

# 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  $f(x) = 6x^2$  because  $\frac{d}{dx}(2x^2) = 6x^2$ . Similarly,  $F(x) = 2x^2 + 7$  is also an antiderivative of  $f(x) = 6x^2$  because  $\frac{d}{dx}(2x^2 + 7) = 6x^2$ .

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  $n \neq -1$ 
  - $\int \frac{1}{x} dx = \ln|x| + C$
  - $\int x^n dx = x^{n+1} + C$
- $\int x^m dx = \frac{1}{m+1}x^{m+1} + C$ , where  $m$  is a constant
- $\int \sin x dx = -\cos x + C$
- $\int \cos x dx = \sin x + C$
- $\int \ln x dx = -\ln|x| + C$
- $\int f'(x) dx + g(x) dx = \int f'(x) dx + \int g(x) dx$
- $\int f(x) dx - g(x) dx = \int f(x) dx - \int g(x) dx$
- $\int f(x) dx = k \int f(x) dx$ , where  $k$  is a constant

### To perform Integration by parts:

If  $u(x)$  and  $v(x)$  are functions, the product rule of differentiation yields  $\frac{d}{dx}(uv) = u'v + uv'$ . 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 integral.

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  $u$  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.

- $y' = 2x + y + 3$
- $\frac{dy}{dx} = 2y = e^x$
- $-2 \frac{dy}{dx} + \left( \frac{dy}{dx} \right)^2 = 3xy$
- $\frac{d^2w}{dx^2} = -\frac{dw}{dx}$

## Solutions of a Differential Equation

A solution of a differential equation is a function such that the derivatives of the function, the independent variable, 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:  $y = e^{2x}$  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.  $\frac{dy}{dx} = \frac{x}{y}$  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.

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

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.

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

### 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.

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

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

### Classification by Linearity

Assume that a differential equation can be written in the form  $y^{(n)} - f_1(y, y', y'', \dots, y^{(n-1)}) = 0$ , 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  $b_0y^{(n)} + b_1y^{(n-1)} + \dots + b_ny = g(x)$ .

EX:

-  $y' - xy = x^2$  is linear because each coefficient of  $y$  or one of its derivatives is a function of  $x$ .

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

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

EX:

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

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

-  $(y'y'')^2 + (1 - xy)y' + y = 10x$  is nonlinear because the coefficient of  $y''$  depends on  $y$ .

# Ordinary Differential Equations Comprehensive Final

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**Seymour Lipschutz**

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