

# Differential Equations

## Review of the Indefinite Integral

The function  $F(x)$  is called an **antiderivative** of  $f(x)$  if  $F'(x) = f(x)$ .

EX:  $F(x) = 2x^2$  is an antiderivative of  $f(x) = 4x$  because  $\frac{d}{dx}(2x^2) = 4x$ . Similarly,  $F(x) = 2x^2 + 7$  is also an antiderivative of  $f(x) = 4x$  because  $\frac{d}{dx}(2x^2 + 7) = 4x$ .

In general, if  $F(x)$  is an antiderivative of  $f(x)$ , then  $F(x) + C$ , where  $C$  is a constant, is also an antiderivative of  $f(x)$ .

The symbol  $\int f(x) dx$  is used to represent any antiderivative of  $f(x)$ . In this notation,  $f(x)$  is called the **integrand**. An antiderivative  $\int f(x) dx$  is also called an **indefinite integral**.

## Review of Integration

- $\int 0 dx = C$ , for some constant  $C$
- $\int 1 dx = x + C$
- $\int k dx = kx + C$ , where  $k$  is a constant
- $\int x^n dx = \frac{x^{n+1}}{n+1} + C$ , for any rational number  $n$ , where  $n \neq -1$ 
  - $\int \frac{1}{x} dx = \ln|x| + C$
  - $\int e^x dx = e^x + C$
- $\int e^{kx} dx = \frac{1}{k}e^{kx} + C$ , where  $k$  is a constant
- $\int \sin x dx = -\cos x + C$
- $\int \cos x dx = \sin x + C$
- $\int \tan x dx = -\ln|\cos x| + C$
- $\int [f(x) + g(x)] dx = \int f(x) dx + \int g(x) dx$
- $\int [f(x) - g(x)] dx = \int f(x) dx - \int g(x) dx$
- $\int kf(x) dx = k \int f(x) dx$ , where  $k$  is a constant

### To perform integration by parts:

If  $u(x)$  and  $v(x)$  are functions, the **product rule** of differentiation yields  $\frac{d}{dx}(uv) = uv' + vu'$ . To use integration by parts, follow these steps to undo the product rule.

**Step 1:** Factor the integrand into two parts,  $u$  and  $dv$ , so that the integral appears as  $\int u dv$ .

**Step 2:** Use differentiation to find  $du$ , and integrate  $dv$  to find  $v$ .

**Step 3:** Apply the rule  $\int u dv = uv - \int v du$ .

**Step 4:** Find  $\int v du$  to complete the integration.

### To perform integration by substitution:

To find an integral of the form  $\int f(g(x))g'(x) dx$ , use substitution to undo the chain rule of differentiation.

**Step 1:** Set  $u = g(x)$ , where  $g(x)$  is chosen so as to simplify the integrand.

**Step 2:** Substitute  $u = g(x)$  and  $du = g'(x) dx$  into the integrand. (NOTE: This step usually requires multiplying or dividing by a constant.)

**Step 3:** Integrate to find the antiderivative  $\int f(u) du = F(u) + C$ .

**Step 4:** Substitute  $u = g(x)$  to rewrite the antiderivative in the form  $F(g(x)) + C$ .

## Basic Definitions

A **differential equation** is an equation involving an unknown function and one or more of its derivatives.

EX: The following equations are differential equations.

- $y' = 2x + y + 3$
- $\frac{dy}{dx} - 2y = e^x$
- $-2\frac{d^2y}{dx^2} + 4\frac{dy}{dx} + y = 3xy$
- $\frac{\partial^2 u}{\partial x^2} = \frac{\partial^2 u}{\partial y^2}$

## Solutions of a Differential Equation

A **solution** of a differential equation is a function such that the derivatives of the function, the independent variables, and the dependent variable all satisfy the original equation. A differential equation can have one unique solution, no solution, or infinitely many solutions.

In an **explicit solution**, the dependent variable can be expressed solely in terms of the independent variable and constants.

EX:  $y = x^2$  is in the form of an explicit solution.

In an **implicit solution**, the dependent variable is not expressed solely in terms of the independent variable and constants. The solution function is an implicit function.

EX:  $x^2 + y^2 - 25 = 0$  is in the form of an implicit solution.

The **trivial solution** is the function  $y = 0$ .

A **general solution** of a differential equation is a function that contains arbitrary constants.

EX:  $y = \sqrt{c - x^2}$  is in the form of a general solution, where  $c$  is a constant.

A **particular solution** of a differential equation is a function that is free of all arbitrary constants.

EX:  $y = \sqrt{16 - x^2}$  is in the form of a particular solution.

## Verifying a Solution of a Differential Equation

You can verify that a function is a solution of a differential equation by substituting the function and its derivatives into the equation and confirming that the result is an identity.

EX: Verify that the function  $y = \sqrt{16 - x^2}$  is a solution of the differential equation  $\frac{dy}{dx} + \frac{x}{y} = 0$ .

a.  $\frac{dy}{dx} + \frac{x}{y} = 0$  Original differential equation

b.  $\frac{dy}{dx} = \frac{1}{2}(16 - x^2)^{-\frac{1}{2}}(-2x) = \frac{-x}{\sqrt{16 - x^2}}$  This is the derivative of the given solution function.

c.  $\frac{-x}{\sqrt{16 - x^2}} + \frac{x}{\sqrt{16 - x^2}} = 0$  Substitute  $x, y$ , and  $y'$  into the equation  $\frac{dy}{dx} + \frac{x}{y} = 0$ .

d.  $0 = 0$  Simplify.

The result is the identity  $0 = 0$ , so the function  $y = \sqrt{16 - x^2}$  is a solution of the differential equation.

## Classifying Differential Equations

### Classification by Type

An **ordinary differential equation (ODE)** is an equation that contains only *ordinary* derivatives of one or more dependent variables.

EX: The following equations are ODEs.

- $y' + 2y = -2x$
- $-4\frac{d^2y}{dx^2} - 4\frac{dy}{dx} + y = 0$
- $y'' + y' - 8y = 0$

A **partial differential equation (PDE)** is an equation that contains the partial derivatives of one or more dependent variables with respect to two or more independent variables.

EX: The following equations are PDEs.

- $\frac{\partial^2 u}{\partial x^2} = 100\frac{\partial^2 u}{\partial y^2}$
- $\frac{\partial u}{\partial x} = -0.25\frac{\partial^2 u}{\partial x^2}$
- $\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial x^2} = 2xy$

### Classification by Order

The **order** of a differential equation is the order of the highest derivative in the equation.

EX:

$y' + 2y = -2x$  is a first-order differential equation.

$-4\frac{d^2y}{dx^2} - 4\frac{dy}{dx} + y = 0$  is a second-order ODE.

$\frac{\partial u}{\partial x} = -0.25\frac{\partial^2 u}{\partial x^2}$  is a second-order PDE.

### Classification by Linearity

Assume that a differential equation can be written in the form  $y^{(n)} = f(x, y, y', \dots, y^{(n-1)})$ , where  $y^{(n)}$  is the highest-order derivative and  $f$  is a function of the independent variable, dependent variable, and lower-order derivatives.

A **linear differential equation** is an equation in which  $f$  is a linear function of  $y, y', y'', \dots, y^{(n-1)}$ . That is, the differential equation can be written in the form  $b_1(x)y^{(n)} + b_2(x)y^{(n-1)} + \dots + b_n(x)y' + b_{n+1}(x)y = g(x)$ .

EX:

$x^2y'' + \sin(x)y' = e^x$  is linear because each coefficient of  $y$  or one of its derivatives is a function of  $x$ .

$-4\frac{d^2y}{dx^2} - 4\frac{dy}{dx} + y = 0$  is also linear.

If an equation contains functions of  $y$  such as  $e^y$  or functions of the derivatives of  $y$  such as  $\sin(y')$ , then the differential equation is **nonlinear**.

EX:

$y'' + e^y y' + y' = 2x$  is nonlinear because the coefficient of  $y''$  is a function of  $y$ .

$-4\frac{d^2y}{dx^2} + \left(\frac{dy}{dx}\right)^2 + xy = 0$  is nonlinear because the power of  $\frac{dy}{dx}$  is not 1.

$(5y)y'' + (1 - x)y' + y = 10x$  is nonlinear because the coefficient of  $y''$  depends on  $y$ .

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