

# Title Undecided

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**Question:** Given that

$$f(t) = e^{-at}u(t) + e^{bt}u(-t) \quad (1.1)$$

$$u(t) = \begin{cases} 0, & t < 0 \\ \frac{1}{2}, & t = 0 \\ 1, & t > 0 \end{cases} \quad (1.2)$$

$$\int_{-\infty}^{\infty} f(t) dt = 1 \quad (1.3)$$

Find the possible values of  $(a, b)$  if these are the end points of the latus recta of the associated conic. Plot  $f(t)$  for these values of  $(a, b)$

**Solution:** We expand the integral as

$$\int_{-\infty}^{\infty} f(t) dt = \int_{-\infty}^0 f(t) dt + \int_0^{\infty} g(t) dt \quad (1.4)$$

$$= \int_{-\infty}^0 e^{bt} dt + \int_0^{\infty} e^{-at} dt \quad (1.5)$$

$$= \frac{1}{b} + \frac{1}{a} \quad (1.6)$$

Substituting (1.3) in (1.6)

$$\frac{1}{a} + \frac{1}{b} = 1 \quad (1.7)$$

$$ab - a - b = 0 \quad (1.8)$$

Which is the equation of a conic. If we take  $a$  to be  $x$  and  $b$  to be  $y$  and then express this as a conic in standard form we get

$$g(\mathbf{x}) = \mathbf{x}^T \mathbf{V} \mathbf{x} + 2\mathbf{u}^T \mathbf{x} + f \quad (1.9)$$

By comparison we obtain:

$$\mathbf{V} = \begin{pmatrix} 0 & \frac{1}{2} \\ \frac{1}{2} & 0 \end{pmatrix} \quad (1.10)$$

$$\mathbf{u} = \begin{pmatrix} -\frac{1}{2} \\ \frac{1}{2} \end{pmatrix} \quad (1.11)$$

$$f = 0 \quad (1.12)$$

We eigen decompose  $\mathbf{V}$  as

$$\mathbf{V} = \mathbf{P}\mathbf{D}\mathbf{P}^T \quad (1.13)$$

$$\mathbf{P} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \quad (1.14)$$

$$\mathbf{D} = \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{-1}{2} \end{pmatrix} \quad (1.15)$$

And convert the conic into a standard conic to make it simpler to solve using affine transformations.

$$\mathbf{y}^T \left( \frac{\mathbf{D}}{f_0} \right) \mathbf{y} = 1 \quad (1.16)$$

$$\mathbf{x} = \mathbf{P}\mathbf{y} + \mathbf{c} \quad (1.17)$$

$$(1.18)$$

Where

$$f_0 = \mathbf{u}^T \mathbf{V}^{-1} \mathbf{u} - f = 1 \quad (1.19)$$

$$\mathbf{c} = -\mathbf{V}^{-1} \mathbf{u} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (1.20)$$

Since eigenvalues of  $\mathbf{D}$  are  $\lambda_1 = \frac{1}{2}$  and  $\lambda_2 = -\frac{1}{2}$  We use another transformation to shift the negative eigenvalue of  $\mathbf{D}$  to get the hyperbola in standard form, finally giving us

$$\mathbf{z}^T \left( \frac{\mathbf{D}_0}{f_0} \right) \mathbf{z} = 1 \quad (1.21)$$

$$\mathbf{z}^T \mathbf{D}_0 \mathbf{z} - f_0 = 0 \quad (1.22)$$

$$\mathbf{y} = \mathbf{P}_0 \mathbf{z} \quad (1.23)$$

$$(1.24)$$

Here  $\mathbf{P}_0$  is the reflection matrix  $\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$  and  $\mathbf{D}_0$  is defined as

$$\mathbf{D} = \mathbf{P}_0 \mathbf{D}_0 \mathbf{P}_0^T \quad (1.25)$$

$$\mathbf{P}_0^T \mathbf{D} \mathbf{P}_0 = \mathbf{D}_0 \quad (1.26)$$

$$\mathbf{D}_0 = \begin{pmatrix} -\frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix} \quad (1.27)$$

Now we solve to find the endpoints of the latus recta of this standard conic

$$\mathbf{n} = \sqrt{\lambda_2} \mathbf{p}_1 = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} \end{pmatrix} \quad (1.28)$$

$$e = \sqrt{1 - \frac{\lambda_1}{\lambda_2}} = \sqrt{2} \quad (1.29)$$

$$c = \frac{e \mathbf{u}^T \mathbf{n} \pm \sqrt{e^2 (\mathbf{u}^T \mathbf{n})^2 - \lambda_2 (e^2 - 1) (\|\mathbf{u}\|^2 - \lambda_2 f)}}{\lambda_2 e (e^2 - 1)} \quad (1.30)$$

$$= \pm \frac{1}{\sqrt{2}} \quad (1.31)$$

$$\mathbf{F} = \frac{ce^2 \mathbf{n} - \mathbf{u}}{\lambda_2} = \pm 2 \mathbf{e}_2 \quad (1.32)$$

$$(1.33)$$

Equation of latus recta is

$$\mathbf{n}^T \mathbf{x} = \mathbf{n}^T \mathbf{F} \quad (1.34)$$

$$\equiv \mathbf{n}^T \mathbf{x} = \sqrt{2} \quad (1.35)$$

Let  $\hat{\mathbf{z}}$  be the endpoints of the latus recta.

From (1.35) we can say  $\hat{\mathbf{z}}$  is of the form  $\begin{pmatrix} k_i \\ \pm 2 \end{pmatrix}$ . Substituting back in (1.22)

$$\mathbf{z}^T \mathbf{D}_0 \mathbf{z} - f_0 = 0 \quad (1.36)$$

$$-\frac{k_i^2}{2} + 2 - 1 = 0 \quad (1.37)$$

$$k_i^2 = 2 \quad (1.38)$$

$$k_i = \pm \sqrt{2} \quad (1.39)$$

$$\therefore \hat{\mathbf{z}} = \begin{pmatrix} \pm \sqrt{2} \\ \pm 2 \end{pmatrix} \quad (1.40)$$

Now transforming  $\hat{\mathbf{z}}$  back using (1.17), (1.23) to get endpoints of original conic  $\hat{\mathbf{x}}$ .

$$\hat{\mathbf{x}} = \mathbf{P}(\mathbf{P}_0 \hat{\mathbf{z}}) + \mathbf{c} \quad (1.41)$$

Which gives us values of  $\hat{\mathbf{x}}$  to be

$$\hat{\mathbf{x}}_1 = \begin{pmatrix} 2 + \sqrt{2} \\ \sqrt{2} \end{pmatrix}$$

$$\hat{\mathbf{x}}_2 = \begin{pmatrix} \sqrt{2} \\ 2 + \sqrt{2} \end{pmatrix}$$

$$\hat{\mathbf{x}}_3 = \begin{pmatrix} 2 - \sqrt{2} \\ -\sqrt{2} \end{pmatrix}$$

$$\hat{\mathbf{x}}_4 = \begin{pmatrix} -\sqrt{2} \\ 2 - \sqrt{2} \end{pmatrix}$$

We can plot out the original conic in (1.9) to verify our solution

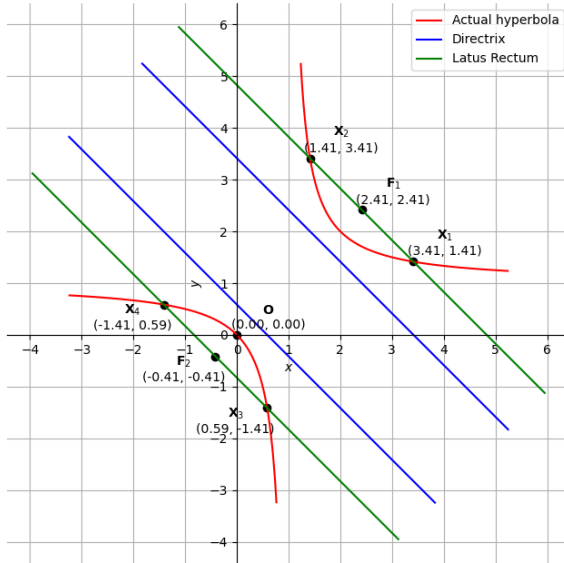


Fig. 1.1

Out of these,  $\hat{\mathbf{x}}_1$  and  $\hat{\mathbf{x}}_3$  are unfit to be used as values for  $(a, b)$  as negative values of  $a$  or  $b$  will cause  $f(t)$  to tend to infinity near  $t = 0$  and thus the integral in (1.3) will not converge and condition will not be met.

Lastly, We plot the function  $f(t)$  for  $(a, b) = \hat{\mathbf{x}}_2$  and  $(a, b) = \hat{\mathbf{x}}_4$

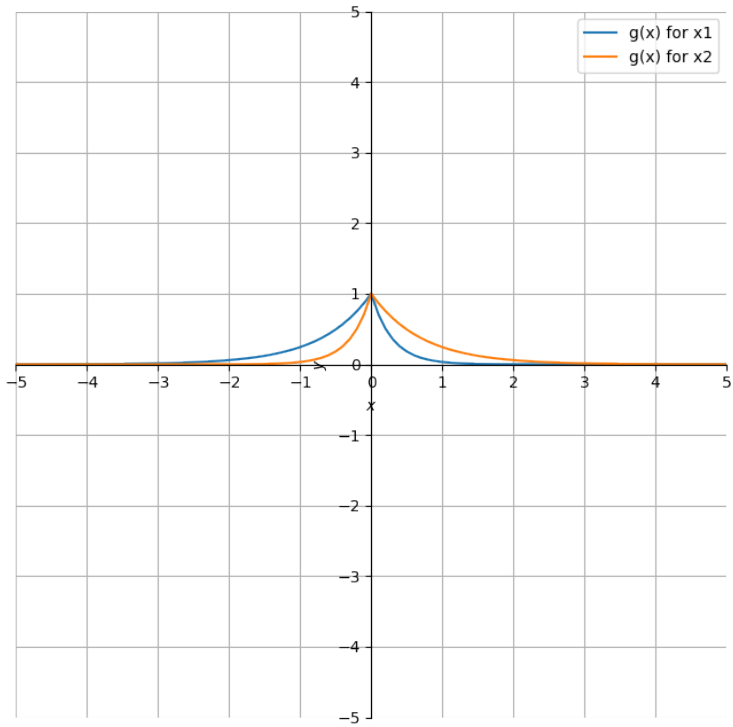


Fig. 1.2

Code for Figures 1.1 and 1.2 can be found at:

`Codes/solution.py`