Systems of Differential Equations and Laplace's Method

- Solving $\boldsymbol{x}' = C\boldsymbol{x}$
- The Resolvent
- An Illustration for $\mathbf{x}' = C\mathbf{x}$

Solving $x' = Cx$

Apply $\boldsymbol{L}$ to each side to obtain $\boldsymbol{L}(\mathrm{x}') = \boldsymbol{C}\boldsymbol{L}(\mathrm{x})$. Use the parts rule

$$\boldsymbol{L}(\mathrm{x}') = \boldsymbol{s}\boldsymbol{L}(\boldsymbol{x}) - \mathrm{x}(0)$$

to obtain

$$\begin{array}{rcl} \boldsymbol{s}\boldsymbol{L}(\mathrm{x}) - \mathrm{x}(0) & = & \boldsymbol{L}(\boldsymbol{C}\mathrm{x}) \\ \boldsymbol{s}\boldsymbol{L}(\mathrm{x}) - \boldsymbol{L}(\boldsymbol{C}\mathrm{x}) & = & \mathrm{x}(0) \\ \boldsymbol{s}\boldsymbol{I}\,\boldsymbol{L}(\mathrm{x}) - \boldsymbol{C}\,\boldsymbol{L}(\mathrm{x}) & = & \mathrm{x}(0) \\ (\boldsymbol{s}\boldsymbol{I} - \boldsymbol{C})\boldsymbol{L}(\mathrm{x}) & = & \mathrm{x}(0). \end{array}$$

Resolvent

The inverse of $\boldsymbol{s}\boldsymbol{I} - \boldsymbol{C}$ is called the **resolvent**, a term invented to describe the equation

$$\boldsymbol{L}(\mathrm{x}(\boldsymbol{t})) = (\boldsymbol{s}\boldsymbol{I} - \boldsymbol{C})^{-1}\mathrm{x}(0).$$

An Illustration for $\mathrm{x}' = C\mathrm{x}$

Define $\boldsymbol{C} = \begin{pmatrix} \mathbf{2} & \mathbf{3} \\ \mathbf{0} & \mathbf{4} \end{pmatrix}$, $\mathrm{x} = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$, $\mathrm{x}(0) = \begin{pmatrix} \mathbf{1} \\ \mathbf{2} \end{pmatrix}$, which gives a scalar initial value problem

$$\begin{cases} x_1'(t) &= 2x_1(t) + 3x_2(t), \\ x_2'(t) &= \qquad\qquad\quad 4x_2(t), \\ x_1(0) &= 1, \\ x_2(0) &= 2. \end{cases}$$

Then the adjugate formula $A^{-1} = \dfrac{\mathsf{adj}(A)}{\det(A)}$ gives the resolvent

$$(sI - C)^{-1} = \frac{1}{(s-2)(s-4)} \begin{pmatrix} s-4 & 3 \\ 0 & s-2 \end{pmatrix}.$$

The Laplace transform of the solution is then

$$\boldsymbol{L}(\mathbf{x}(\boldsymbol{t})) = (\boldsymbol{sI} - \boldsymbol{C})^{-1} \begin{pmatrix} \mathbf{1} \\ \mathbf{2} \end{pmatrix} = \begin{pmatrix} \dfrac{\boldsymbol{s}+\mathbf{2}}{(\boldsymbol{s}-\mathbf{2})(\boldsymbol{s}-\mathbf{4})} \\ \dfrac{\mathbf{2}}{\boldsymbol{s}-\mathbf{4}} \end{pmatrix}.$$

Partial fractions and use of the backward Laplace table imply

$$\mathbf{x}(\boldsymbol{t}) = \begin{pmatrix} \mathbf{3}\boldsymbol{e}^{\mathbf{4}\boldsymbol{t}} - \mathbf{2}\boldsymbol{e}^{\mathbf{2}\boldsymbol{t}} \\ \mathbf{2}\boldsymbol{e}^{\mathbf{4}\boldsymbol{t}} \end{pmatrix}.$$