

$$\text{Solve } \mathbf{x}'(t) = \begin{bmatrix} 1 & 3 \\ 4 & 5 \end{bmatrix} \mathbf{x}(t)$$

**Step 1. Find eigenvalues:**

$$\begin{aligned} A - \lambda I &= \begin{vmatrix} 1 - \lambda & 3 \\ 4 & 5 - \lambda \end{vmatrix} = (1 - \lambda)(5 - \lambda) - 12 \\ &= \lambda^2 - 6\lambda + 5 - 12 = \lambda^2 - 6\lambda - 7 = (\lambda - 7)(\lambda + 1) = 0 \end{aligned}$$

Thus  $\lambda = 7, -1$

**Step 2. Find eigenvectors:**

$$\lambda = 7: \quad A - 7I = \begin{bmatrix} 1 - 7 & 3 \\ 4 & 5 - 7 \end{bmatrix} = \begin{bmatrix} -6 & 3 \\ 4 & -2 \end{bmatrix}$$

$$\text{Note } \begin{bmatrix} -6 & 3 \\ 4 & -2 \end{bmatrix} \begin{bmatrix} 1 \\ 2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Note the dimension of the nullspace of  $\begin{bmatrix} -6 & 3 \\ 4 & -2 \end{bmatrix}$  is 1.

Or in other words, solution space for

$$\begin{bmatrix} -6 & 3 \\ 4 & -2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \text{ is 1-dimensional}$$

Thus a basis for the eigenspace for  $\lambda = 7$  is  $\left\{ \begin{bmatrix} 1 \\ 2 \end{bmatrix} \right\}$

$$\lambda = -1 \quad A - (-1)I = \begin{bmatrix} 1+1 & 3 \\ 4 & 5+1 \end{bmatrix} = \begin{bmatrix} 2 & 3 \\ 4 & 6 \end{bmatrix}$$

$$\text{Note } \begin{bmatrix} 2 & 3 \\ 4 & 6 \end{bmatrix} \begin{bmatrix} 3 \\ -2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Thus a basis for the eigenspace for  $\lambda = -1$  is  $\left\{ \begin{bmatrix} 3 \\ -2 \end{bmatrix} \right\}$

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Thus a basis for the solution space to  $\mathbf{x}' = \begin{bmatrix} 1 & 3 \\ 4 & 5 \end{bmatrix} \mathbf{x}$  is

$$\left\{ \begin{bmatrix} 1 \\ 2 \end{bmatrix} e^{7t}, \begin{bmatrix} 3 \\ -2 \end{bmatrix} e^{-t} \right\}$$

Hence the general solution is

$$\mathbf{x}(t) = c_1 \begin{bmatrix} 1 \\ 2 \end{bmatrix} e^{7t} + c_2 \begin{bmatrix} 3 \\ -2 \end{bmatrix} e^{-t}$$

Note we can take any basis for the solution space to create the general solution

$$\text{Alternate basis: } \left\{ \begin{bmatrix} 2 \\ 4 \end{bmatrix} e^{7t}, \begin{bmatrix} -9 \\ 6 \end{bmatrix} e^{-t} \right\}$$

Alternate format of general solution:

$$\mathbf{x}(t) = c_1 \begin{bmatrix} 2 \\ 4 \end{bmatrix} e^{7t} + c_2 \begin{bmatrix} -9 \\ 6 \end{bmatrix} e^{-t}$$

$$\text{IVP: } \mathbf{x}' = \begin{bmatrix} 1 & 3 \\ 4 & 5 \end{bmatrix} \mathbf{x}, \quad \mathbf{x}(0) = \begin{bmatrix} e \\ f \end{bmatrix}$$

$$\begin{bmatrix} e \\ f \end{bmatrix} = c_1 \begin{bmatrix} 1 \\ 2 \end{bmatrix} + c_2 \begin{bmatrix} 3 \\ -2 \end{bmatrix} = \begin{bmatrix} c_1 + 3c_2 \\ 2c_1 - 2c_2 \end{bmatrix}$$

Solve using any method you like. We will use matrix form:

$$\begin{bmatrix} e \\ f \end{bmatrix} = \begin{bmatrix} 1 & 3 \\ 2 & -2 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$$

Solution exists if Wronskian evaluated at 0 is not zero.

$$\begin{aligned} W \left( \begin{bmatrix} 1 \\ 2 \end{bmatrix} e^{7t}, \begin{bmatrix} 3 \\ -2 \end{bmatrix} e^{-t} \right) &= \begin{vmatrix} e^{7t} & 3e^{-t} \\ 2e^{7t} & -2e^{-t} \end{vmatrix} \\ &= -2e^{6t} - 6e^{6t} = -8e^{6t} \neq 0 \end{aligned}$$

$$\text{Fundamental matrix: } \Psi(t) = \begin{bmatrix} e^{7t} & 3e^{-t} \\ 2e^{7t} & -2e^{-t} \end{bmatrix}$$

$$\text{Back to IVP: } \begin{bmatrix} e \\ f \end{bmatrix} = \begin{bmatrix} 1 & 3 \\ 2 & -2 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 3 \\ 2 & -2 \end{bmatrix}^{-1} \begin{bmatrix} e \\ f \end{bmatrix} = \begin{bmatrix} 1 & 3 \\ 2 & -2 \end{bmatrix}^{-1} \begin{bmatrix} 2 & 3 \\ 2 & -2 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$$

$$\text{Thus } \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} 1 & 3 \\ 2 & -2 \end{bmatrix}^{-1} \begin{bmatrix} e \\ f \end{bmatrix}$$

But I would prefer a fundamental matrix whose inverse is easier to calculate, at least when  $t_0 = 0$ .

Thus we will find another basis for the solution set to  $\mathbf{x}' = A\mathbf{x}$  so that the corresponding fundamental matrix  $\Phi$  has the property that  $\Phi(0) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ , the 2x2 identity matrix via long method:

**Step 1: Solve IVP:**  $\mathbf{x}' = A\mathbf{x}$ ,  $\mathbf{x}(0) = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$

$$\begin{bmatrix} 1 \\ 0 \end{bmatrix} = c_1 \begin{bmatrix} 1 \\ 2 \end{bmatrix} e^0 + c_2 \begin{bmatrix} 3 \\ -2 \end{bmatrix} e^0 = \begin{bmatrix} 1 & 3 \\ 2 & -2 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$$

$$\begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & 3 \\ 2 & -2 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} \text{ implies } \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} 1 & 3 \\ 2 & -2 \end{bmatrix}^{-1} \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$\left(-\frac{1}{8}\right) \begin{bmatrix} -2 & -3 \\ -2 & 1 \end{bmatrix} \begin{bmatrix} 1 & 3 \\ 2 & -2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 3 \\ 2 & -2 \end{bmatrix}^{-1} = \begin{bmatrix} \frac{1}{4} & \frac{3}{8} \\ \frac{1}{4} & -\frac{1}{8} \end{bmatrix} \quad \& \quad \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{4} & \frac{3}{8} \\ \frac{1}{4} & -\frac{1}{8} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{1}{4} \\ \frac{1}{4} \end{bmatrix}$$

Thus IVP solution where  $\mathbf{x}(0) = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$  is

$$\mathbf{x}(t) = \frac{1}{4} \begin{bmatrix} 1 \\ 2 \end{bmatrix} e^{7t} + \frac{1}{4} \begin{bmatrix} 3 \\ -2 \end{bmatrix} e^{-t} = \begin{bmatrix} \frac{1}{4}e^{7t} + \frac{3}{4}e^{-t} \\ \frac{1}{2}e^{7t} - \frac{1}{2}e^{-t} \end{bmatrix}$$

**Step 2: Solve IVP:**  $\mathbf{x}' = A\mathbf{x}$ ,  $\mathbf{x}(0) = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$

$$\begin{bmatrix} 0 \\ 1 \end{bmatrix} = c_1 \begin{bmatrix} 1 \\ 2 \end{bmatrix} e^0 + c_2 \begin{bmatrix} 3 \\ -2 \end{bmatrix} e^0 = \begin{bmatrix} 1 & 3 \\ 2 & -2 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$$

$$\text{Thus } \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{4} & \frac{3}{8} \\ \frac{1}{4} & -\frac{1}{8} \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} \frac{3}{8} \\ -\frac{1}{8} \end{bmatrix}$$

Thus IVP solution where  $\mathbf{x}(0) = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$  is

$$\mathbf{x}(t) = \frac{3}{8} \begin{bmatrix} 1 \\ 2 \end{bmatrix} e^{7t} - \frac{1}{8} \begin{bmatrix} 3 \\ -2 \end{bmatrix} e^{-t} = \begin{bmatrix} \frac{3}{8}e^{7t} - \frac{3}{8}e^{-t} \\ \frac{3}{4}e^{7t} + \frac{1}{4}e^{-t} \end{bmatrix}$$

Thus another basis for the solution space to  $\mathbf{x}' = \begin{bmatrix} 1 & 3 \\ 4 & 5 \end{bmatrix} \mathbf{x}$

$$\text{is } \left\{ \begin{bmatrix} \frac{1}{4}e^{7t} + \frac{3}{4}e^{-t} \\ \frac{1}{2}e^{7t} - \frac{1}{2}e^{-t} \end{bmatrix}, \begin{bmatrix} \frac{3}{8}e^{7t} - \frac{3}{8}e^{-t} \\ \frac{3}{4}e^{7t} + \frac{1}{4}e^{-t} \end{bmatrix} \right\}$$

Its corresponding fundamental matrix is

$$\Phi(t) = \begin{bmatrix} \frac{1}{4}e^{7t} + \frac{3}{4}e^{-t} & \frac{3}{8}e^{7t} - \frac{3}{8}e^{-t} \\ \frac{1}{2}e^{7t} - \frac{1}{2}e^{-t} & \frac{3}{4}e^{7t} + \frac{1}{4}e^{-t} \end{bmatrix}$$

Thus to solve IVP where  $\mathbf{x}(t_0) = \begin{bmatrix} e \\ f \end{bmatrix}$ , we solve

$$\begin{bmatrix} e \\ f \end{bmatrix} = \begin{bmatrix} \frac{1}{4}e^{7t_0} + \frac{3}{4}e^{-t_0} & \frac{3}{8}e^{7t_0} - \frac{3}{8}e^{-t_0} \\ \frac{1}{2}e^{7t_0} - \frac{1}{2}e^{-t_0} & \frac{3}{4}e^{7t_0} + \frac{1}{4}e^{-t_0} \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$$

When  $t_0 = 0$ . I.e., we have an IVP where  $\mathbf{x}(0) = \begin{bmatrix} e \\ f \end{bmatrix}$

$$\begin{bmatrix} e \\ f \end{bmatrix} = \begin{bmatrix} \frac{1}{4}e^0 + \frac{3}{4}e^0 & \frac{3}{8}e^0 - \frac{3}{8}e^0 \\ \frac{1}{2}e^0 - \frac{1}{2}e^0 & \frac{3}{4}e^0 + \frac{1}{4}e^0 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$$

which simplifies to

$$\begin{bmatrix} e \\ f \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$$

In other words,  $c_1 = e$  and  $c_2 = f$ .



$x' = \{\{1, 3\}, \{4, 5\}\}^*x$  ☆ ☰

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Input:

$$\vec{x}'(t) = \begin{pmatrix} 1 & 3 \\ 4 & 5 \end{pmatrix} \cdot \vec{x}(t)$$

ODE classification:

First-order system of linear differential equations

Differential equation solution:

$$\vec{x}(t) = \begin{pmatrix} \frac{1}{4}c_1 e^{-t}(e^{8t} + 3) + \frac{3}{8}c_2 e^{-t}(e^{8t} - 1) \\ \frac{1}{2}c_1 e^{-t}(e^{8t} - 1) + \frac{1}{4}c_2 e^{-t}(3e^{8t} + 1) \end{pmatrix}$$