

# Differential Equations

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## Module C: Constant coefficient linear ODEs

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# How can we solve and apply linear constant coefficient ODEs?

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At the end of this module, students will be able to...

- C1. Constant coefficient first order.** ...find the general solution to a first order constant coefficient ODE.
- C2. Modeling motion in viscous fluids.** ...model the motion of a falling object with linear drag
- C3. Homogeneous constant coefficient second order.** ...find the general solution to a homogeneous second order constant coefficient ODE.
- C4. IVPs.** ...solve initial value problems for constant coefficient ODEs
- C5. Non-homogenous constant coefficient second order.** ...find the general solution to a non-homogeneous second order constant coefficient ODE
- C6. Modeling oscillators.** ...model (free or forced, damped or undamped) mechanical oscillators with a second order ODE

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## Readiness Assurance Outcomes

Before beginning this module, each student should be able to...

- Find all roots of a quadratic polynomial.
- Use Euler's theorem to relate  $\sin(t)$ ,  $\cos(t)$ , and  $e^t$ .
- Use Euler's theorem to simplify complex exponentials.
- Describe Newton's laws in terms of differential equations.
- Use substitution to compute indefinite integrals.
- Use integration by parts to compute indefinite integrals.
- Solve systems of two linear equations in two variables.

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The following resources will help you prepare for this module.

- Systems of linear equations (Khan Academy): <http://bit.ly/2l21etm>
- Solving linear systems with substitution (Khan Academy):  
<http://bit.ly/1SlMpix>
- Set builder notation: <https://youtu.be/xnfUZ-NTsCE>

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# Module C Section 1

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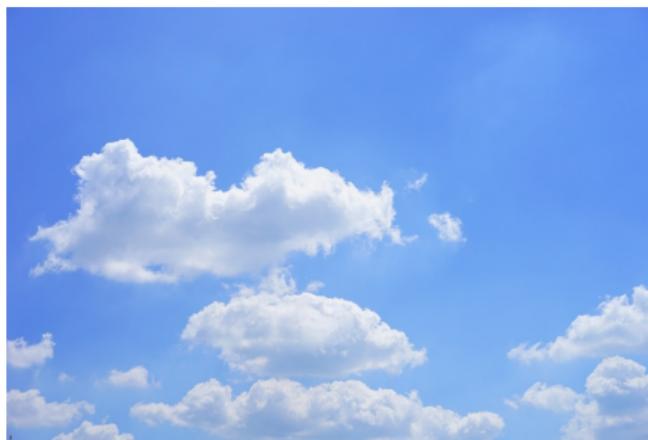
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## Activity C.1.1 ( $\sim 5 \text{ min}$ )

Why don't clouds fall out of the sky?



- (a) They are lighter than air
- (b) Wind keeps them from falling
- (c) Electrostatic charge
- (d) They do fall, just very slowly

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## Activity C.1.2 ( $\sim 5 \text{ min}$ )

List all of the forces acting on a tiny droplet of water falling from the sky.

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### Activity C.1.3 ( $\sim 5 \text{ min}$ )

Tiny droplets of water obey **Stoke's law**, which says that air resistance is proportional to velocity.

Use Newton's laws to write a differential equation that models the velocity of a falling droplet of water.

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## Definition C.1.4

A **first order constant coefficient** differential equation can be written in the form

$$y' + by = c,$$

or equivalently,

$$\frac{dy}{dx} + by = c.$$

We will use both notations interchangeably.

Here, **first order** refers to the fact that the highest derivative we see is the first derivative of  $y$ .

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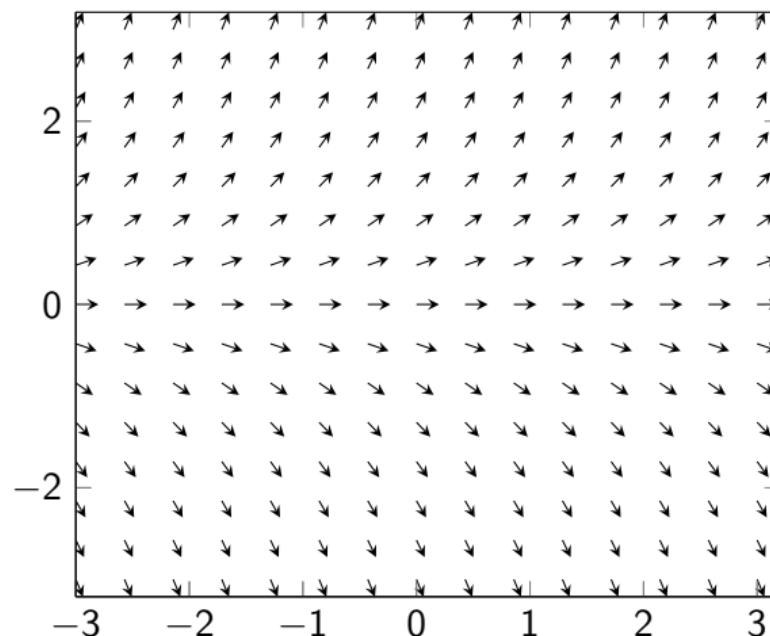
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## Observation C.1.5

Consider the differential equation  $y' = y$ .

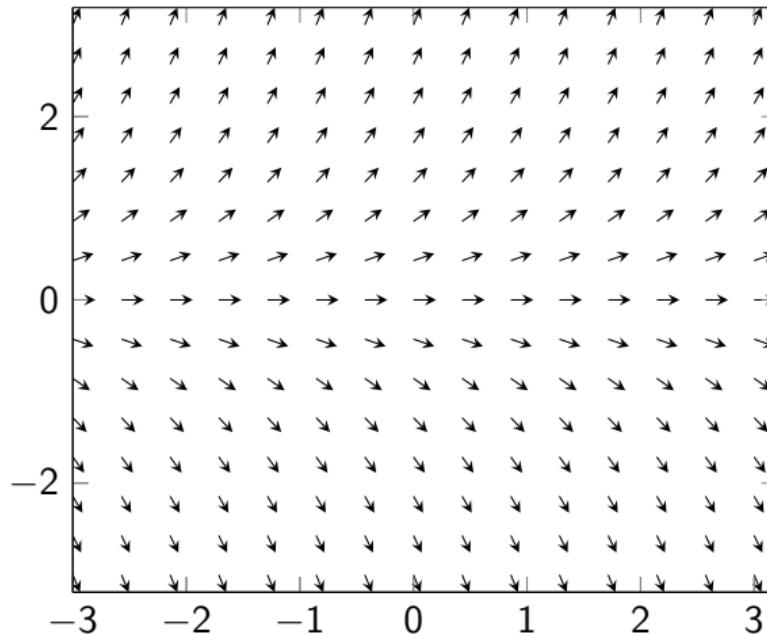
A useful way to visualize a first order differential equation is by a **slope field**



Each arrow represents the slope of a solution **trajectory** through that point.

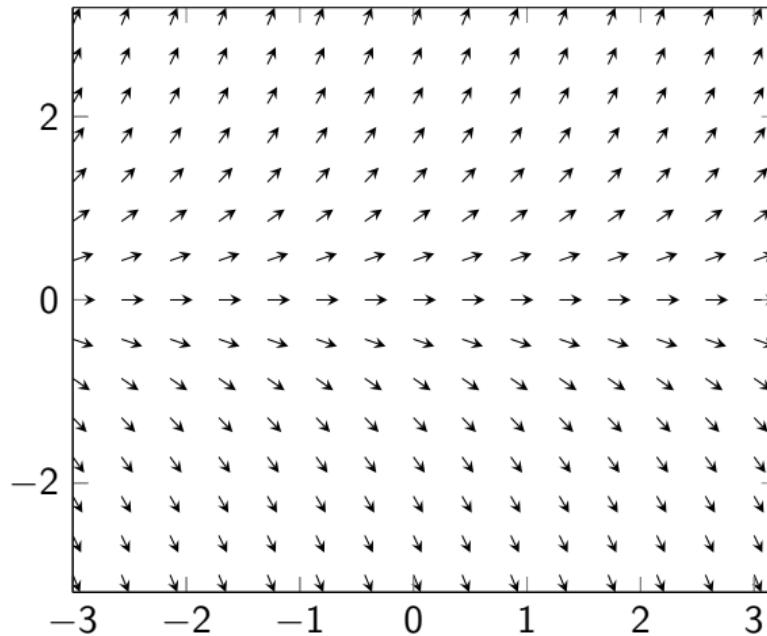
## Activity C.1.6 ( $\sim 5 \text{ min}$ )

Consider the differential equation  $y' = y$  with slope field below.



## Activity C.1.6 ( $\sim 5 \text{ min}$ )

Consider the differential equation  $y' = y$  with slope field below.



*Part 1:* Draw a trajectory through the point  $(0, 1)$ .

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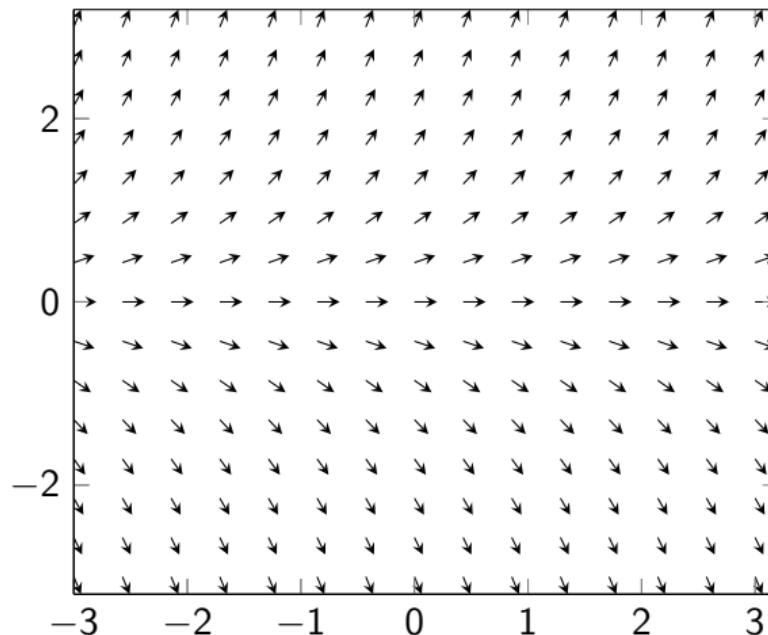
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**Activity C.1.6 ( $\sim 5 \text{ min}$ )**

Consider the differential equation  $y' = y$  with slope field below.



*Part 1:* Draw a trajectory through the point  $(0, 1)$ .

*Part 2:* Draw a trajectory through the point  $(-1, -1)$ .

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## Activity C.1.7 ( $\sim 15 \text{ min}$ )

Consider the differential equation  $y' = y$ .

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## Activity C.1.7 ( $\sim 15 \text{ min}$ )

Consider the differential equation  $y' = y$ .

*Part 1:* Find a solution to  $y' = y$ .

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## Activity C.1.7 ( $\sim 15 \text{ min}$ )

Consider the differential equation  $y' = y$ .

*Part 1:* Find a solution to  $y' = y$ .

*Part 2:* Find all solutions to  $y' = y$ .

## Definition C.1.8

A differential equation will have many solutions. The **general solution** encompasses all of these by using parameters such as  $C, k, c_0, c_1$  and so on. For example:

- The general solution to the differential equation  $y' = 2x - 3$  is  $y = x^2 - 3x + C$  (as done in Calculus courses).
- The general solution for  $y' = y$  is  $y = c_0 e^x$  (as done in the previous activity).

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## Activity C.1.9 ( $\sim 15 \text{ min}$ )

Adapt the solution  $y = c_0 e^x$  for  $y' = y$  to find a general solutions for the following differential equations.

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## Activity C.1.9 ( $\sim 15 \text{ min}$ )

Adapt the solution  $y = c_0 e^x$  for  $y' = y$  to find a general solutions for the following differential equations.

*Part 1:* Solve  $y' = 2y$ .

## Activity C.1.9 ( $\sim 15 \text{ min}$ )

Adapt the solution  $y = c_0 e^x$  for  $y' = y$  to find a general solutions for the following differential equations.

*Part 1:* Solve  $y' = 2y$ .

*Part 2:* Solve  $y' = y + 2$ .

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## Observation C.2.1

Recall the last activity from yesterday:

Solve  $y' = y + 2$

This is very similar to the equation  $y' = y$ , which we know how to solve.

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**Activity C.2.2 ( $\sim 15 \text{ min}$ )**Solve  $y' = y + 2$ 

**Simple idea:** Since  $e^t$  is a solution of  $y' = y$ , we suppose a solution is of the form  $y_p = \mu e^t$  for some function  $\mu$ .

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**Activity C.2.2 ( $\sim 15 \text{ min}$ )**Solve  $y' = y + 2$ 

**Simple idea:** Since  $e^t$  is a solution of  $y' = y$ , we suppose a solution is of the form  $y_p = \mu e^t$  for some function  $\mu$ .

*Part 1:* Substitute  $y_p$  into the equation  $y' = y + 2$  and simplify.

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## Activity C.2.2 ( $\sim 15 \text{ min}$ )

Solve  $y' = y + 2$

**Simple idea:** Since  $e^t$  is a solution of  $y' = y$ , we suppose a solution is of the form  $y_p = \mu e^t$  for some function  $\mu$ .

*Part 1:* Substitute  $y_p$  into the equation  $y' = y + 2$  and simplify.

*Part 2:* Find  $\mu$ .

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## Activity C.2.2 ( $\sim 15 \text{ min}$ )

Solve  $y' = y + 2$

**Simple idea:** Since  $e^t$  is a solution of  $y' = y$ , we suppose a solution is of the form  $y_p = \mu e^t$  for some function  $\mu$ .

*Part 1:* Substitute  $y_p$  into the equation  $y' = y + 2$  and simplify.

*Part 2:* Find  $\mu$ .

*Part 3:* Find  $y_p$ .

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## Observation C.2.3

This technique is called **variation of parameters**. If  $y_0$  is a solution of the **homogeneous** equation, we suppose a solution of the **non-homogeneous** equation has the form  $y_p = \mu y_0$ , and then determine what  $\mu$  must be.

### Example:

$$y' + 3y = 0 \quad \text{homogeneous}$$

$$y' + 3y = x \quad \text{non-homogeneous}$$

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**Activity C.2.4 ( $\sim 20 \text{ min}$ )**

Solve  $y' = x - 3y$ .

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## Activity C.2.4 ( $\sim 20 \text{ min}$ )

Solve  $y' = x - 3y$ .

Part 1: Solve the homogeneous equation  $y' + 3y = 0$ .

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## Activity C.2.4 ( $\sim 20 \text{ min}$ )

Solve  $y' = x - 3y$ .

*Part 1:* Solve the homogeneous equation  $y' + 3y = 0$ .

*Part 2:* If  $y_0$  is a solution of the homogeneous equation, let  $y_p = \mu y_0$  for some **function**  $\mu$ . Substitute  $y_p$  in to original equation and simplify.

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## Activity C.2.4 ( $\sim 20 \text{ min}$ )

Solve  $y' = x - 3y$ .

*Part 1:* Solve the homogeneous equation  $y' + 3y = 0$ .

*Part 2:* If  $y_0$  is a solution of the homogeneous equation, let  $y_p = \mu y_0$  for some **function**  $\mu$ . Substitute  $y_p$  in to original equation and simplify.

*Part 3:* Determine  $\mu$ , and then determine  $y_p$ .

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## Observation C.2.5

Since  $y_0 = c_0 e^{-3x}$  was the general solution of the homogeneous equation, and  $y_p = \frac{x}{3} - \frac{1}{9}$  is a particular solution of the non-homogeneous equation, a general solution to the non-homogeneous equation

$$y' + 3y = x$$

is

$$y_0 + y_p = c_0 e^{-3x} + \frac{x}{3} - \frac{1}{9}.$$

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## Activity C.2.6 ( $\sim 15 \text{ min}$ )

Find the general solution to  $y' = 2y + x + 1$ .

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## Observation C.3.1

Recall that we can model the velocity of a water droplet in a cloud by

$$mv' = -mg - bv$$

where here, negative denotes downward velocity.  $m$  is the mass,  $g$  is Newton's gravitational constant, and  $b$  is a physical constant (like a coefficient of friction).



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## Activity C.3.2 ( $\sim 25 \text{ min}$ )

A water droplet with a radius of  $10 \mu\text{m}$  has a mass of about  $4 \times 10^{-15}\text{kg}$ . It is determined in a laboratory that for a droplet this size, the constant  $b$  has a value of  $0.003\text{kg/s}$ .

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### Activity C.3.2 ( $\sim 25 \text{ min}$ )

A water droplet with a radius of  $10 \mu\text{m}$  has a mass of about  $4 \times 10^{-15} \text{ kg}$ . It is determined in a laboratory that for a droplet this size, the constant  $b$  has a value of  $0.003 \text{ kg/s}$ .

*Part 1:* Write down the differential equation modelling this scenario.

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A water droplet with a radius of  $10 \mu\text{m}$  has a mass of about  $4 \times 10^{-15} \text{ kg}$ . It is determined in a laboratory that for a droplet this size, the constant  $b$  has a value of  $0.003 \text{ kg/s}$ .

*Part 1:* Write down the differential equation modelling this scenario.

*Part 2:* Find the general solution of this ODE.

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## Activity C.3.2 ( $\sim 25 \text{ min}$ )

A water droplet with a radius of  $10 \mu\text{m}$  has a mass of about  $4 \times 10^{-15} \text{ kg}$ . It is determined in a laboratory that for a droplet this size, the constant  $b$  has a value of  $0.003 \text{ kg/s}$ .

*Part 1:* Write down the differential equation modelling this scenario.

*Part 2:* Find the general solution of this ODE.

*Part 3:* What is the terminal velocity of the droplet?

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## Activity C.3.2 ( $\sim 25 \text{ min}$ )

A water droplet with a radius of  $10 \mu\text{m}$  has a mass of about  $4 \times 10^{-15} \text{ kg}$ . It is determined in a laboratory that for a droplet this size, the constant  $b$  has a value of  $0.003 \text{ kg/s}$ .

*Part 1:* Write down the differential equation modelling this scenario.

*Part 2:* Find the general solution of this ODE.

*Part 3:* What is the terminal velocity of the droplet?

*Part 4:* If the droplet starts from rest ( $v = 0$ ), what is its velocity after  $0.01 \text{ s}$ ?

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### Definition C.3.3

The second part of the previous activity is an example of an **Initial Value Problem (IVP)**; we were given the initial value of the velocity in addition to our differential equation.

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## Activity C.3.4 ( $\sim 10 \text{ min}$ )

Solve the IVP

$$y' + 3y = 0, y(0) = 2.$$

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## Activity C.3.5 ( $\sim 10 \text{ min}$ )

Solve the IVP

$$y' - 2y = 2, y(0) = 1.$$

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## Activity C.3.6 ( $\sim 5 \text{ min}$ )

Solve the IVP

$$y' - 2y = 2, y(2) = 1.$$

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## Observation C.4.1

What happens when your tire hits a pothole?

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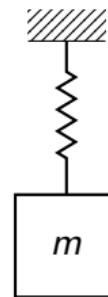
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## Activity C.4.2 ( $\sim 5 \text{ min}$ )

More abstractly, let's attach a mass (weighing  $m\text{kg}$ ) to a spring.



List all forces acting on the mass.

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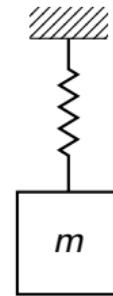
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## Activity C.4.3 ( $\sim 5 \text{ min}$ )

**Hooke's law** says that the force exerted by the spring is proportional to the distance the spring is stretched.



Write a differential equation modeling the displacement of the mass.

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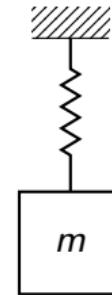
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## Observation C.4.4

There is an equilibrium point where the force of gravity balances the spring force. If we measure displacement from this point, we can model the mass-spring system by

$$my'' = ky.$$



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## Activity C.4.5 ( $\sim 15 \text{ min}$ )

Consider the (numerically simplified) mass-spring equation

$$y'' = -y.$$

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## Activity C.4.5 ( $\sim 15 \text{ min}$ )

Consider the (numerically simplified) mass-spring equation

$$y'' = -y.$$

*Part 1:* Find a solution.

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## Activity C.4.5 ( $\sim 15 \text{ min}$ )

Consider the (numerically simplified) mass-spring equation

$$y'' = -y.$$

*Part 1:* Find a solution.

*Part 2:* Find the general solution.

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## Activity C.4.5 ( $\sim 15 \text{ min}$ )

Consider the (numerically simplified) mass-spring equation

$$y'' = -y.$$

*Part 1:* Find a solution.

*Part 2:* Find the general solution.

*Part 3:* Describe the long term behavior of the mass-spring system.

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## Activity C.4.6 ( $\sim 5 \text{ min}$ )

In applications, this infinitely oscillating behavior is often inappropriate.

Thus, a damper (dashpot) is often incorporated. This provides a force proportional to the velocity.

Write a differential equation modeling the displacement of a mass in a **damped** mass-spring system.

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## Definition C.4.7

A **homogeneous second order constant coefficient** differential equation can be written in the form

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

Here, **homogeneous** refers to the 0 on the right hand side of the equation.

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## Activity C.4.8 ( $\sim 15 \text{ min}$ )

Consider the second order constant coefficient equation

$$y'' = y.$$

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## Activity C.4.8 ( $\sim 15 \text{ min}$ )

Consider the second order constant coefficient equation

$$y'' = y.$$

*Part 1:* Find a solution.

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## Activity C.4.8 ( $\sim 15 \text{ min}$ )

Consider the second order constant coefficient equation

$$y'' = y.$$

*Part 1:* Find a solution.

*Part 2:* Find the general solution.

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## Activity C.4.8 ( $\sim 15 \text{ min}$ )

Consider the second order constant coefficient equation

$$y'' = y.$$

*Part 1:* Find a solution.

*Part 2:* Find the general solution.

*Part 3:* Describe the long term behavior of the solutions.

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## Module C Section 5

## Observation C.5.1

It is sometimes useful to think in terms of **differential operators**.

- We will use  $D$  to represent a derivative; another common notation is  $\frac{\partial}{\partial x}$ . So for any function  $y$ ,

$$D(y) = \frac{\partial y}{\partial x} = y'.$$

- $D^2$  will denote the second derivative operator (i.e. differentiate twice, or apply  $D$  twice).
- We will use  $I$  for the identity operator; it does nothing to a function. That is,  $I(y) = y$ . It can be thought of as  $I = D^0$  (i.e. differentiate zero times).

In this language, the differential equation  $y' + 3y = 0$  can be rewritten as  $D(y) + 3I(y) = 0$ , or  $(D + 3I)(y) = 0$ .

Thus, the question of solving the homogeneous differential equation is the question of finding the kernel of the differential operator  $D + 3I$ .

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## Activity C.5.2 ( $\sim 5 \text{ min}$ )

What is the kernel of  $D - I$  ?

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## Activity C.5.2 ( $\sim 5 \text{ min}$ )

What is the kernel of  $D - I$ ?

*Part 1:* Write a differential equation that corresponds to this question.

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## Activity C.5.2 ( $\sim 5 \text{ min}$ )

What is the kernel of  $D - I$  ?

- Part 1:* Write a differential equation that corresponds to this question.  
*Part 2:* Find the general solution of this differential equation.

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## Activity C.5.3 ( $\sim 5 \text{ min}$ )

Find a differential operator whose kernel is the solution set of the ODE  $y' = 4y$ .

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## Activity C.5.4 ( $\sim 10 \text{ min}$ )

Consider the ODE

$$y'' + 5y' + 6y = 0.$$

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## Activity C.5.4 ( $\sim 10 \text{ min}$ )

Consider the ODE

$$y'' + 5y' + 6y = 0.$$

*Part 1:* Find a differential operator whose kernel is the solution set of the above ODE.

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## Activity C.5.4 ( $\sim 10 \text{ min}$ )

Consider the ODE

$$y'' + 5y' + 6y = 0.$$

*Part 1:* Find a differential operator whose kernel is the solution set of the above ODE.

*Part 2:* Factor this differential operator as a composition of two operators. (This works because  $D$  and  $I$  commute).

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## Activity C.5.4 ( $\sim 10 \text{ min}$ )

Consider the ODE

$$y'' + 5y' + 6y = 0.$$

*Part 1:* Find a differential operator whose kernel is the solution set of the above ODE.

*Part 2:* Factor this differential operator as a composition of two operators. (This works because  $D$  and  $I$  commute).

*Part 3:* Find the general solution of the ODE.

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## Observation C.5.5

If we let  $\mathcal{L} = D^2 + 5D + 6I$ , we can write the ODE

$$y'' + 5y' + 6y = 0$$

as

$$\mathcal{L}(y) = 0.$$

Note that such an  $\mathcal{L}$  is always a **linear transformation**.

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## Activity C.6.1 ( $\sim 10 \text{ min}$ )

Consider the ODE

$$y'' + 5y - 6y = 0.$$

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## Activity C.6.1 ( $\sim 10 \text{ min}$ )

Consider the ODE

$$y'' + 5y - 6y = 0.$$

*Part 1:* Find a differential operator whose kernel is the solution set of the above ODE.

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## Activity C.6.1 ( $\sim 10 \text{ min}$ )

Consider the ODE

$$y'' + 5y - 6y = 0.$$

*Part 1:* Find a differential operator whose kernel is the solution set of the above ODE.

*Part 2:* Factor this differential operator as a composition of two operators. (This works because  $D$  and  $I$  commute).

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## Activity C.6.1 ( $\sim 10 \text{ min}$ )

Consider the ODE

$$y'' + 5y - 6y = 0.$$

*Part 1:* Find a differential operator whose kernel is the solution set of the above ODE.

*Part 2:* Factor this differential operator as a composition of two operators. (This works because  $D$  and  $I$  commute).

*Part 3:* Find the general solution of the ODE.

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## Activity C.6.2 ( $\sim 10 \text{ min}$ )

Solve the ODE

$$2y'' + 7y' + 6y = 0.$$

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## Activity C.6.3 ( $\sim 15 \text{ min}$ )

Solve the ODE

$$y'' + y = 0.$$

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## **Activity C.6.4 ( $\sim 15 \text{ min}$ )**

Consider the ODE

$$y'' + 2y' + 5y = 0$$

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## Activity C.6.4 ( $\sim 15 \text{ min}$ )

Consider the ODE

$$y'' + 2y' + 5y = 0$$

.

*Part 1:* Find the general solution.

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## Activity C.6.4 ( $\sim 15 \text{ min}$ )

Consider the ODE

$$y'' + 2y' + 5y = 0$$

.

*Part 1:* Find the general solution.

*Part 2:* Describe the long-term behavior of the solutions.

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## Activity C.7.1 ( $\sim 10 \text{ min}$ )

Solve the ODE

$$y'' - 4y' + 4y = 0.$$

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## Observation C.7.2

To solve this, we need to find the kernel of  $(D - 2I)(D - 2I)$ .

- The kernel of  $D - 2I$  is  $\{ce^{2t} \mid c \in \mathbb{R}\}$ .
- However, if  $(D - 2I)(y) = Ae^{2t}$ , then applying  $D - 2I$  twice will yield zero.
- So we must solve the ODE

$$y' - 2y = e^{2t}.$$

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**Activity C.7.3 ( $\sim 15 \text{ min}$ )**

Solve  $y' - 2y = e^{2t}$ .

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## Observation C.7.4

Thus, we have shown that the general solution of  $y'' - 4y' + 4y = 0$  is  $c_0 e^{2t} + c_1 t e^{2t}$ .

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**Activity C.7.5 ( $\sim 15 \text{ min}$ )**

Solve  $y'' - 6y' + 9y = 0$ .

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[Module F](#)[Module S](#)[Module N](#)[Module D](#)**Activity C.7.6 ( $\sim 10 \text{ min}$ )**

Consider the homogeneous second order constant coefficient ODE

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

If  $r$  is a number such that  $ar^2 + br + cr = 0$ , what can you conclude?

- (a)  $e^{rt}$  is a solution.
- (b)  $e^{-rt}$  is a solution.
- (c)  $te^{rt}$  is a solution.
- (d) There are no solutions.

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## Activity C.7.7 ( $\sim 5 \text{ min}$ )

Consider the homogeneous second order constant coefficient ODE

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

When does the general solution have the form  $c_0 e^{rt} + t e^{rt}$ ?

- (a) When the polynomial  $ax^2 + bx + c$  has two distinct real roots.
- (b) When the polynomial  $ax^2 + bx + c$  has a repeated real root.
- (c) When the polynomial  $ax^2 + bx + c$  has two distinct non-real roots.
- (d) When the polynomial  $ax^2 + bx + c$  has a repeated non-real root.

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## Observation C.7.8

Consider the homogeneous second order constant coefficient ODE

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

- If  $r$  is a root of  $ar^2 + br + c = 0$ , then  $e^{rt}$  is a solution of the ODE.
- If  $r$  is a double root, variation of parameters shows that  $te^{rt}$  is also a solution.
- if  $r$  is not real, Euler's formula allows us to express the solution in terms of  $\sin(rt)$  and  $\cos(rt)$ .

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## Observation C.8.1

Consider the homogeneous second order constant coefficient ODE

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

- If  $r$  is a root of  $ar^2 + br + c = 0$ , then  $e^{rt}$  is a solution of the ODE.
- If  $r$  is a double root, variation of parameters shows that  $te^{rt}$  is also a solution.
- if  $r$  is not real, Euler's formula allows us to express the solution in terms of  $\sin(rt)$  and  $\cos(rt)$ .

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**Activity C.8.2 ( $\sim 15 \text{ min}$ )**

Consider a mass of 4 kg suspended from a damped spring with spring constant  $k = 2 \text{ kg/s}^2$  and damping constant  $b = 6 \text{ kg/s}$ .

The mass is pulled down 0.3 m and released from rest. How many times does it pass back through its equilibrium state?

- (a) 0
- (b) 1
- (c) 2
- (d) Infinitely many

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**Activity C.8.3 ( $\sim 15 \text{ min}$ )**

Consider a mass of 5 kg suspended from a damped spring with spring constant  $k = 2 \text{ kg/s}^2$  and damping constant  $b = 6\text{kg/s}$ .

The mass is pulled down 0.3m and released from rest. How many times does it pass back through its equilibrium state?

- (a) 0
- (b) 1
- (c) 2
- (d) Infinitely many

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## Observation C.8.4

It can be shown that in the **overdamped** situation, the spring might pass through the equilibrium position once (e.g. if given an initial push), but never more than once.

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## Activity C.9.1 ( $\sim 10 \text{ min}$ )

A 1 kg mass is suspended from a spring with spring constant  $k = 9 \text{ kg/s}^2$ . An external force is applied by an electromagnet and is modeled by the function  $F(t) = \sin(t)$ . Write an ODE modeling the displacement of the spring.

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## Observation C.9.2

In the previous activity, we encountered a **nonhomogeneous** second order constant coefficient ODE, i.e. of the form

$$ay'' + by' + cy = f$$

where  $a, b, c$  are constants, and  $f(t)$  is a function.

We will again use **variation of parameters** to find a particular solution.

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## Activity C.9.3 ( $\sim 15 \text{ min}$ )

Suppose  $y_1$  and  $y_2$  are two independent solutions of  $\mathcal{L}(y) = 0$ .

Our goal is to find a particular solution of the form  $y_p = v_1 y_1 + v_2 y_2$  for some TBD functions  $v_1, v_2$ .

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[Module F](#)[Module S](#)[Module N](#)[Module D](#)**Activity C.9.3 ( $\sim 15 \text{ min}$ )**

Suppose  $y_1$  and  $y_2$  are two independent solutions of  $\mathcal{L}(y) = 0$ .

Our goal is to find a particular solution of the form  $y_p = v_1 y_1 + v_2 y_2$  for some TBD functions  $v_1, v_2$ .

*Part 1:* Compute  $y'_p$ .

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**Activity C.9.3** ( $\sim 15 \text{ min}$ )

Suppose  $y_1$  and  $y_2$  are two independent solutions of  $\mathcal{L}(y) = 0$ .

Our goal is to find a particular solution of the form  $y_p = v_1 y_1 + v_2 y_2$  for some TBD functions  $v_1, v_2$ .

*Part 1:* Compute  $y'_p$ .

*Part 2:* To simplify calculations, we will **assume**  $v'_1 y_1 + v'_2 y_2 = 0$ . Assuming this, compute  $y''_p$ .

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**Activity C.9.3 ( $\sim 15 \text{ min}$ )**

Suppose  $y_1$  and  $y_2$  are two independent solutions of  $\mathcal{L}(y) = 0$ .

Our goal is to find a particular solution of the form  $y_p = v_1 y_1 + v_2 y_2$  for some TBD functions  $v_1, v_2$ .

*Part 1:* Compute  $y'_p$ .

*Part 2:* To simplify calculations, we will **assume**  $v'_1 y_1 + v'_2 y_2 = 0$ . Assuming this, compute  $y''_p$ .

*Part 3:* Compute  $\mathcal{L}(y_p)$ ; simplify the ODE  $\mathcal{L}(y_p) = f$ .

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**Observation C.9.4**

If we can find  $v_1$  and  $v_2$  that satisfy

$$y_1 v'_1 + y_2 v'_2 = 0$$

$$y'_1 v'_1 + y'_2 v'_2 = \frac{f}{a}$$

then we have a solution. So we just need to solve this system of equations for  $v'_1$  and  $v'_2$ .

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## Activity C.9.5 ( $\sim 15 \text{ min}$ )

Consider the nonhomogeneous ODE  $y'' + 9y = \sin(t)$ .

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**Section C.9**

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**Activity C.9.5 ( $\sim 15 \text{ min}$ )**

Consider the nonhomogeneous ODE  $y'' + 9y = \sin(t)$ .

*Part 1:* Find  $y_1$  and  $y_2$ , two independent solutions of  $y'' + 9y = 0$ .

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**Activity C.9.5 ( $\sim 15 \text{ min}$ )**

Consider the nonhomogeneous ODE  $y'' + 9y = \sin(t)$ .

*Part 1:* Find  $y_1$  and  $y_2$ , two independent solutions of  $y'' + 9y = 0$ .

*Part 2:* Find  $v_1$  and  $v_2$  by solving

$$\cos(3t)v'_1 + \sin(3t)v'_2 = 0$$

$$-3\sin(3t)v'_1 + 3\cos(3t)v'_2 = \sin(t)$$

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**Activity C.9.5 ( $\sim 15 \text{ min}$ )**

Consider the nonhomogeneous ODE  $y'' + 9y = \sin(t)$ .

*Part 1:* Find  $y_1$  and  $y_2$ , two independent solutions of  $y'' + 9y = 0$ .

*Part 2:* Find  $v_1$  and  $v_2$  by solving

$$\cos(3t)v'_1 + \sin(3t)v'_2 = 0$$

$$-3\sin(3t)v'_1 + 3\cos(3t)v'_2 = \sin(t)$$

*Part 3:* Write the general solution of the original nonhomogeneous ODE.

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## Activity C.9.6 ( $\sim 10 \text{ min}$ )

Consider the nonhomogeneous ODE  $y'' + 9y = \sin(3t)$ .

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**Activity C.9.6 ( $\sim 10$  min)**

Consider the nonhomogeneous ODE  $y'' + 9y = \sin(3t)$ .

*Part 1:* Find  $v_1$  and  $v_2$  by solving

$$\cos(3t)v'_1 + \sin(3t)v'_2 = 0$$

$$-3\sin(3t)v'_1 + 3\cos(3t)v'_2 = \sin(3t)$$

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**Activity C.9.6 ( $\sim 10$  min)**

Consider the nonhomogeneous ODE  $y'' + 9y = \sin(3t)$ .

*Part 1:* Find  $v_1$  and  $v_2$  by solving

$$\cos(3t)v'_1 + \sin(3t)v'_2 = 0$$

$$-3\sin(3t)v'_1 + 3\cos(3t)v'_2 = \sin(3t)$$

*Part 2:* Write the general solution of the original nonhomogeneous ODE.

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## Module F: First order ODEs

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# How can we solve and apply first order ODEs?

At the end of this module, students will be able to...

- F1. Sketching trajectories.** ...given a slope field, sketch a trajectory of a solution to a first order ODE
- F2. Separable ODEs.** ...find the general solution to a separable first order ODE
- F3. Autonomous ODEs.** ...find and classify the equilibria of an autonomous first order ODE, and describe the long term behavior of solutions
- F4. First order linear ODEs.** ...find the general solution to a first order linear ODE
- F5. Exact ODES.** ...find the general solution to an exact first order ODE
- F6. Modeling motion.** ...model the motion of an object with quadratic drag

## Readiness Assurance Outcomes

Before beginning this module, each student should be able to...

- Add Euclidean vectors and multiply Euclidean vectors by scalars.
- Add complex numbers and multiply complex numbers by scalars.
- Add polynomials and multiply polynomials by scalars.
- Perform basic manipulations of augmented matrices and linear systems  
**E1,E2,E3.**

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The following resources will help you prepare for this module.

- Adding and subtracting Euclidean vectors (Khan Academy):  
<http://bit.ly/2y8AOwa>
- Linear combinations of Euclidean vectors (Khan Academy):  
<http://bit.ly/2nK3wne>
- Adding and subtracting complex numbers (Khan Academy):  
<http://bit.ly/1PE3ZMQ>
- Adding and subtracting polynomials (Khan Academy):  
<http://bit.ly/2d5SLGZ>

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## Module F Section 1

## Definition F.1.1

A **first order ODE** is an equation involving (for a function  $y(x)$ ) only  $y'$ ,  $y$ , and  $x$ .

$$y' = f(y, x)$$

for some function  $f(y, x)$ .

## Activity F.1.2 ( $\sim 5 \text{ min}$ )

Consider the (explicit) first order ODE

$$y' = y^2 - x^2$$

.

**Activity F.1.2 ( $\sim 5 \text{ min}$ )**

Consider the (explicit) first order ODE

$$y' = y^2 - x^2$$

.

*Part 1:* Compute  $y'$  at each of the points  $(1, 1)$ ,  $(2, 1)$ ,  $(3, -2)$ , and  $(4, -7)$ .

**Activity F.1.2 ( $\sim 5 \text{ min}$ )**

Consider the (explicit) first order ODE

$$y' = y^2 - x^2$$

.

*Part 1:* Compute  $y'$  at each of the points  $(1, 1)$ ,  $(2, 1)$ ,  $(3, -2)$ , and  $(4, -7)$ .

*Part 2:*

Let  $y_0(x)$  be a solution that passes through the point  $(1, 1)$ . What can you conclude about  $\lim_{x \rightarrow \infty} y_0(x)$  ?

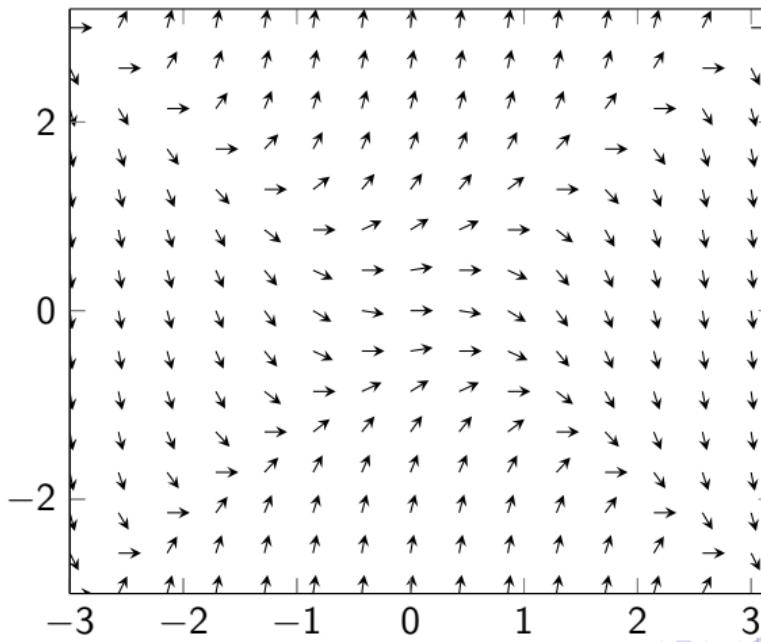
- (A)  $\lim_{x \rightarrow \infty} y_0(x) = -\infty$
- (B)  $\lim_{x \rightarrow \infty} y_0(x)$  is a finite number
- (C)  $\lim_{x \rightarrow \infty} y_0(x) = \infty$

## Definition F.1.3

These kinds of questions are easier to answer if we draw a **slope field** (sometimes called a **direction field**).

To draw one, draw a small line segment or arrow with the correct slope at each point.

$$y' = y^2 - x^2$$



## Activity F.1.4 ( $\sim 5 \text{ min}$ )

Drew Lewis

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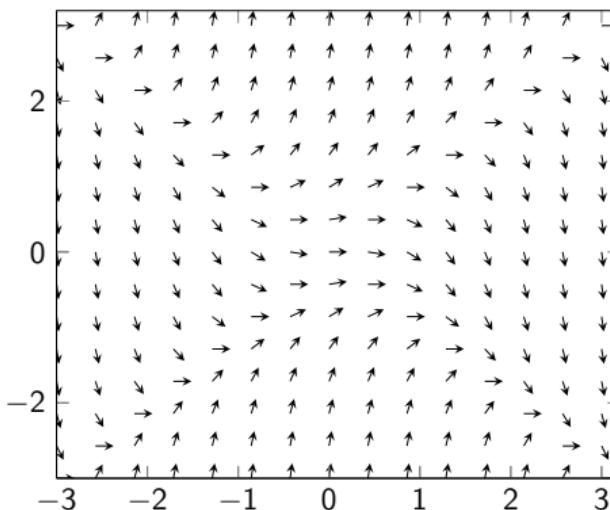
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$$y' = y^2 - x^2$$



Let  $y_1(x)$  be a solution that passes through the point  $(1, 3)$ . What can you conclude about  $\lim_{x \rightarrow \infty} y_0(x)$  ?

- (A)  $\lim_{x \rightarrow \infty} y_0(x) = -\infty$
- (B)  $\lim_{x \rightarrow \infty} y_0(x)$  is a finite number
- (C)  $\lim_{x \rightarrow \infty} y_0(x) = \infty$

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## Activity F.1.5 ( $\sim 15 \text{ min}$ )

Consider the ODE

$$y' = xy - x.$$

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## Activity F.1.5 ( $\sim 15 \text{ min}$ )

Consider the ODE

$$y' = xy - x.$$

*Part 1:* Draw a slope field for this ODE.

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## Activity F.1.5 ( $\sim 15 \text{ min}$ )

Consider the ODE

$$y' = xy - x.$$

*Part 1:* Draw a slope field for this ODE.

*Part 2:* Draw a solution that passes through the point  $(0,0)$ .

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## Activity F.1.5 ( $\sim 15 \text{ min}$ )

Consider the ODE

$$y' = xy - x.$$

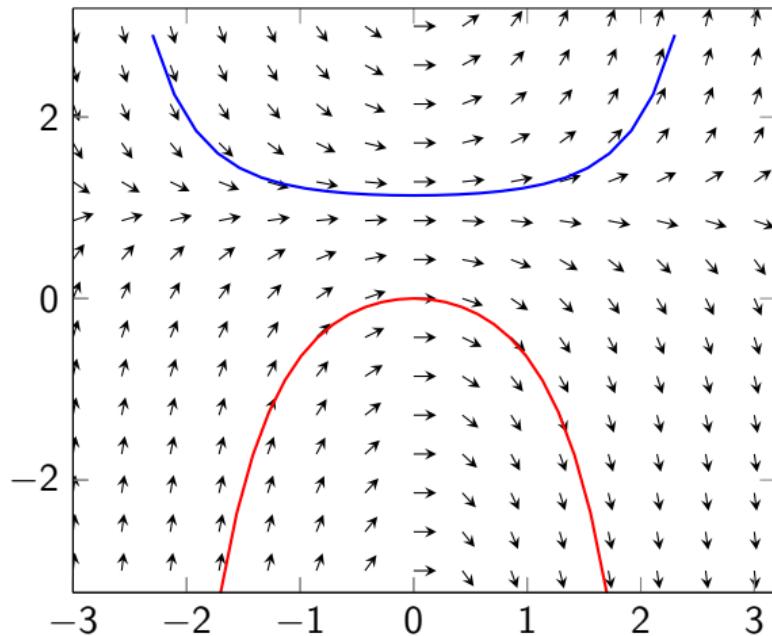
*Part 1:* Draw a slope field for this ODE.

*Part 2:* Draw a solution that passes through the point  $(0,0)$ .

*Part 3:* Draw a solution that passes through the point  $(-2,2)$ .

# Observation F.1.6

$$y' = xy - x$$



## Observation F.1.7

How can we solve  $y' = xy - x$  exactly?

Notice  $xy - x = x(y - 1)$ , so we can write  $y' = x(y - 1)$ .

Write

$$\frac{y'}{y - 1} = x.$$

This is called a **separable** DE.

## Observation F.1.8

Integrate both sides (and switch to Leibniz notation):

$$\int \frac{1}{y-1} \frac{dy}{dx} dx = \int x dx.$$

The substitution rule (i.e. chain rule) says this is equivalent to

$$\int \frac{1}{y-1} dy = \int x dx.$$

Thus,  $\ln|y-1| = \frac{1}{2}x^2 + c$ . Exponentiating, we have

$$|y-1| = e^{\frac{1}{2}x^2+c} = e^{\frac{1}{2}x^2} e^c = c_0 e^{\frac{1}{2}x^2}.$$

Allowing  $c_0$  to take on negative values, we can drop the absolute value sign, and obtain

$$y = 1 + c_0 e^{\frac{1}{2}x^2}.$$

## Activity F.1.9 ( $\sim 10 \text{ min}$ )

Find the general solution to

$$y' = xy + y.$$

## Activity F.1.10 ( $\sim 10 \text{ min}$ )

Solve the IVP

$$y' = \frac{x}{y}, y(0) = -1.$$

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## Module F Section 2

## Observation F.2.1

There are two very simple kinds of separable ODEs.

Equations of the form  $y' = f(x)$  can be solved immediately by integrating and produce explicit solutions.

Equations of the form  $y' = f(y)$  are often impossible or difficult to solve explicitly. They are called **autonomous** equations.

**Activity F.2.2 ( $\sim 10 \text{ min}$ )**

Consider the autonomous equation

$$y' = y^2$$

.

Suppose a solution goes through the point  $y(10) = 50$ . What can you say about  $y(11)$ ?

- (a)  $y(10) < y(11)$
- (b)  $y(10) = y(11)$
- (c)  $y(10) > y(11)$

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## Activity F.2.3 ( $\sim 10 \text{ min}$ )

Consider the autonomous equation

$$y' = y^2(y - 2)$$

## Activity F.2.3 ( $\sim 10 \text{ min}$ )

Consider the autonomous equation

$$y' = y^2(y - 2)$$

.

*Part 1:* Draw a number line for  $y'$ , indicating where it is positive or negative.

## Activity F.2.3 ( $\sim 10 \text{ min}$ )

Consider the autonomous equation

$$y' = y^2(y - 2)$$

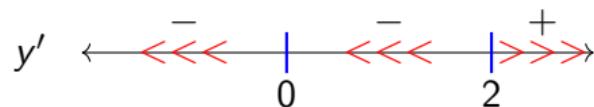
Part 1: Draw a number line for  $y'$ , indicating where it is positive or negative.

Part 2: What can you say about the long term behavior of a solution passing through  $y(4) = 1$ ?

## Definition F.2.4

The **phase line** is a useful way to visualize the long term behavior of an autonomous DE.

For example, here is a phase line for the autonomous DE  $y' = y^2(y - 2)$ .



## Activity F.2.5 ( $\sim 15 \text{ min}$ )

Consider the autonomous equation

$$y' = y(y + 1)^2(y - 2).$$

## Activity F.2.5 ( $\sim 15 \text{ min}$ )

Consider the autonomous equation

$$y' = y(y + 1)^2(y - 2).$$

*Part 1:* Draw a phase line.

## Activity F.2.5 ( $\sim 15 \text{ min}$ )

Consider the autonomous equation

$$y' = y(y + 1)^2(y - 2).$$

*Part 1:* Draw a phase line.

*Part 2:* Describe the long term behavior of a solution passing through  $y(2) = -0.9999$ .

## Activity F.2.5 ( $\sim 15 \text{ min}$ )

Consider the autonomous equation

$$y' = y(y + 1)^2(y - 2).$$

*Part 1:* Draw a phase line.

*Part 2:* Describe the long term behavior of a solution passing through  $y(2) = -0.9999$ .

*Part 3:* Describe the long term behavior of a solution passing through  $y(7) = -1.0001$ .

## Activity F.2.5 ( $\sim 15 \text{ min}$ )

Consider the autonomous equation

$$y' = y(y + 1)^2(y - 2).$$

*Part 1:* Draw a phase line.

*Part 2:* Describe the long term behavior of a solution passing through  $y(2) = -0.9999$ .

*Part 3:* Describe the long term behavior of a solution passing through  $y(7) = -1.0001$ .

*Part 4:* Describe the long term behavior of a solution passing through  $y(4) = -1$ .

## Activity F.2.5 ( $\sim 15 \text{ min}$ )

Consider the autonomous equation

$$y' = y(y + 1)^2(y - 2).$$

*Part 1:* Draw a phase line.

*Part 2:* Describe the long term behavior of a solution passing through  $y(2) = -0.9999$ .

*Part 3:* Describe the long term behavior of a solution passing through  $y(7) = -1.0001$ .

*Part 4:* Describe the long term behavior of a solution passing through  $y(4) = -1$ .

*Part 5:* Describe the long term behavior of solutions passing near the point  $y(3) = 0$ .

## Activity F.2.5 ( $\sim 15 \text{ min}$ )

Consider the autonomous equation

$$y' = y(y + 1)^2(y - 2).$$

*Part 1:* Draw a phase line.

*Part 2:* Describe the long term behavior of a solution passing through  $y(2) = -0.9999$ .

*Part 3:* Describe the long term behavior of a solution passing through  $y(7) = -1.0001$ .

*Part 4:* Describe the long term behavior of a solution passing through  $y(4) = -1$ .

*Part 5:* Describe the long term behavior of solutions passing near the point  $y(3) = 0$ .

*Part 6:* Describe the long term behavior of solutions passing near the point  $y(11) = 2$ .

## Definition F.2.6

The **critical points** of an autonomous DE are the numbers that give rise to equilibrium solutions (e.g.  $0, -1, 2$  in the previous problem).

A **source** is an unstable equilibrium in which all nearby trajectories move away in the limit.

A **sink** is a stable equilibrium in which all nearby trajectories approach the equilibrium in the limit.

There are also unstable equilibria in which some nearby trajectories return, while others diverge, analogous to a saddle point.

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## Activity F.2.7 ( $\sim 10 \text{ min}$ )

Consider the autonomous equation

$$y' = y^3(y - 2)^2(y + 1)(y - 1).$$

Find and classify all of the critical points.

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## Module F Section 3

## Observation F.3.1

In module C, we solved **constant coefficient linear ODEs**.

Today we will observe that our existing techniques allow us to solve all **first order linear ODES**, i.e. ODEs of the form

$$a(x)y' + b(x)y + c(x) = 0.$$

Such equations can always be rewritten (by rearranging and dividing by  $a(x)$ ) in **standard form**:

$$y' + P(x)y = Q(x).$$

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## Module F Section 5

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## Module S: Systems of ODEs

# How can we solve and apply systems of linear ODEs?

At the end of this module, students will be able to...

- S1. Solving systems.** ...solve systems of constant coefficient ODEs
- S2. Modeling interacting populations.** ...model the populations of two interacting populations with a system of ODEs
- S3. Modeling coupled oscillators.** ...model systems of coupled mechanical oscillators using a system of ODEs

## Readiness Assurance Outcomes

Before beginning this module, each student should be able to...

- Add Euclidean vectors and multiply Euclidean vectors by scalars.
- Perform basic manipulations of augmented matrices and linear systems **E1,E2,E3**.
- Apply linear combinations and spanning sets **V3,V4**.

The following resources will help you prepare for this module.

- Adding and subtracting Euclidean vectors (Khan Academy):  
<http://bit.ly/2y8AOwa>
- Linear combinations of Euclidean vectors (Khan Academy):  
<http://bit.ly/2nK3wne>
- Adding and subtracting complex numbers (Khan Academy):  
<http://bit.ly/1PE3ZMQ>
- Adding and subtracting polynomials (Khan Academy):  
<http://bit.ly/2d5SLGZ>

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## Module S Section 1

**Activity S.1.1 ( $\sim 10 \text{ min}$ )**

Consider the two sets

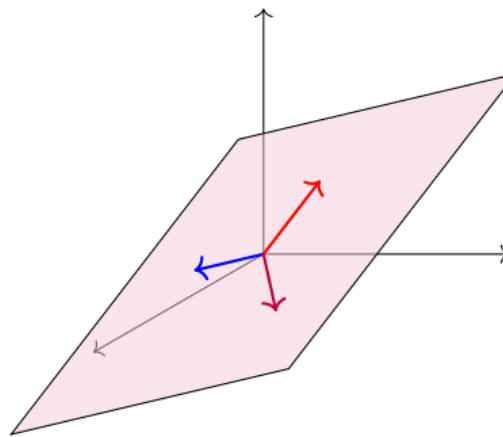
$$S = \left\{ \begin{bmatrix} 2 \\ 3 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \\ 4 \end{bmatrix} \right\}$$
$$T = \left\{ \begin{bmatrix} 2 \\ 3 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \\ 4 \end{bmatrix}, \begin{bmatrix} -1 \\ 0 \\ -11 \end{bmatrix} \right\}$$

Which of the following is true?

- (A)  $\text{span } S$  is bigger than  $\text{span } T$ .
- (B)  $\text{span } S$  and  $\text{span } T$  are the same size.
- (C)  $\text{span } S$  is smaller than  $\text{span } T$ .

## Definition S.1.2

We say that a set of vectors is **linearly dependent** if one vector in the set belongs to the span of the others. Otherwise, we say the set is **linearly independent**.



You can think of linearly dependent sets as containing a redundant vector, in the sense that you can drop a vector out without reducing the span of the set. In the above image, all three vectors lay on the same planar subspace, but only two vectors are needed to span the plane, so the set is linearly dependent.

**Activity S.1.3 ( $\sim 10 \text{ min}$ )**

Let  $\mathbf{u}, \mathbf{v}, \mathbf{w}$  be vectors in  $\mathbb{R}^n$ . Suppose  $3\mathbf{u} - 5\mathbf{v} = \mathbf{w}$ , so the set  $\{\mathbf{u}, \mathbf{v}, \mathbf{w}\}$  is linearly dependent. Which of the following is true of the vector equation  $x\mathbf{u} + y\mathbf{v} + z\mathbf{w} = \mathbf{0}$ ?

- (A) It is consistent with one solution
- (B) It is consistent with infinitely many solutions
- (C) It is inconsistent.

## Fact S.1.4

For any vector space, the set  $\{\mathbf{v}_1, \dots, \mathbf{v}_n\}$  is linearly dependent if and only if  $x_1\mathbf{v}_1 + \dots + x_n\mathbf{v}_n = \mathbf{z}$  is consistent with infinitely many solutions.

**Activity S.1.5 ( $\sim 10 \text{ min}$ )**

Find

$$\text{RREF} \left[ \begin{array}{ccccc|c} 2 & 2 & 3 & -1 & 4 & 0 \\ 3 & 0 & 13 & 10 & 3 & 0 \\ 0 & 0 & 7 & 7 & 0 & 0 \\ -1 & 3 & 16 & 14 & 2 & 0 \end{array} \right]$$

and mark the part of the matrix that demonstrates that

$$S = \left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 0 \\ 3 \end{bmatrix}, \begin{bmatrix} 3 \\ 13 \\ 7 \\ 16 \end{bmatrix}, \begin{bmatrix} -1 \\ 10 \\ 7 \\ 14 \end{bmatrix}, \begin{bmatrix} 4 \\ 3 \\ 0 \\ 2 \end{bmatrix} \right\}$$

is linearly dependent (the part that shows its linear system has infinitely many solutions).

## Fact S.1.6

A set of Euclidean vectors  $\{\mathbf{v}_1, \dots, \mathbf{v}_n\}$  is linearly dependent if and only if RREF  $[\mathbf{v}_1 \ \dots \ \mathbf{v}_n]$  has a column without a pivot position.

**Activity S.1.7 ( $\sim 5 \text{ min}$ )**

Is the set of Euclidean vectors  $\left\{ \begin{bmatrix} -4 \\ 2 \\ 3 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 1 \\ 2 \\ 0 \\ 0 \\ 3 \end{bmatrix}, \begin{bmatrix} 1 \\ 10 \\ 10 \\ 2 \\ 6 \end{bmatrix}, \begin{bmatrix} 3 \\ 4 \\ 7 \\ 2 \\ 1 \end{bmatrix} \right\}$  linearly dependent or linearly independent?

### **Activity S.1.8 ( $\sim 10 \text{ min}$ )**

Is the set of polynomials  $\{x^3 + 1, x^2 + 2x, x^2 + 7x + 4\}$  linearly dependent or linearly independent?

### Activity S.1.9 ( $\sim 5 \text{ min}$ )

What is the largest number of vectors in  $\mathbb{R}^4$  that can form a linearly independent set?

- (a) 3
- (b) 4
- (c) 5
- (d) You can have infinitely many vectors and still be linearly independent.

**Activity S.1.10 ( $\sim 5 \text{ min}$ )**

What is the largest number of vectors in

$$\mathcal{P}^4 = \{ ax^4 + bx^3 + cx^2 + dx + e \mid a, b, c, d, e \in \mathbb{R} \}$$

that can form a linearly independent set?

- (a) 3
- (b) 4
- (c) 5
- (d) You can have infinitely many vectors and still be linearly independent.

**Activity S.1.11 ( $\sim 5 \text{ min}$ )**

What is the largest number of vectors in

$$\mathcal{P} = \{f(x) \mid f(x) \text{ is any polynomial}\}$$

that can form a linearly independent set?

- (a) 3
- (b) 4
- (c) 5
- (d) You can have infinitely many vectors and still be linearly independent.

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## Module N: Numerical

**How can we use numerical approximation methods to apply and solve unsolvable ODEs?**

At the end of this module, students will be able to...

- N1. First Order Existence and Uniqueness.** ...determine when a unique solution exists for a first order ODE
- N2. Second Order Linear Existence and Uniqueness.** ...determine when a unique solution exists for a second order linear ODE
- N3. Systems Existence and Uniqueness.** ...determine when a unique solution exists for a system of first order ODEs
- N4. Euler's method for first order ODES.** ...use Euler's method to find approximate solution to first order ODEs
- N5. Euler's method for systems.** ...use Euler's method to find approximate solutions to systems of first order ODEs

## Readiness Assurance Outcomes

Before beginning this module, each student should be able to...

- State the definition of a spanning set, and determine if a set of Euclidean vectors spans  $\mathbb{R}^n$  **V4**.
- State the definition of linear independence, and determine if a set of Euclidean vectors is linearly dependent or independent **S1**.
- State the definition of a basis, and determine if a set of Euclidean vectors is a basis **S2,S3**.
- Find a basis of the solution space to a homogeneous system of linear equations **S6**.

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## Module N Section 1

## Definition N.1.1

A **linear transformation** (also known as a **linear map**) is a map between vector spaces that preserves the vector space operations. More precisely, if  $V$  and  $W$  are vector spaces, a map  $T : V \rightarrow W$  is called a linear transformation if

- ①  $T(\mathbf{v} + \mathbf{w}) = T(\mathbf{v}) + T(\mathbf{w})$  for any  $\mathbf{v}, \mathbf{w} \in V$ .
- ②  $T(c\mathbf{v}) = cT(\mathbf{v})$  for any  $c \in \mathbb{R}, \mathbf{v} \in V$ .

In other words, a map is linear when vector space operations can be applied before or after the transformation without affecting the result.

Module C

Module F

Module S

Module N

Module D

Section D.1

## Module D: Discontinuous functions in ODEs

**How can we solve and apply ODEs involving functions that are not continuous?**

At the end of this module, students will be able to...

- D1. Laplace Transform.** ...compute the Laplace transform of a function
- D2. Discontinuous ODEs.** ...solve initial value problems for ODEs with discontinuous coefficients
- D3. Modeling non-smooth motion.** ...model the motion of an object undergoing discontinuous acceleration
- D4. Modeling non-smooth oscillators.** ...model mechanical oscillators undergoing discontinuous acceleration

## Readiness Assurance Outcomes

Before beginning this module, each student should be able to...

- State the definition of a spanning set, and determine if a set of Euclidean vectors spans  $\mathbb{R}^n$  **V4**.
- State the definition of linear independence, and determine if a set of Euclidean vectors is linearly dependent or independent **S1**.
- State the definition of a basis, and determine if a set of Euclidean vectors is a basis **S2,S3**.
- Find a basis of the solution space to a homogeneous system of linear equations **S6**.

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## Module D Section 1

## Definition D.1.1

A **linear transformation** (also known as a **linear map**) is a map between vector spaces that preserves the vector space operations. More precisely, if  $V$  and  $W$  are vector spaces, a map  $T : V \rightarrow W$  is called a linear transformation if

- ①  $T(\mathbf{v} + \mathbf{w}) = T(\mathbf{v}) + T(\mathbf{w})$  for any  $\mathbf{v}, \mathbf{w} \in V$ .
- ②  $T(c\mathbf{v}) = cT(\mathbf{v})$  for any  $c \in \mathbb{R}, \mathbf{v} \in V$ .

In other words, a map is linear when vector space operations can be applied before or after the transformation without affecting the result.