

# Differential Equations

## Review of the Indefinite Integral

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

**EX:**  $F(x) = 2x^3$  is an antiderivative of  $f(x) = 6x^2$  because  $\frac{d}{dx}(2x^3) = 6x^2$ . Similarly,  $F(x) = 2x^3 + 7$  is also an antiderivative of  $f(x) = 6x^2$  because  $\frac{d}{dx}(2x^3 + 7) = 6x^2$ .

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  $n \neq -1$ 
  - $\int \frac{1}{x} dx = \ln|x| + C$
  - $\int e^x dx = e^x + C$
- $\int e^{kx} dx = \frac{1}{k}e^{kx} + C$ , 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  $du = g'(x)$  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.

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

## 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.

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

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.

$\frac{d^2y}{dx^2} - 4\frac{dy}{dx} + y = 0$  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  $k_1 y^{(n)} + k_2 y^{(n-1)} + \dots + k_n y' + k_{n+1} y = g(x)$ .

**EX:**

$x^2 y'' + \sin(x)y' = e^x$  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  $e^y$  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  $y$ .

$\frac{d^2y}{dx^2} + \left(\frac{dy}{dx}\right)^2 + xy = 0$  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  $y$ .

# Differential Equation Learning Guide

**Daniel Zwillinger, Vladimir Dobrushkin**



## **Differential Equation Learning Guide:**

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Differential Equations Ken Yablonsky, 2013-12-31 This handy reference to core concepts is designed to help students in courses that are a gateway to jobs in engineering and science Students can find facts fast maximize study time and increase test scores with our uniquely designed format that offers support for mathematics that are a building block in a highly competitive area *Physics for Science and Engineering* Paul M. Fishbane, Stephen Gasiorowicz, Stephen T. Thornton, Princeton University. Department of Physics, 1993

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for *Differential Equations and Linear Algebra* C. Henry Edwards, David E. Penney, David Calvis, 2017-03      **Introduction to Ordinary Differential Equations with Mathematica®** Alfred Gray, Mike Mezzino, Mark Pinsky, 1998-10-02 The purpose of this companion volume to our text is to provide instructors and eventually students with some additional information to ease the learning process while further documenting the implementations of Mathematica and ODE In an ideal world this volume would not be necessary since we have systematically worked to make the text unambiguous and directly useful by providing in the text worked examples of every technique which is discussed at the theoretical level However in our teaching we have found that it is helpful to have further documentation of the various solution techniques introduced in the text The subject of differential equations is particularly well suited to self study since one can always verify by hand calculation whether or not a given proposed solution is a bona fide solution of the differential equation and initial conditions Accordingly we have not reproduced the steps of the verification process in every case rather content with the illustration of some basic cases of verification in the text As we state there students are strongly encouraged to verify that the proposed solution indeed satisfies the requisite equation and supplementary conditions      **Maple V by Example** Martha L. Abell, James P. Braselton, 1999 Accompanying CD ROM includes all Maple V input that appears in the book      **A Workbook for Differential Equations** Bernd S. W. Schröder, 2009-12-02 An accessible and hands on approach to modeling and predicting real world phenomena using differential equations A Workbook for Differential Equations presents an interactive introduction to fundamental solution methods for ordinary differential equations The author emphasizes the importance of manually working through computations and models rather than simply reading or memorizing formulas Utilizing real world applications from spring mass systems and circuits to vibrating strings and an overview of the hydrogen atom the book connects modern research with the presented topics including first order equations constant coefficient equations Laplace transforms partial differential equations series solutions systems and numerical methods The result is a unique guide to understanding the significance of differential equations in mathematics science and engineering The workbook contains modules that involve readers in as many ways as possible and each module begins with Prerequisites and Learning Objectives sections that outline both the skills needed to understand the presented material and what new skills will be obtained by the conclusion of the module Detailed applications are intertwined in the discussion motivating the investigation of new classes of differential equations and their accompanying techniques Introductory modeling sections discuss applications and why certain known solution techniques may not be enough to successfully analyze certain situations Almost every module concludes with a section that contains various projects ranging from programming tasks to theoretical investigations The book is specifically designed to promote the development of effective mathematical reading habits such as double checking results and filling in omitted steps in a computation Rather than provide lengthy explanations of what readers should do good habits are demonstrated in short sections and a wide range of exercises provide the opportunity to

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