

## Problem

(20 points) *Linear vector fields and maps.*

- (a) For the following linear ODE, compute the stable, unstable, and center subspaces  $E^s$ ,  $E^u$ ,  $E^c$  of the origin. Sketch these subspaces and some representative trajectories of the system in the phase space.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 1 & -3 & 3 \\ 3 & -5 & 3 \\ 6 & -6 & 4 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

- (b) For the following linear map on  $\mathbb{R}^2$ , compute the stable, unstable, and center subspaces  $E^s$ ,  $E^u$ ,  $E^c$  of the origin. What are the qualitative differences in the dynamics between  $\lambda < 0$ ,  $\lambda = 0$ , and  $\lambda > 0$ ? Sketch the subspaces and some representative trajectories of the system in the phase space.

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \mapsto \begin{bmatrix} 1 & -1 \\ 0 & \lambda \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \quad |\lambda| < 1.$$


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## Notes

**Part (a)** Let's start with finding the eigenvalues. It's a slog, but we can write

$$A - \lambda I = \begin{bmatrix} 1 & -3 & 3 \\ 3 & -5 & 3 \\ 6 & -6 & 4 \end{bmatrix} - \lambda \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1-\lambda & -3 & 3 \\ 3 & -5-\lambda & 3 \\ 6 & -6 & 4-\lambda \end{bmatrix}$$

where the eigenvalues are computed as  $\det(A - \lambda I) = 0$ . Thankfully, we can use the formula for  $3 \times 3$  matrix determinants of

$$a_1(b_2c_3 - b_3c_2) - a_2(b_1c_3 - b_3c_1) + a_3(b_1c_2 - b_2c_1)$$

Plugging everything in we get

$$\begin{aligned} & (1-\lambda)((-5-\lambda)(4-\lambda) - 3(-6)) - (-3)(3(4-\lambda) - 3 \cdot 6) + (3)(3(-6) - (-5-\lambda) \cdot 6) \\ & ((1-\lambda)(-5-\lambda)(4-\lambda) + 18(1-\lambda)) + (9(4-\lambda) - 54) + (-54 - 18(-5-\lambda)) \\ & ((-5+4\lambda+\lambda^2)(4-\lambda) + 18 - 18\lambda) + (36 - 9\lambda - 54) + (-54 + 90 + 18\lambda) \\ & (-20 + 21\lambda - \lambda^3) + 18 - 18\lambda + 36 - 9\lambda - 54 - 54 + 90 + 18\lambda \\ & (-20 + 18 + 36 - 54 - 54 + 90) + (21 - 18 - 9 + 18)\lambda + \lambda^3 \\ & 16 + 12\lambda + \lambda^3 \end{aligned}$$

Setting it equal to zero and doing some factorization, we get

$$\begin{aligned} & 16 + 12\lambda + \lambda^3 = 0 \\ & (4-\lambda)(4+4x+x^2) = 0 \\ & (4-\lambda)(2+\lambda)(2+\lambda) = 0 \end{aligned}$$

where it follows that the eigenvalues are  $\lambda_1 = 4$ ,  $\lambda_2 = -2$ , and  $\lambda_3 = -2$ .

To find eigenvalues, we can solve for the equation

$$\begin{bmatrix} 1 - \lambda & -3 & 3 \\ 3 & -5 - \lambda & 3 \\ 6 & -6 & 4 - \lambda \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

for each eigenvalue. Starting with  $\lambda_1 = 4$ , we have

$$\begin{bmatrix} 1 - 4 & -3 & 3 \\ 3 & -5 - 4 & 3 \\ 6 & -6 & 4 - 4 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} -3 & -3 & 3 \\ 3 & -9 & 3 \\ 6 & -6 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

where the last row implies that  $x_1 = x_2$ . Plugging that into the expression  $-3x_1 - 3x_2 + 3x_3 = 0$ , we have

$$\begin{aligned} -3x_1 - 3x_1 + 3x_3 &= 0 \\ -6x_1 + 3x_3 &= 0 \\ x_3 &= 2x_1 \end{aligned}$$

Choosing  $x_1 = 1$ , we have an eigenvector corresponding to the eigenvalue  $\lambda_1 = 4$  of

$$v_1 = \begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix}$$

Moving on to the eigenvalue  $\lambda_{2,3} = -2$ , we can write

$$\begin{bmatrix} 1 + 2 & -3 & 3 \\ 3 & -5 + 2 & 3 \\ 6 & -6 & 4 + 2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} 3 & -3 & 3 \\ 3 & -3 & 3 \\ 6 & -6 & 6 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

and since all rows are the same, we are justified in writing

$$x_3 = -x_1 + x_2$$

where the eigenvectors corresponding to  $\lambda_{2,3} = -2$  span this plane. Choosing two arbitrarily, we have

$$v_2 = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}, \quad v_3 = \begin{bmatrix} -1 \\ 0 \\ -1 \end{bmatrix}$$

Compiling our work into the stable, unstable, and center subspaces  $E^s$ ,  $E^u$ ,  $E^c$ , we can write

$$\begin{aligned} E^u &= \text{span} \left\{ \begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix} \right\} \\ E^s &= \text{span} \left\{ \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}, \begin{bmatrix} -1 \\ 0 \\ -1 \end{bmatrix} \right\} \\ E^c &= \text{span} \{0\} \end{aligned}$$

**Part (b)** Okay so we can use SymPy to do the eigenvalues and eigenvectors. Praise be. We have

$$\left[ \left( \text{eigenvalue } 1, \text{ eigenvector } \begin{bmatrix} 1 \\ 0 \end{bmatrix} \right), \left( \text{eigenvalue } \lambda, \text{ eigenvector } \begin{bmatrix} -\frac{1}{\lambda-1} \\ 1 \end{bmatrix} \right) \right]$$

Compiling our “work” into the stable, unstable, and center subspaces  $E^s$ ,  $E^u$ ,  $E^c$ , we can write

$$\begin{aligned} E^u &= \text{span} \left\{ \begin{bmatrix} -\frac{1}{\lambda-1} \\ 1 \end{bmatrix} \right\} \\ E^s &= \text{span} \{0\} \\ E^c &= \text{span} \left\{ \begin{bmatrix} 1 \\ 0 \end{bmatrix} \right\} \end{aligned}$$

**[Nudge] Hint**

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You’re in great shape on part (a). For part (b), remember that the stability criteria for maps differ from flows — think carefully about what determines whether an eigenvalue corresponds to  $E^s$ ,  $E^u$ , or  $E^c$  for a \*discrete\* map, and how the sign/magnitude of  $\lambda$  affects which subspace each eigenvector belongs to.

Ah yes that’s right. I assigned the eigenvector to the unstable subspace instead of stable because  $|\lambda| < 1$

$$\begin{aligned} E^s &= \text{span} \left\{ \begin{bmatrix} -\frac{1}{\lambda-1} \\ 1 \end{bmatrix} \right\} \\ E^u &= \text{span} \{0\} \\ E^c &= \text{span} \left\{ \begin{bmatrix} 1 \\ 0 \end{bmatrix} \right\} \end{aligned}$$

## Solution