

Real Characteristic Roots

Department of Mathematics

Salt Lake Community College

Constant Coefficient Second-Order DE

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Because the range of e^{rt} is $(0, \infty)$ this will be satisfied only when

$$ar^2 + br + c = 0$$

We call this the **characteristic equation** of the DE and is key to finding the solutions that form a basis of the solution space.

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These roots are called **characteristic roots** or **eigenvalues**.

(The term *eigenvalue* is from Linear Algebra and will be talked about later.)

Solution for Distinct Real Characteristic Roots

For $\Delta > 0$, the characteristic roots of the DE

$$ay'' + by' + cy = 0$$

are

$$r_1 = \frac{-b + \sqrt{b^2 - 4ac}}{2a}, \quad \text{and} \quad r_2 = \frac{-b - \sqrt{b^2 - 4ac}}{2a}$$

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The functions $e^{r_1 t}$ and $e^{r_2 t}$ are linearly independent solutions, and the general solution is given by

$$y(t) = c_1 e^{r_1 t} + c_2 e^{r_2 t}$$

where c_1 and c_2 are arbitrary constants determined by the initial conditions.

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The set $\{e^{r_1 t}, e^{r_2 t}\}$ forms a basis for the solution space \mathbb{S} .

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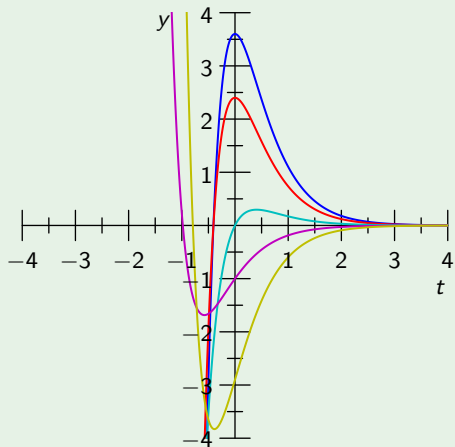
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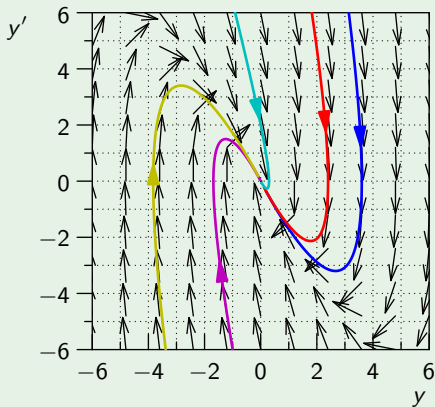
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The set $\{e^{-2t}, e^{-3t}\}$ is a basis of the solution space \mathbb{S} , and **dim** $\mathbb{S} = 2$.

Example 1



(a) Time Series



(b) Phase Portrait

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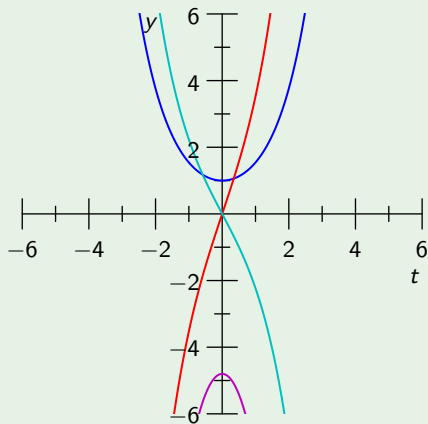
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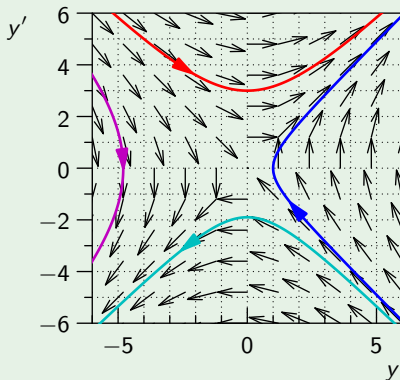
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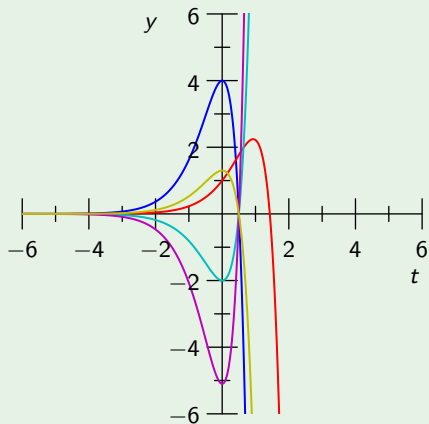
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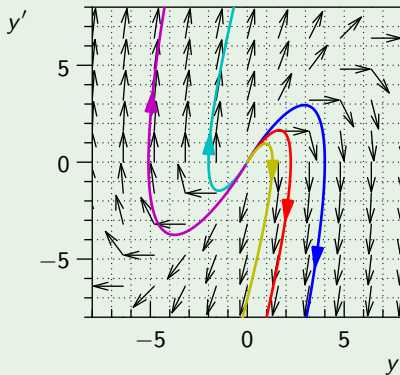
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The set $\{e^{2t}, te^{2t}\}$ is a basis of the solution space \mathbb{S} , and **dim** $\mathbb{S} = 2$.

Example 3



(a) Time Series



(b) Phase Portrait

Overdamped Mass-Spring System

The motion of a mass-spring system is called **overdamped** when we have $\Delta > 0$. Both characteristic roots are negative and the solutions

$$x(t) = c_1 e^{r_1 t} + c_2 e^{r_2 t}$$

tend towards zero with oscillation, crossing the t -axis at most once.

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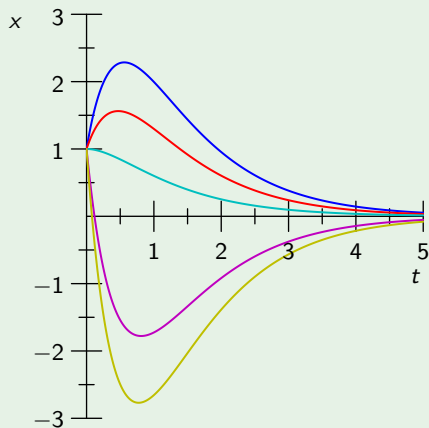
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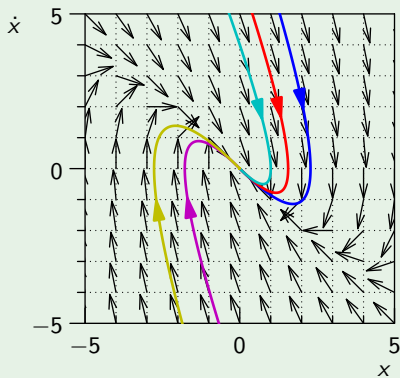
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The set $\{e^{-t}, e^{-2t}\}$ is a basis of the solution space \mathbb{S} , and **dim** $\mathbb{S} = 2$.

Example 4



(a) Time Series



(b) Phase Portrait

Critically Damped Mass-Spring System

The motion of a mass-spring system is called **critically damped** when we have $\Delta = 0$. The single characteristic root are negative and the solutions

$$x(t) = c_1 e^{rt} + c_2 t e^{rt}$$

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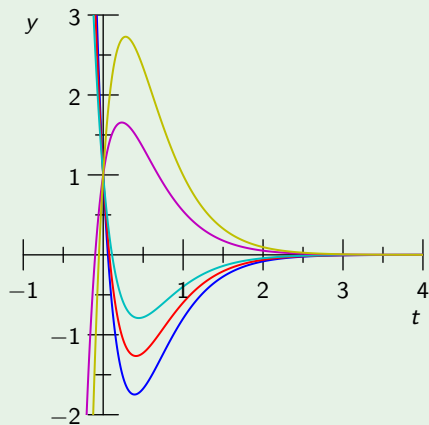
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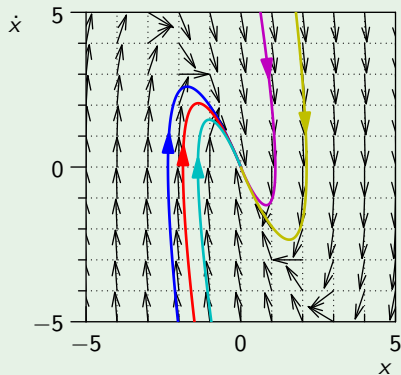
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(a) Time Series



(b) Phase Portrait

Existence and Uniqueness Theorem (Second-Order)

Let $p(t)$ and $q(t)$ be continuous on the open interval (a, b) containing t_0 . For *any* $A, B \in \mathbb{R}$, there exists a unique solution $y(t)$ defined on (a, b) to the IVP

$$y'' + p(t)y' + q(t)y = 0, \quad y(t_0) = A, \quad y'(t_0) = B$$

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This is an extension of Picard's Theorem.

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See Page 217 in your textbook

Solutions of Homogeneous Linear DE (Second-Order)

For any linear second-order homogeneous DE on (a, b) ,

$$y'' + p(t)y' + q(t)y = 0$$

for which p and q are continuous on (a, b) , *any* two linearly independent solutions $\{y_1, y_2\}$ form a basis of the solution space \mathbb{S} , and *every* solution y on (a, b) can be written as

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for some $c_1, c_2 \in \mathbb{R}$.

We can generalize these ideas for n th-order DEs.

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Existence and Uniqueness Theorem (n th-Order)

Let $p_1(t), p_2(t), \dots, p_n(t)$ be continuous on the open interval (a, b) containing t_0 . For any initial conditions $A_0, A_1, \dots, A_{n-1} \in \mathbb{R}$, there exists a unique solution $y(t)$ defined on (a, b) to the IVP

$$y^{(n)} + p_1(t)y^{(n-1)} + p_2(t)y^{(n-2)} + \dots + p_n(t)y = 0$$

where

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The solution space \mathbb{S} for a n th-order linear homogeneous differential equation has dimension n .

Solutions of Homogeneous Linear DE (n th-Order)

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for which $p_1(t), p_2(t), \dots, p_n(t)$ are continuous on (a, b) , any n linearly independent solutions $\{y_1, y_2, \dots, y_n\}$ form a basis of the solution space \mathbb{S} , and every solution y on (a, b) can be written as

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- if $m < n$, the set of solutions does not span \mathbb{S} .

A Wronskian conveys more information in the test for linear independence when the functions are solutions to the same n th-order linear homogeneous DE.

The Wronskian Test for Linear Independence of DE Solutions

Suppose $\{y_1, y_2, \dots, y_n\}$ is a set of solutions on (a, b) of a n th-order linear homogeneous DE,

$$L(y) = a_n(t) \frac{d^n y}{dt^n} + a_{n-1}(t) \frac{d^{n-1} y}{dt^{n-1}} + \cdots + a_1(t) \frac{d^1 y}{dt^1} + a_0 y = 0$$

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- ① If $W[y_1, y_2, \dots, y_n] \neq 0$ at any point $t \in (a, b)$, the set $\{y_1, y_2, \dots, y_n\}$ is linearly independent.

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- 1 If $W[y_1, y_2, \dots, y_n] \neq 0$ at any point $t \in (a, b)$, the set $\{y_1, y_2, \dots, y_n\}$ is linearly independent.
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Proof

See page 220 in your textbook

Example 6

Consider the set of solutions $A = \{2, t - 1, t^2, t^3 + t\}$ to $\frac{d^4 y}{dy^4} = 0$ on \mathbb{R} .

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$$W = \begin{vmatrix} 2 & t - 1 & t^2 & t^3 + t \\ 0 & 1 & 2t & 3t^2 + 1 \\ 0 & 0 & 2 & 6t \\ 0 & 0 & 0 & 6 \end{vmatrix}$$

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So, A is linearly independent and hence a basis of \mathbb{S} .

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Consider the set of solutions $B = \{t, t + 1, t^2 - 1, t^2\}$ to $\frac{d^4 y}{dy^4} = 0$ on \mathbb{R} .

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So, B is linearly dependent.

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So, B is linearly dependent.

For example, $t = (t + 1) + (t^2 - 1) - (t^2)$.

Example 8

Consider the set of solutions $C = \{1, t^2, t^3\}$ to $\frac{d^4 y}{dt^4} = 0$ on \mathbb{R} .

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Here, W is not identically zero, so we know C is a linearly independent set.

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Here, W is not identically zero, so we know C is a linearly independent set. But the strong conclusion of the Wronskian test did not occur here because C contains only three solutions for a fourth-order DE.