w}_1 + \mathrm{w}_2$. **Verify** that z is in the null space of A **using the definition of null space**, by multiplying A times z and verifying that $A\mathrm{z} = 0$.

Step 2b: Answer the following question. What are the weights of z if you write z as a linear combination of $v_1, \ldots, v_k$, and how are these weights related to the weights of $\mathrm{w}_1, \mathrm{w}_2$?

Step 3: An example that Nul(A) **is closed under scalar multiplication.** Let w be either w_1 or w_2 from step 2, one of the random vectors in the null space of A. Choose a random scalar c. Check that $c\mathrm{w}$ is in the null space of A by verifying $A(c\mathrm{w}) = 0$.

Step 3b: Answer the following question. What are the weights of $c\mathrm{w}$ if you write $c\mathrm{w}$ as a linear combination of $v_1, \ldots, v_k$, and how are these weights related to the weights of w?

Step 4: The general case. Try to convince yourself that no matter how A is chosen, Nul(A) is always closed under scalar multiplication and vector addition. *Hint: one way is to use the facts about matrix-vector muliplication that $A(x + y) = Ax + Ay$ and $A(cx) = c(Ax)$, and another option is to think about span and how if x, y are in span$\{v_1, \ldots, v_k\}$ the weights of $x + y$ are related to the weights of x, y and the weights of cx are related to the weights of x.*

Week 7: *Transformations and the determinant.*

Step 1: Sketch a parallelogram somewhere in $\mathbb{R}^2$ such that none of the vertices of the parallelogram lie on the origin. Label the points of the parallelogram a, b, c, d and also label the coordinates (x_1, x_2) for each of the four points. Label the parallelogram S for *shape*.

Step 2b: Showing your work, compute the area area(S) using the content of Section 3.3, by finding a pair of vectors $\vec{v}_1, \vec{v}_2$ which determine the parallelogram from *(Step 1)*. Go back and label the vectors $\vec{v}_1, \vec{v}_2$ in your sketch from *(Step 1)*.

Step 2: Choose a (somewhat random) linear transformation $T : \mathbb{R}^2 \to \mathbb{R}^2$ which can be anything except a transformation from the following list:

(i) the transformation should not have a diagonal standard matrix,

(ii) the transformation should be invertible (one-to-one and onto),

(iii) the transformation should not be a single rotation or a single reflection*.

(*) it is ok for the transformation you pick to be a rotation followed by a reflection, for example. However, if your transformation is 'two rotations' or 'two reflections' but can be represented by a single rotation or single reflection, then you will lose points.

Step 3: Transform your shape S from *(Step 1)* using your transformation T from *(Step 2)*. That is, sketch the **image of** S in $\mathbb{R}^2$. Make a new sketch for this part and label the images $T(a), T(b), T(c), T(d)$ and give the new coordinates for all four points.

Step 3b: Showing all work, compute the area area$(T(S))$ using the same method as *(Step 2b)* by finding the images of $\vec{v}_1, \vec{v}_2$ under the transformation T. Label the images $T(\vec{v}_1), T(\vec{v}_2)$ in your sketch from *(Step 3)*.

Step 4: Compute $\det A$ where A is the standard matrix of $T(\vec{x}) = A\vec{x}$, and compare the areas area(S) and area$(T(S))$ with the value of $\det A$. Write a general formula which relates these three quantities.

Week 8: MATLAB #2 Basis of Eigenvectors and Markov chains.
Note: see instructions pdf on Sal's webpage.

Week 9: Two separate parts.

1. Find a 2×2 matrix A *with real entries* with **no real eigenvalues** and show that it is correct by finding the characteristic polynomial and explaining why it has no real roots.

2. Find all eigenvalues and a corresponding eigenvector for each matrix below **without calculations** by thinking it out using the linear transformation's **geometric interpretation**. Write a few words (like 5) in each case explaining why your eigenvector/eigenvalue pair works. For each matrix, graph each eigenvector and it's image after the transformation as well as a random NON-eigenvector. Check your graph is accurate by showing the matrix multiplication.

(i) $A = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$, T_A =zero.

(ii) $A = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$, T_A =projection onto y-axis.

(iii) $A = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}$, T_A =rotation by θ.

(and state the values of θ for which A has eigenvectors)

(iv) $A = \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix}$, T_A =reflect about the line "$y = -x$".

(v) $A = \begin{bmatrix} 1 & 0 \\ 0 & 3 \end{bmatrix}$, T_A =stretch in x-direction.

(vi) $A = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$, T_A =shear.

(vii) $A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 2 \end{bmatrix}$, T_A =stretch z-axis.

(viii) $A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix}$, T_A =rotate by 90° about the x-axis.

Week 10: NOTE: This week's assignment doesn't have to be handwritten. (For 1pt) Write a paragraph which explains how eigenvectors/eigenvalues or some other topic from the course are used in a field which interests you. Be specific and put some thought into this. (For 2pt) If your paragraph is not essentially the thing on wikipedia about how bridges have something to do with eigenvalues, but actually give some details or original content then you get 2pts instead of 1pt. (For 3pt) If you also support your research with real math or alternately something creative. This has to include *some mathematical content* but can take *any form whatsoever*. Last year's submissions included a poem, several posters, a few slide-show presentations like using PowerPoint, etc., and quite a few of them actually were pretty decent research project results that I was quite impressed by, but I remember the poem the best; it was funny and it used the right math ideas about linear algebra to *be* funny, which essentially forces that the person *understood* the concepts. It was brilliant.

Please understand the point of this exercise, should you choose to do it: Pick any scientific discipline. I mean ANY. If it is scientific it's ok: how to build a bridge, how do design a new chemical, how to solve some hard algorithmic problem using computers (like how many stars the Netflix algorithm should predict for your enjoyment of the 1977 original version of Disney's Pete's Dragon, for example). Take 5 steps into your chosen scientific field and you will bump into linear algebra. That's the exercise. 1pt is essentially "write down in your own words what wiki has to say about it", 2pts is essentially "do something a little better but without any real math content", and then 3pts is "a pretty good job explaining how a specific concept from linear algebra is used in a scientific field you are interested in", where I will collect and grade these myself so it is up to my subjective expert opinion if what you say is a good job with the math explaining.

Week 11: *This exercise will ask you to explore the equality* $Null(A^T) = (Col(A))^{\perp}$.

This is a **hybrid** exploration: We recommend that you use MATLAB initially to find good vectors (hand calculations not too terrible) for the submission, but you need to submit **hand-written** work with steps shown for the actual submission in Gradescope.

Step 1: Pick two random looking and linearly independent vectors $\vec{u}$ and $\vec{v}$ in $\mathbb{R}^n$ with $n \geq 3$, and use technology to find a vector $\vec{w}$ which is orthogonal to both $\vec{u}$ and $\vec{v}$ by guess-and-check (if after a few attempts you can not find a suitable vector w then proceed to the next step).

Step 2: Next, we will explore how to find all possible vectors w using systems of equations. Starting with an **arbitrary vector** (e.g., `w=[a;b;c;d]` if $n = 4$) write down a system of linear equations coming from the fact that $\vec{u} \cdot \vec{w} = 0$ and $\vec{v} \cdot \vec{w} = 0$ and using the entries of $\vec{u}, \vec{v}$ as coefficients and the entries of $\vec{w}$ as variables.

Solve this system of equations to find a **general solution** to the vectors $\vec{w}$ such that $\vec{w}$ is perpendicular to both $\vec{u}$ and $\vec{v}$. Check that $\vec{u} \cdot \vec{w} = 0$ and $\vec{v} \cdot \vec{w} = 0$. Then, answer the following:

(i) How many equations did you need to solve in order to find a general solution for the $\vec{w}$'s? and how many variables were in each equation?

(ii) Why is **any** vector in Col($[\vec{u}\ \vec{v}]$) perpendicular to $\vec{w}$? Give a short proof.

(iii) Explain in at most two sentences why it is true that for any two vectors $\vec{x}, \vec{y}$ we have that $\vec{x} \cdot \vec{y} = \vec{x}^T \vec{y}$. Your explanation needs to be general, not specific to an example.

(iv) Why is **any** vector in Nul($[\vec{u}\ \vec{v}]^T$) orthogonal to both $\vec{u}$ and $\vec{v}$? Give a short proof.

Week 12: MATLAB #3 - see Sal's website for instructions and supplementary documents.

Week 13: MATLAB #4 - see Sal's website for instructions.

Week 14: Thanksgiving Break, no exploration this week.

Week 13: MATLAB #5 - see Sal's website for instructions.