

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: $y = 3x^2$ 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 $\frac{dy}{dx} + \frac{y}{x} = 0$.

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

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:

$y'' + xy' + y' = 2x$ 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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