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3. Mechanical Matrix (12 points)

Consider the matrix \mathbf{A} below:

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

(a) (4 points) **Calculate \mathbf{A}^2 .**

(b) (2 points) **What is $\det(\mathbf{A})$?**

(c) (6 points) **Calculate \mathbf{A}^{-1} , the inverse of \mathbf{A} .**

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4. You Have Null Idea (12 points)

Consider the matrix \mathbf{A} below:

$$\mathbf{A} = \begin{bmatrix} 4 & 1 & 2 \\ 2 & 5 & 1 \\ 6 & 3 & 3 \end{bmatrix}$$

(a) (2 points) **Is \mathbf{A} invertible? Justify your answer.**

(b) (4 points) **Find a basis for the column space of \mathbf{A} .**

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A copy of the matrix for reference: $\mathbf{A} = \begin{bmatrix} 4 & 1 & 2 \\ 2 & 5 & 1 \\ 6 & 3 & 3 \end{bmatrix}$

(c) (6 points) **Find a basis for the null space of \mathbf{A} .**

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5. Diagonalization (8 points)

Consider the matrix \mathbf{A} below:

$$\mathbf{A} = \begin{bmatrix} 6 & -1 \\ 2 & 3 \end{bmatrix}$$

If the matrix \mathbf{A} is diagonalizable as $\mathbf{A} = \mathbf{V}\mathbf{\Lambda}\mathbf{V}^{-1}$, write out the matrices \mathbf{V} , $\mathbf{\Lambda}$, and \mathbf{V}^{-1} explicitly. If the matrix \mathbf{A} is not diagonalizable, explain why.

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6. Vector Space (16 points)

Consider \mathbb{R}^3 , a vector space with the usual operations of matrix addition and scalar matrix multiplication. Let S be the following set of vectors from \mathbb{R}^3 :

$$S = \left\{ \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix} \right\}$$

(a) (2 points) **Is the set S linearly independent or is it linearly dependent? Justify your answer.**

(b) (6 points) Let $\mathbb{W} = \text{span}(S)$. **Show that \mathbb{W} forms a subspace of \mathbb{R}^3 .**

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(c) (6 points) Let $\vec{v} = \begin{bmatrix} 2m \\ m+3 \\ 0 \end{bmatrix}$, $m \in \mathbb{R}$.

For what value(s) of m is $\vec{v} \in \text{span}(S)$?

(d) (2 points) We define a new set

$$S_{\text{new}} = \left\{ \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix}, \begin{bmatrix} 2m \\ m+3 \\ 0 \end{bmatrix} \right\}$$

For what value(s) of m will S_{new} be a valid basis for \mathbb{R}^3 ?

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7. Matrix Trix (10 points)

Let $n \in \{1, 2, \dots\}$ be a positive integer. We define the transformation $T : \mathbb{R}^n \rightarrow \mathbb{R}^n$ as follows:

Given a vector $\vec{x} \in \mathbb{R}^n$, $T(\vec{x})$ reverses the order of the n components in the input vector.

$$\text{Explicitly, } T \left(\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \right) \triangleq \begin{bmatrix} x_n \\ x_{n-1} \\ \vdots \\ x_1 \end{bmatrix}.$$

(a) (2 points) Let's start with an example where $n = 4$. Suppose we have a vector $\vec{a} \in \mathbb{R}^4$, where $\vec{a} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}$.

Then, if we apply the transformation T , we reverse the order of the entries, so $T(\vec{a}) = \begin{bmatrix} a_4 \\ a_3 \\ a_2 \\ a_1 \end{bmatrix}$. **Find the matrix representation \mathbf{A} of the transformation T , such that $T(\vec{a}) = \mathbf{A}\vec{a}$.**

(b) (1 point) We now go back to the general case. Let $n \in \{1, 2, \dots\}$ be a positive integer. Again, $T : \mathbb{R}^n \rightarrow$

\mathbb{R}^n is defined, as described above, as $T \left(\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \right) = \begin{bmatrix} x_n \\ x_{n-1} \\ \vdots \\ x_1 \end{bmatrix}$. Let \mathbf{B} be the matrix representation of the transformation T . **For any $\vec{x} \in \mathbb{R}^n$, write $\mathbf{B}^2\vec{x}$ in terms of \vec{x} .**

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- (c) (7 points) **Show that if λ is an eigenvalue of the matrix \mathbf{B} , then either $\lambda = 1$ or $\lambda = -1$ (that is, λ can't have any value other than 1 or -1).**

Hint: You don't need to write out the matrix \mathbf{B} explicitly.

8. Aw Snap, I'm All Ears (15 points)

One day while Daniel, Vasuki, and Fil are playing with the filters on Snapchat, they realize that what they're teaching in EE16A is sufficient to understand how the animated filters can be adjusted to match different facial structures.

Each animated face filter needs three anchor points to place the filter. The default anchor points are $\vec{p}_1 = \begin{bmatrix} 5 \\ 15 \end{bmatrix}$, $\vec{p}_2 = \begin{bmatrix} 15 \\ 15 \end{bmatrix}$, and $\vec{p}_3 = \begin{bmatrix} 10 \\ 0 \end{bmatrix}$. See Figure 8.1 for an example placement.

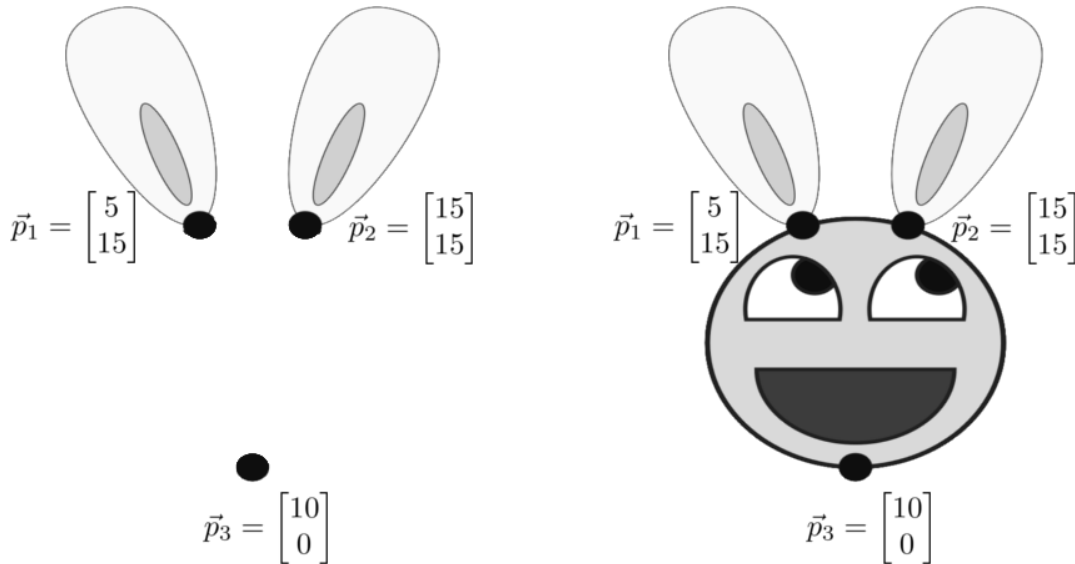


Figure 8.1: Left: bunny ears filter with default anchor points. Right: bunny ears filter placed onto a face using the default anchor points.

However, these default anchor points don't always work for all users. Now, it's up to you to line up each filter's anchor points to the user's face's matching anchor points.

The parts for this problem start on the next page.

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- (a) (3 points) Daniel's anchor points are $\vec{d}_1 = \begin{bmatrix} 12.5 \\ 45 \end{bmatrix}$, $\vec{d}_2 = \begin{bmatrix} 37.5 \\ 45 \end{bmatrix}$, and $\vec{d}_3 = \begin{bmatrix} 25 \\ 0 \end{bmatrix}$ (see Figure 8.2). **Derive a linear transformation matrix A that appropriately scales the default anchor points to fit Daniel's face. Precisely, the transformation should achieve $A\vec{p}_i = \vec{d}_i$ for all $i \in \{1, 2, 3\}$. It should take the form of $A = \begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix}$, $a, b \in \mathbb{R}$. If this is not possible, prove that it is not possible.**

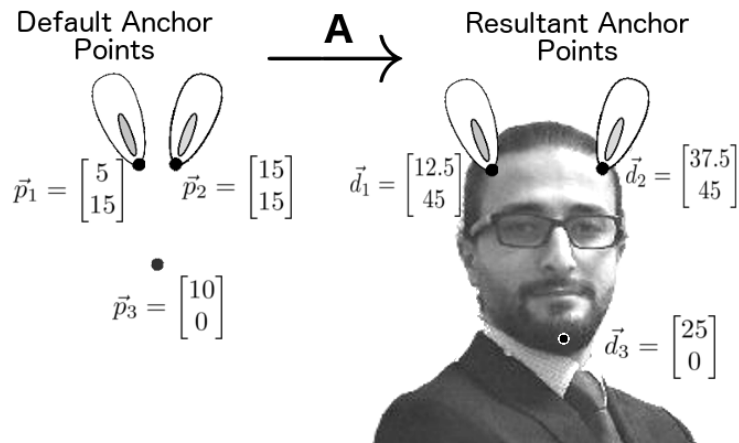


Figure 8.2: Daniel as a bunny.

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- (b) (4 points) Rotation is also important to properly align a filter. Say the user's head is tilted 30° **clockwise**, resulting in the anchor points being at \vec{r}_1, \vec{r}_2 and \vec{r}_3 (see Figure 8.3). **Derive a linear transformation matrix \mathbf{B} that appropriately rotates the default anchor points to match the user's head. Precisely, the derived matrix should achieve $\mathbf{B}\vec{p}_i = \vec{r}_i$ for all $i \in \{1, 2, 3\}$. If this is not possible, prove that it is not possible.**

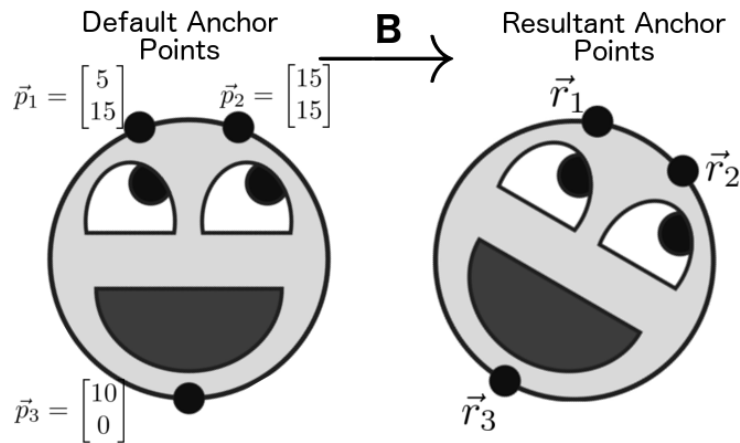


Figure 8.3: Rotation by 30° clockwise.

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- (c) (2 points) Filters should also work on reflections! Vasuki has a mirror positioned as shown in Figure 8.4. The mirror results in Vasuki's anchor points to be at $\vec{v}_1 = \begin{bmatrix} -5 \\ 15 \end{bmatrix}$, $\vec{v}_2 = \begin{bmatrix} -15 \\ 15 \end{bmatrix}$, and $\vec{v}_3 = \begin{bmatrix} -10 \\ 0 \end{bmatrix}$. **Derive a linear transformation matrix C that appropriately reflects the default anchor points to match Vasuki's reflection's face. Precisely, the derived transformation should achieve $C\vec{p}_i = \vec{v}_i$ for all $i \in \{1, 2, 3\}$. If this is not possible, prove that it is not possible.**

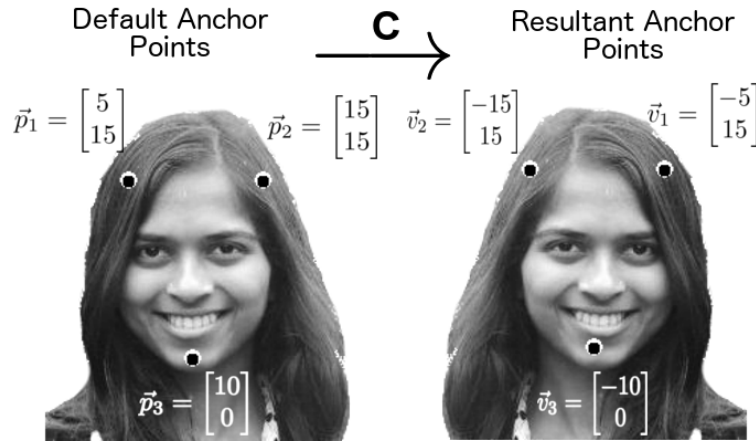


Figure 8.4: Vasuki's face mirrored.

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- (d) (2 points) When the user's head that is both rotated 30° clockwise and then reflected in the mirror, the resultant anchor points are \vec{w}_1, \vec{w}_2 , and \vec{w}_3 (see Figure 8.5). We would like to derive a linear transformation matrix \mathbf{D} that transforms the default anchor points to the user's head in this scenario. Precisely, the derived matrix should achieve $\mathbf{D}\vec{p}_i = \vec{w}_i$ for all $i \in \{1, 2, 3\}$. **Give an expression for \mathbf{D} in terms of \mathbf{B} and \mathbf{C} (you don't have to explicitly calculate the matrix \mathbf{D}). If this is not possible, prove that it is not possible.**

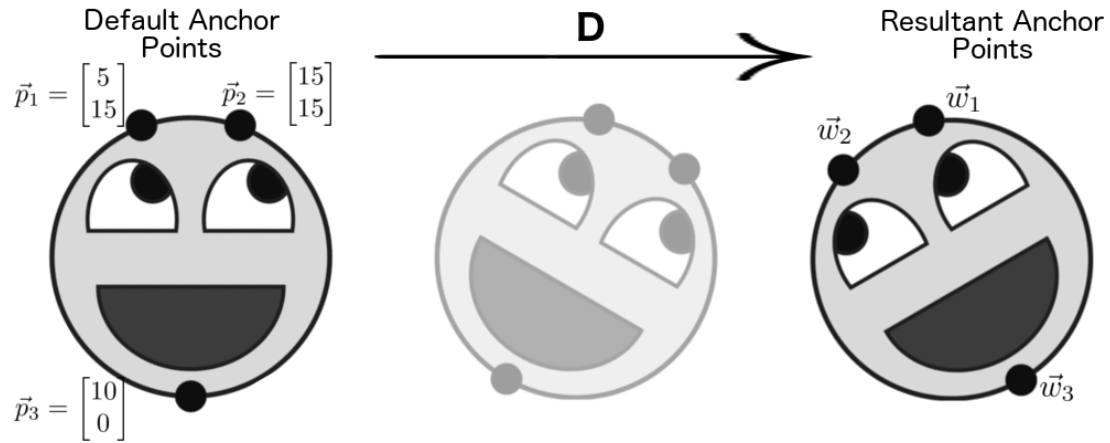


Figure 8.5: Rotation by 30° clockwise followed by mirroring.

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- (e) (4 points) Fil decides that he wants to design his own Snapchat filter that will take just the three default anchor points on a user's face and have it offset the user's body by translation along the x axis by 10 units of length. Fil's desired transformation results in the anchor points being located at $\vec{f}_1 = \begin{bmatrix} 15 \\ 15 \end{bmatrix}$, $\vec{f}_2 = \begin{bmatrix} 25 \\ 15 \end{bmatrix}$, and $\vec{f}_3 = \begin{bmatrix} 20 \\ 0 \end{bmatrix}$ (see Figure 8.6). **Derive a linear transformation matrix E that transforms the default anchor points to Fil's anchor points after translation. Precisely, the derived matrix should achieve $E\vec{p}_i = \vec{f}_i$ for all $i \in \{1, 2, 3\}$. If this is not possible, prove that it is not possible.**

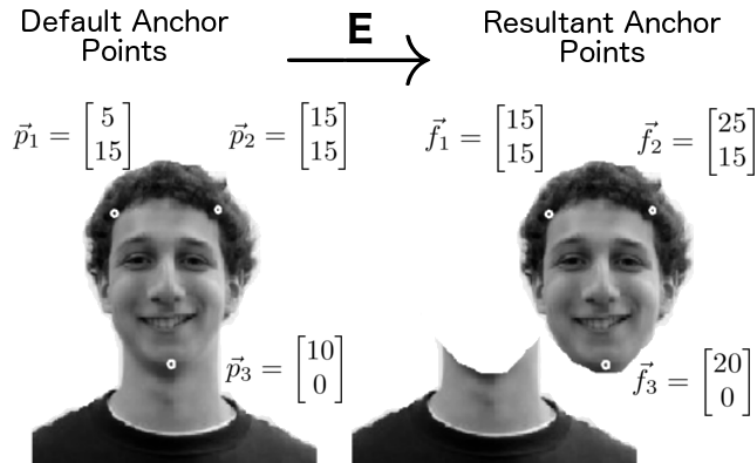


Figure 8.6: The “Fil”-ter.

9. 16A Hogwarts Edition (10 points)

After seeing its success at Berkeley, Hogwarts has decided to add EE16A to its course offerings this semester! You are attending one of their pilot discussion sections on matrix transformations and eigenvalues. In order to teach these concepts, your TA (Hermitian Ranger) has provided a set of cubes. These cubes are matrices that perform a transformation on your position in the coordinate system of your classroom. When the cube is dropped at your feet, it transports you to some new location based on your current one. **Each cube can be modeled with a different matrix transformation T such that $T\vec{x}_i = \vec{x}_f$ where \vec{x}_i is your initial position and \vec{x}_f is your new position after dropping the cube.**

(a) (2 points) You are given a yellow cube to experiment with. The matrix associated with the yellow cube is Y , and your current position in the classroom is $\begin{bmatrix} 2 \\ -3 \end{bmatrix}$. After dropping the yellow cube, you find yourself at position $\begin{bmatrix} -2 \\ 3 \end{bmatrix}$. **Find one of the eigenvalues of Y , λ , and an eigenvector associated with λ . Note that since the yellow cube is given to you, you can't pick an arbitrary Y if you can't uniquely determine Y .**

(b) (6 points) You now start from a new location, $\vec{d} = \begin{bmatrix} 4 \\ 3 \end{bmatrix}$. Your TA presents to you a brown cube B and two green cubes, G_1 and G_2 . She says that you need to use one green cube *and* the brown cube *one after the other*, such that at the end, you are back at your starting point $\vec{d} = \begin{bmatrix} 4 \\ 3 \end{bmatrix}$. Table 9.1 lists the eigenvalue/eigenvector pairs of each of the three cubes in this part. **Which of the two green cubes would you use to achieve this? Prove mathematically that your answer is correct.**

Hint 1: You do not have to explicitly write out the matrices.

Hint 2: In this part, the order in which you use the cubes does not matter.

Table 9.1: Cubes and their eigenpairs.

| Green Cubes | Eigenpairs | Brown Cube | Eigenpairs |
|-------------|--|------------|---|
| G_1 | $\left(2, \begin{bmatrix} 1 \\ -3 \end{bmatrix}\right), \left(-0.5, \begin{bmatrix} 1 \\ 1 \end{bmatrix}\right)$ | B | $\left(0.5, \begin{bmatrix} -1 \\ 1 \end{bmatrix}\right), \left(1, \begin{bmatrix} 2 \\ 0 \end{bmatrix}\right)$ |
| G_2 | $\left(1, \begin{bmatrix} 2 \\ 0 \end{bmatrix}\right), \left(2, \begin{bmatrix} -1 \\ 1 \end{bmatrix}\right)$ | | |

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Extra space for part (b).

- (c) (2 points) **Would the same choice of green cube from part (b) still work if you started from a different location? Justify your answer.**

10. Aww, nuts! (18 points)

In all of your spare time outside of EE 16A, you have started working as a server at San Francisco’s newest bougie chic boutique restaurant, “Brasserie E^22^4A : The Peanut Gallery,” featuring peanut-infused dishes from around the world. One hipster feature of the restaurant’s kitchen is a “peanut sensor” used to prevent delivering plates with allergens to people with peanut allergies. In the figures, each sensor measurement is represented by an arrow, and the output measurement (labeled at the end of the arrow) is equal to the sum of the individual dish readings. **For illustration purposes only**, Figure 10.1 shows an example of a measurement b that satisfies $p_1 + p_2 + p_3 = b$.

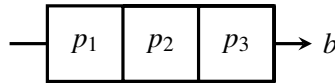


Figure 10.1: Example reading of 3 dishes yielding measurement b **for illustration purposes only**.

Formatting Your Answer: In this problem, whenever you are asked to find all solutions for a vector of variables, say $\vec{p} = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix}$, present the answer in vector format. Examples of acceptable vector formats are:

$$\bullet \vec{p} = \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}. \quad \bullet \vec{p} = \begin{bmatrix} 1 - 3\beta \\ 2 - \alpha + 2\beta \\ 3 + \alpha \end{bmatrix}, \forall \alpha, \beta \in \mathbb{R}. \quad \bullet \vec{p} = \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix} + \alpha \begin{bmatrix} 0 \\ -1 \\ 1 \end{bmatrix} + \beta \begin{bmatrix} -3 \\ 2 \\ 0 \end{bmatrix}, \forall \alpha, \beta \in \mathbb{R}.$$

(a) (2 points) In your first order, there are two dishes. You place them in the peanut sensor as depicted in the following figure (Figure 10.2):

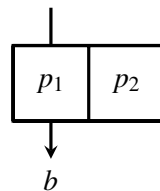


Figure 10.2: Order up! First order.

Let $\vec{p} = \begin{bmatrix} p_1 \\ p_2 \end{bmatrix}$ represent the peanut content in both dishes. Given that the result of your peanut measurement is b , **find all possible solutions for \vec{p} in terms of b and any free variables, if needed.**

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- (b) (2 points) Using the same order from part (a). **Draw the line that represents all possible solutions for \vec{p} for $b = 0$ on the axes below (Figure 10.3) and label the line $b = 0$. Then, on the same set of axes, plot the line that represents all possible solutions for \vec{p} for $b = 1$ and label the line $b = 1$.**

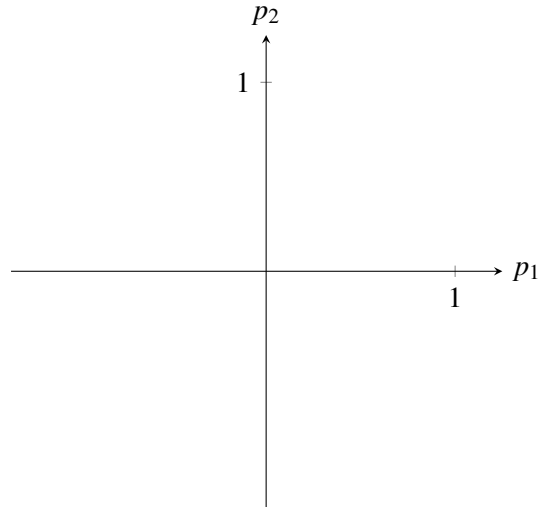


Figure 10.3: Plot the possible peanut content solutions.

- (c) This part of the problem consists of two sub-parts (c)i. and (c)ii.. **Only for both of these sub-parts** do we know the following two pieces of extra information. First, the chef now tells you that, for the same order as in parts (a) and (b), one dish contains peanuts, and the other dish has no peanuts. Second, you set the sensor to work as follows: 1) A dish with peanuts will yield a reading of 1; and 2) a dish without peanuts will yield a reading of 0.

- i. (4 points) **Now find all possible solutions for $\vec{p} = \begin{bmatrix} p_1 \\ p_2 \end{bmatrix}$ for both cases when $b = 0$ and $b = 1$.**

$b = 0$

$b = 1$



- ii. (1 point) Given the new information presented in this part, is the single measurement $b = 0$ or $b = 1$ now sufficient to uniquely determine which of the two dishes in the first order has peanuts? **Circle your answer.**

YES

NO

- (d) (5 points) Now it's time for your second order. This one has four dishes:

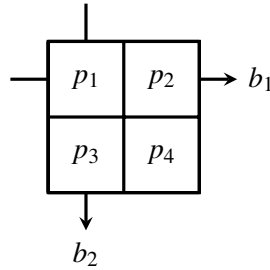


Figure 10.4: Second order!

Let $\vec{p} = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{bmatrix}$ represent the peanut content in the four dishes. Given the two measurements b_1 and b_2 , **find all possible solutions for \vec{p} in terms of b_1 , b_2 , and any free variables, if needed.**

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- (e) (4 points) **Only for this part**, the chef now tells you that, for the same order as in part (d), it is one of the four following layouts of peanut dishes with each set of four dishes containing exactly three peanut dishes (see Figure 10.5). Moreover, only for this part, you once again set the sensor to work as follows: 1) A dish with peanuts will yield a reading of 1; and 2) a dish without peanuts will yield a reading of 0.

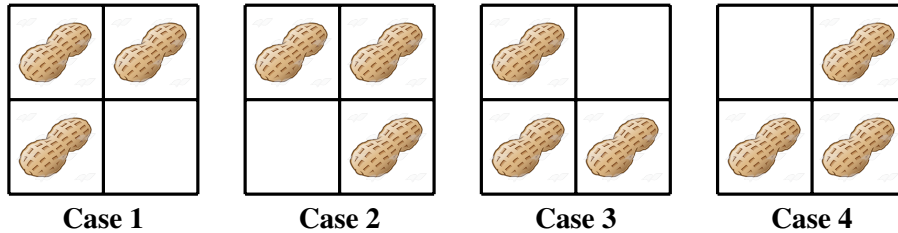


Figure 10.5: Possible Peanut Portioning.

For each of the given arrangements in Figure 10.5, based on the measurement scheme in Figure 10.4, **fill in the values for the measurements b_1 and b_2 in the table below.**

| | Case 1 | Case 2 | Case 3 | Case 4 |
|-------|--------|--------|--------|--------|
| b_1 | | | | |
| b_2 | | | | |

11. StateRank Car Rentals (21 points)

You are an analyst at StateRank Car Rentals, which operates in California, Oregon, and Nevada. You are hired to analyze the number of rental cars going into and out of each of the three states (CA, OR, and NV).

The number of cars in each state on day $n \in \{0, 1, \dots\}$ can be represented by the state vector $\vec{s}[n] = \begin{bmatrix} s_{CA}[n] \\ s_{OR}[n] \\ s_{NV}[n] \end{bmatrix}$.

The state vector follows the state evolution equation $\vec{s}[n+1] = \mathbf{A}\vec{s}[n], \forall n \in \{0, 1, \dots\}$, where the transition matrix, \mathbf{A} , of this linear dynamic system is

$$\mathbf{A} = \begin{bmatrix} 7/10 & 1/10 & 1/10 \\ 1/10 & 6/10 & 1/10 \\ 2/10 & 3/10 & 8/10 \end{bmatrix}.$$

- (a) (3 points) Use the designated boxes in Figure 11.1 to **fill in the weights for the daily travel dynamics of rental cars between the three states**, as described by the state transition matrix \mathbf{A} .

Note the order of the elements in the state vector $\vec{s}[n]$.

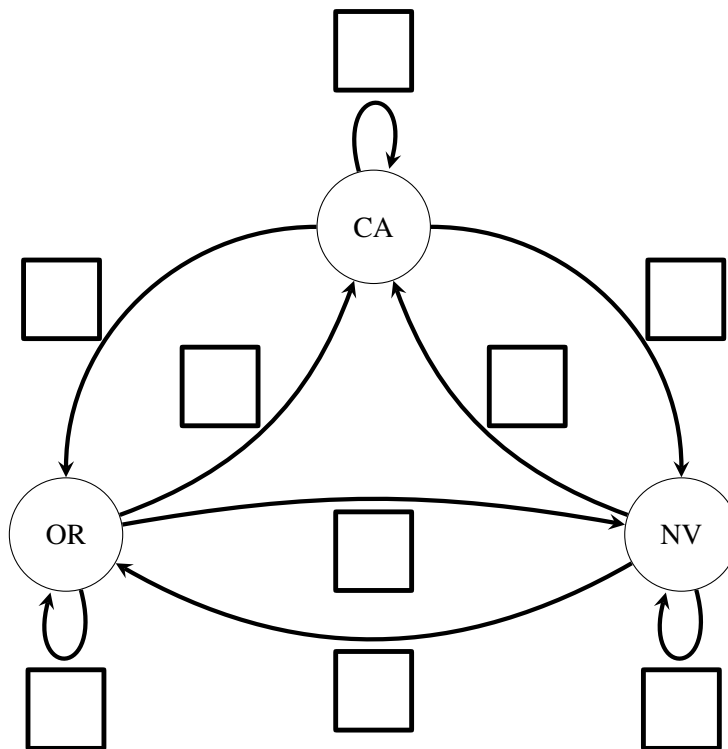


Figure 11.1: StateRank Rental Cars Daily Travel Dynamics.

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A copy of the state transition matrix for reference: $\mathbf{A} = \begin{bmatrix} 7/10 & 1/10 & 1/10 \\ 1/10 & 6/10 & 1/10 \\ 2/10 & 3/10 & 8/10 \end{bmatrix}$

(b) (2 points) Suppose the state vector on day $n = 4$ is $\vec{s}[4] = \begin{bmatrix} 100 \\ 200 \\ 100 \end{bmatrix}$. Calculate the state vector on day 5, $\vec{s}[5]$.

(c) (2 points) We want to express the number of cars in each state on day n as a function of the initial number of cars in each state on day 0. That is, we write $\vec{s}[n]$ in terms of $\vec{s}[0]$ as follows:

$$\vec{s}[n] = \mathbf{B}\vec{s}[0]$$

Express the matrix \mathbf{B} in terms of \mathbf{A} and n .

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A copy of the state transition matrix for reference: $\mathbf{A} = \begin{bmatrix} 7/10 & 1/10 & 1/10 \\ 1/10 & 6/10 & 1/10 \\ 2/10 & 3/10 & 8/10 \end{bmatrix}$

(d) (4 points) We denote the eigenvalue/eigenvector pairs of the matrix \mathbf{A} by

$$\left(\lambda_1 = 1, \vec{u}_1 = \begin{bmatrix} 50 \\ 40 \\ 110 \end{bmatrix} \right), \left(\lambda_2, \vec{u}_2 = \begin{bmatrix} 0 \\ -10 \\ 10 \end{bmatrix} \right), \text{ and } \left(\lambda_3, \vec{u}_3 = \begin{bmatrix} -10 \\ 0 \\ 10 \end{bmatrix} \right).$$

Find the eigenvalues λ_2 and λ_3 corresponding to the eigenvectors \vec{u}_2 and \vec{u}_3 , respectively. Note that since $\lambda_1 = 1$ is given, you don't have to calculate it.

(e) (2 points) For the given dynamics in this problem, **does a matrix \mathbf{C} exist such that $\vec{s}[n-1] = \mathbf{C}\vec{s}[n]$, for $n \in \{1, 2, \dots\}$?** **Justify your answer.**

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A copy of the state transition matrix for reference: $\mathbf{A} = \begin{bmatrix} 7/10 & 1/10 & 1/10 \\ 1/10 & 6/10 & 1/10 \\ 2/10 & 3/10 & 8/10 \end{bmatrix}$

(f) (8 points) Suppose that the initial number of rental cars in each state on day 0 is

$$\vec{s}[0] = \begin{bmatrix} 7000 \\ 5000 \\ 8000 \end{bmatrix} = 100\vec{u}_1 - 100\vec{u}_2 - 200\vec{u}_3,$$

where \vec{u}_1, \vec{u}_2 and \vec{u}_3 are the eigenvectors from part (d).

After a very large number of days n , how many rental cars will there be in each state?

That is, i) calculate

$$\vec{s}^* = \lim_{n \rightarrow \infty} \vec{s}[n]$$

and ii) show that the system will indeed converge to \vec{s}^* as $n \rightarrow \infty$ if it starts from $\vec{s}[0]$.

Hint: If you didn't solve part (d), the eigenvalues satisfy $\lambda_1 = 1, |\lambda_2| < 1$ and $|\lambda_3| < 1$.

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Extra page for scratchwork.

If you want any work on this page to be graded, please refer to this page on the problem's main page.