

# Lecture R – Introduction to Differential Equation

## Section R.1 – Derivative

### Constant Rule

$$\frac{d}{dx}[c] = 0 \quad c \text{ is constant}$$

### Example

Find the derivative:

$$a) \quad f(x) = -2 \qquad f'(x) = 0$$

$$b) \quad y = \pi \qquad y' = 0$$

### Power Rule

$$\frac{d}{dx}[x^n] = nx^{n-1} \quad n \text{ is any real number}$$

### Constant Times a Function

$$\frac{d}{dx}[cf(x)] = cf'(x)$$

### Example

Find the derivative each function

$$a. \quad y = \frac{9}{4x^2} = \frac{9}{4}x^{-2}$$

#### Solution

$$\rightarrow y' = \frac{9}{4}(-2)x^{-3} = -\frac{9}{2x^3}$$

$$b. \quad y = \sqrt[3]{x} = x^{1/3}$$

#### Solution

$$\begin{aligned} \rightarrow y' &= \frac{1}{3}x^{(1/3)-1} \\ &= \frac{1}{3}x^{-2/3} \\ &= \frac{1}{3\sqrt[3]{x^2}} \end{aligned}$$

## ***The Product Rule***

The derivative of the product of two differentiable functions is equal to the first function times the derivative of the second plus the second function times the derivative of the first,

$$(f \cdot g)' = f \cdot g' + f' \cdot g$$

$$\frac{d}{dx}[f(x)g(x)h(x)] = f'gh + fg'h + fgh'$$

### ***Example***

Find the derivative of  $y = (4x + 3x^2)(6 - 3x)$

#### **Solution**

$$y = 24x + 6x^2 - 9x^3$$

$$\begin{aligned} y' &= (4x + 3x^2) \frac{d}{dx}(6 - 3x) + (6 - 3x) \frac{d}{dx}(4x + 3x^2) \\ &= (4x + 3x^2)(-3) + (6 - 3x)(4 + 6x) \\ &= -12x - 9x^2 + 24 + 36x - 12x - 18x^2 \\ &= \underline{-27x^2 + 12x + 24} \end{aligned}$$

### ***Example***

Find the derivative of  $y = \left(\frac{1}{x} + 1\right)(2x + 1)$

#### **Solution**

$$\begin{aligned} y' &= \left(x^{-1} + 1\right) \frac{d}{dx}(2x + 1) + (2x + 1) \frac{d}{dx}\left(x^{-1} + 1\right) \\ &= \left(x^{-1} + 1\right)(2) + (2x + 1)(-x^{-2}) \\ &= \frac{2}{x} + 2 + (2x + 1)\left(-\frac{1}{x^2}\right) \\ &= \frac{2}{x} + 2 - \frac{2x}{x^2} - \frac{1}{x^2} \\ &= \frac{2}{x} + 2 - \frac{2}{x} - \frac{1}{x^2} \\ &= 2 - \frac{1}{x^2} \\ &= \underline{\frac{2x^2 - 1}{x^2}} \end{aligned}$$

## Quotient Rule

$$\frac{d}{dx} \left[ \frac{f(x)}{g(x)} \right] = \frac{g(x)f'(x) - f(x)g'(x)}{[g(x)]^2} = \frac{gf' - fg'}{g^2}$$

### Example

Find the derivative of  $y = \frac{x+4}{5x-2}$

#### Solution

$$\begin{aligned} y' &= \frac{(5x-2) \frac{d}{dx} [(x+4)] - (x+4) \frac{d}{dx} [(5x-2)]}{(5x-2)^2} \\ &= \frac{(5x-2)(1) - (x+4)(5)}{(5x-2)^2} \\ &= \frac{5x-2-5x-20}{(5x-2)^2} \\ &= -\frac{22}{(5x-2)^2} \end{aligned}$$

### Example

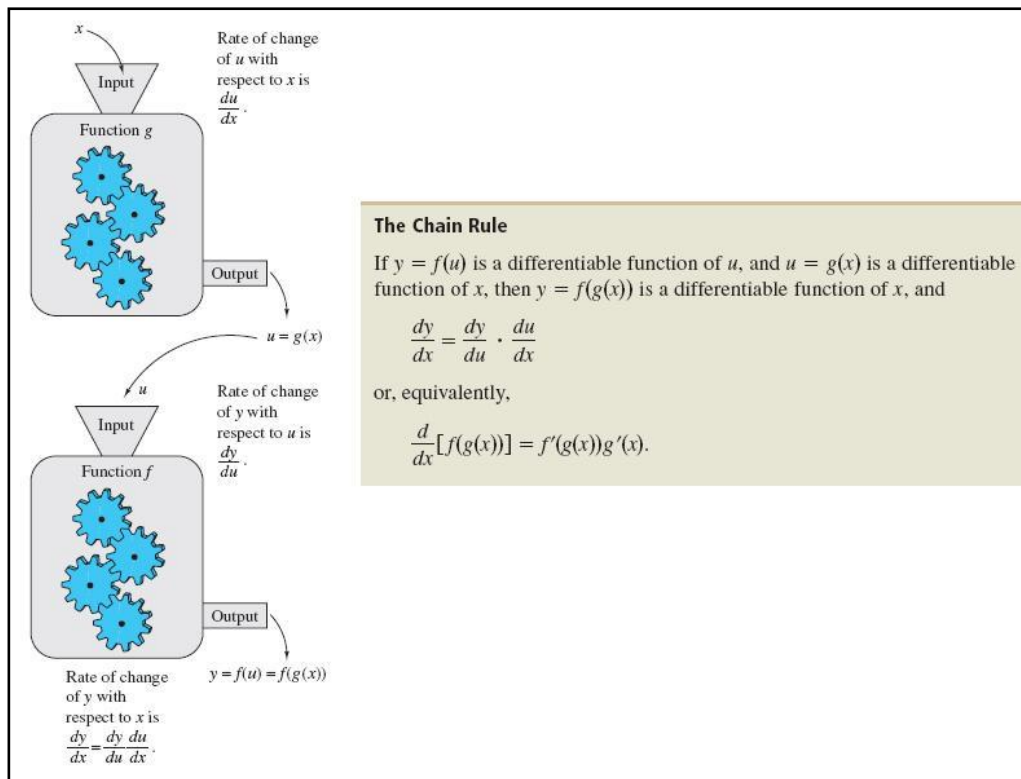
Find the derivative of  $y = \frac{3-\frac{2}{x}}{x+4}$

#### Solution

$$\begin{aligned} y &= \frac{\frac{3x-2}{x}}{x+4} = \frac{3x-2}{x} \cdot \frac{1}{x+4} = \frac{3x-2}{x^2+4x} \\ y' &= \frac{(x^2+4x)(3) - (3x-2)(2x+4)}{[x(x+4)]^2} \\ &= \frac{3x^2+12x-6x^2-12x+4x+8}{x^2(x+4)^2} \\ &= \frac{-3x^2+4x+8}{x^2(x+4)^2} \end{aligned}$$

$$\left( \frac{u}{v} \right)' = \frac{u'v - v'u}{v^2}$$

## The Chain Rule



## The General Power Rule

$$\frac{dy}{dx} = \frac{d}{dx} \left[ u(x)^n \right] = n u^{n-1} \frac{du}{dx}$$

$$\frac{dy}{dx} = \frac{d}{dx} \left[ u^n \right] = n u^{n-1} u'$$

### Example

Find the derivative of  $y = (x^2 + 3x)^4$

### Solution

$$u = x^2 + 3x$$

$$y' = n \quad (u)^{n-1} \quad \frac{d}{dx} [u]$$

$$= 4 \left( x^2 + 3x \right)^3 \frac{d}{dx} [x^2 + 3x]$$

$$= 4 \left( x^2 + 3x \right)^3 (2x + 3)$$

## Derivatives of Trigonometric Functions

$(\sin x)' = \cos x$	$(\cos x)' = -\sin x$	$(\tan x)' = \sec^2 x$
$(\csc x)' = -\csc x \cot x$	$(\sec x)' = \sec x \tan x$	$(\cot x)' = -\csc^2 x$

### Example

Find the derivatives

a)  $y = \sin x \cos x$

$$\begin{aligned}y' &= \sin x (\cos x)' + \cos x (\sin x)' \\&= \sin x (-\sin x) + \cos x (\cos x) \\&= \cos^2 x - \sin^2 x\end{aligned}$$

b)  $y = \frac{\cos x}{1 - \sin x}$

$$\begin{aligned}y' &= \frac{(1 - \sin x)(\cos x)' - \cos x(1 - \sin x)'}{(1 - \sin x)^2} \\&= \frac{(1 - \sin x)(-\sin x) - \cos x(-\cos x)}{(1 - \sin x)^2} \\&= \frac{-\sin x + \sin^2 x + \cos^2 x}{(1 - \sin x)^2} \\&= \frac{1 - \sin x}{(1 - \sin x)^2} \\&= \frac{1}{1 - \sin x}\end{aligned}$$

$$\sin^2 x + \cos^2 x = 1$$

## *Derivative of the Natural Exponential Function*

$$\frac{d}{dx}[e^x] = e^x$$

$$\frac{d}{dx}[e^U] = e^U \frac{dU}{dx}$$

Differentiate each function.

a)  $f(x) = e^{-2x^3}$

$$f'(x) = e^{-2x^3} \frac{d}{dx}[-2x^3]$$

$$= e^{-2x^3} [-6x^2]$$

$$= -\frac{6x^2}{e^{2x^3}}$$

b)  $f(x) = 4e^{x^2}$

$$f'(x) = 4e^{x^2} \frac{d}{dx}[x^2]$$

$$= 4e^{x^2} (2x)$$

$$= 8xe^{x^2}$$

c)  $y = 10e^{3x^2}$

$$y' = 10e^{3x^2} (3x^2)'$$

$$= 10e^{3x^2} (6x)$$

$$= 60x e^{3x^2}$$

## Derivative of $\ln$

$$\frac{d}{dx}(\ln x) = \frac{1}{x}$$

$$\frac{d}{dx}(\ln u) = \frac{1}{u} \cdot \frac{du}{dx} = \frac{u'}{u}$$

**Note:**  $\ln U \Rightarrow U > 0$

## Derivative of $\log_a x$

$$\frac{d}{dx}[\log_a x] = \frac{1}{(\ln a)x}$$

## Example

Find the Derivatives

a)  $f(x) = \ln(x^2 - 4)$

$$\text{Let } u = x^2 - 4 \Rightarrow \frac{du}{dx} = 2x$$

$$f'(x) = \frac{1}{u} \frac{du}{dx}$$

$$= \frac{1}{x^2 - 4} (2x)$$

$$= \frac{2x}{x^2 - 4}$$

b)  $f(x) = x^2 \ln x$

$$f' = x^2 \frac{d}{dx}[\ln x] + \ln x \frac{d}{dx}[x^2] \quad (fg)' = f'g + fg'$$

$$= x^2 \left( \frac{1}{x} \right) + 2x \ln x$$

$$= x + 2x \ln x$$

$$= x(1 + 2 \ln x)$$

c)  $f(x) = -\frac{\ln x}{x^2}$

$$f' = -\frac{x^2 \frac{d}{dx}[\ln x] - \ln x \frac{d}{dx}[x^2]}{(x^2)^2}$$

$$= -\frac{x^2 \frac{1}{x} - 2x \ln x}{x^4}$$

$$\begin{aligned}
&= -\frac{x-2x\ln x}{x^4} \\
&= -\frac{x(1-2\ln x)}{x^4} \\
&= \underline{-\frac{1-2\ln x}{x^3}}
\end{aligned}$$

## Other Bases and Differentiation

$$\frac{d}{dx} \left[ a^x \right] = a^x \ln a$$

$$\frac{d}{dx} \left[ a^u \right] = a^u (\ln a) \frac{du}{dx}$$

$$\frac{d}{dx} \left[ \log_a x \right] = \left( \frac{1}{\ln a} \right) \frac{1}{x} \frac{d}{dx} \left[ \log_a u \right] = \left( \frac{1}{\ln a} \right) \left( \frac{1}{u} \right) \frac{du}{dx}$$

**Formula**  $\left( U^m V^n W^p \right)' = U^{m-1} V^{n-1} W^{p-1} (m U' V W + n U V' W + p U V W')$

**Proof**

$$\begin{aligned}
\left( U^m V^n W^p \right)' &= \left( U^m \right)' V^n W^p + U^m \left( V^n \right)' W^p + U^m V^n \left( W^p \right)' \\
&= m U^{m-1} U' V^n W^p + n U^m V^{n-1} V' W^p + p U^m V^n W^{p-1} W' \quad \text{factor } U^{m-1} V^{n-1} W^{p-1} \\
&= U^{m-1} V^{n-1} W^{p-1} (m U' V W + n U V' W + p U V W')
\end{aligned}$$

$$\left( U^m V^n \right)' = U^{m-1} V^{n-1} (m U' V + n U V')$$



## Exercises      Section R.1 – Derivative

Find the derivative to the following functions

1.  $f(t) = -3t^2 + 2t - 4$

2.  $g(x) = 4\sqrt[3]{x} + 2$

3.  $f(x) = x(x^2 + 1)$

4.  $f(x) = \frac{2x^2 - 3x + 1}{x}$

5.  $f(x) = \frac{4x^3 - 3x^2 + 2x + 5}{x^2}$

6.  $f(x) = \frac{-6x^3 + 3x^2 - 2x + 1}{x}$

7.  $f(x) = x\left(1 - \frac{2}{x+1}\right)$

8.  $g(s) = \frac{s^2 - 2s + 5}{\sqrt{s}}$

9.  $f(x) = \frac{x+1}{\sqrt{x}}$

10.  $f(x) = 3x(2x^2 + 5x)$

11.  $y = 3(2x^2 + 5x)$

12.  $y = \frac{x^2 + 4x}{5}$

13.  $y = \frac{3x^4}{5}$

14.  $y = \frac{x^2 - 4}{2x + 5}$

15.  $y = \frac{(1+x)(2x-1)}{x-1}$

16.  $y = \frac{4}{2x+1}$

17.  $y = \frac{2}{(x-1)^3}$

Use the General Power Rule to find the derivative of the function

18.  $f(x) = \sqrt{2t^2 + 5t + 2}$

19.  $f(x) = \frac{1}{(x^2 - 3x)^2}$

20.  $y = t^2\sqrt{t-2}$

21.  $y = \left(\frac{6-5x}{x^2-1}\right)^2$

22.  $y = x^2\sqrt{x^2+1}$

23.  $y = \left(\frac{x+1}{x-5}\right)^2$

24.  $y = \sqrt[3]{(x+4)^2}$

Find the derivative of the trigonometric function

25.  $y = x^2 \sin x$

26.  $y = \frac{\sin x}{x}$

27.  $y = \frac{\cot x}{1 + \cot x}$

28.  $y = x^2 \sin x + 2x \cos x - 2 \sin x$

29.  $y = x^3 \sin x \cos x$

30.  $y = \frac{4}{\cos x} + \frac{1}{\tan x}$

Differentiate each function.

31.  $f(x) = x^2 e^x$

32.  $f(x) = \frac{e^x + e^{-x}}{2}$

33.  $f(x) = (1+2x)e^{4x}$

34.  $y = x^2 e^{5x}$

35.  $y = e^{x^2+1} \sqrt{5x+2}$

36.  $f(x) = \frac{e^x}{x^2}$

37.  $f(x) = x^2 e^x - e^x$

$$38. \quad f(x) = \ln \sqrt[3]{x+1}$$

$$39. \quad f(x) = \ln \left[ x^2 \sqrt{x^2 + 1} \right]$$

$$40. \quad y = \ln \frac{x^2}{x^2 + 1}$$

$$41. \quad y = \ln \frac{1 + e^x}{1 - e^x}$$

$$42. \quad y = x \cdot 3^{x+1}$$

$$43. \quad f(t) = \frac{\log_8(t^{3/2} + 1)}{t}$$

## Section R.2 – Integration

### Definition of Antiderivative

A Function  $F$  is an Antiderivative of a function  $f$  if for every  $x$  in the domain of  $f$ , it follows that  $F'(x) = f(x)$

### Notation for Antiderivatives and indefinite integrals

The notation

$$\int f(x)dx = F(x) + C$$

where  $C$  is an arbitrary constant, means that  $F$  is an Antiderivative of  $f$ .  
That is  $F'(x) = f(x)$  for all  $x$  in the domain of  $f$ .

$$\int f(x)dx \text{ Indefinite integral}$$

The diagram shows the notation  $\int f(x)dx = F(x) + C$  with four red labels and arrows: 'Integral sign' points to the integral symbol; 'Integrand' points to  $f(x)$ ; 'Antiderivative' points to  $F(x)$ ; and 'Differential' points to  $dx$ .

### Basic Integration Rules

$$\int kdx = kx + C$$

$$\int kf(x)dx = k \int f(x)dx$$

$$\int [f(x) + g(x)]dx = \int f(x)dx + \int g(x)dx$$

$$\int [f(x) - g(x)]dx = \int f(x)dx - \int g(x)dx$$

$$\int x^n dx = \frac{x^{n+1}}{n+1} + C \quad n \neq -1$$

## The General Power Rule

The Simple Power Rule is given by:

$$\int x^n dx = \frac{x^{n+1}}{n+1} + C \quad n \neq -1$$

$$\begin{aligned} \int \overbrace{(x^2 + 1)^3}^{u^3} \underbrace{2x dx}_{du} &= \int u^3 du \\ &= \frac{u^4}{4} + C \end{aligned}$$

## General Power Rule for Integration

If  $u$  is a differentiable function of  $x$ , then

$$\int u^n \frac{du}{dx} dx = \int u^n du = \frac{u^{n+1}}{n+1} + C \quad n \neq -1$$

### Example

Find each indefinite integral.

$$\begin{aligned} \int 5x dx &= \int 5x^1 dx \\ &= 5 \frac{x^{1+1}}{1+1} + C \\ &= \frac{5}{2} x^2 + C \end{aligned}$$

$$\begin{aligned} \int \sqrt[3]{x} dx &= \int x^{1/3} dx \\ &= \frac{x^{1/3+1}}{1/3+1} + C \\ &= \frac{x^{4/3}}{4/3} + C \\ &= \frac{3}{4} x^{4/3} + C \quad \text{or} \quad = \frac{3}{4} x \sqrt[3]{x} + C \end{aligned}$$

## Using the Exponential Rule

Let  $u$  be a differentiable function of  $x$

$$\int e^u du = e^u + C$$

General Exponential Rule

### Example

Find the indefinite integral  $\int e^{2x+3} dx$

### Solution

Let  $u = 2x + 3 \rightarrow du = 2dx$

$$\begin{aligned}\int e^{2x+3} dx &= \int e^u \frac{1}{2} du \\ &= \frac{1}{2} \int e^u du \\ &= \frac{1}{2} e^u + C \\ &= \frac{1}{2} e^{2x+3} + C\end{aligned}$$

## Using the Log Rule

Let  $u$  be a differentiable function of  $x$ .

$$\int \frac{du / dx}{u} dx = \int \frac{1}{u} du = \ln|u| + C$$

General Logarithmic Rule

### Example

Find the indefinite integral  $\int \frac{1}{4x+1} dx$

### Solution

Let  $u = 4x + 1 \rightarrow du = 4dx \rightarrow \frac{1}{4} du = dx$

$$\begin{aligned}\int \frac{1}{4x+1} dx &= \int \frac{1}{u} \frac{1}{4} du \\ &= \frac{1}{4} \int \frac{1}{u} du \\ &= \frac{1}{4} \ln|u| + C \\ &= \frac{1}{4} \ln|4x+1| + C\end{aligned}$$

## Integration by Parts

Let  $u$  and  $v$  be differentiable functions of  $x$ .

$$\int u dv = uv - \int v du$$

### Guidelines for integration by Parts

1. Let  $dv$  be the most complicated portion of the integrand that fits a basic integration formula. Let  $u$  be the remaining factor.
2. Let  $u$  be the portion of the integrand whose derivative is a function simpler than  $u$ . Let  $dv$  be the remaining factor.

### Example

Find  $\int x \cos x dx$

### Solution

Let:

$$u = x \quad dv = \cos x dx$$

$$du = dx \quad v = \int dv = \int \cos x dx = \sin x$$

$$\int u dv = uv - \int v du$$

$$\begin{aligned} \int x \cos x dx &= x \sin x - \int \sin x dx \\ &= \underline{x \sin x + \cos x + C} \end{aligned}$$

### Example

Evaluate  $\int x^2 e^x dx$

### Solution

$$f(x) = x^2 \quad \text{and} \quad g(x) = e^x$$

$$\int x^2 e^x dx = \underline{x^2 e^x - 2x e^x + 2e^x + C}$$

	derivative	$\int e^x dx$
(+)	$x^2$	$e^x$
(-)	$2x$	$e^x$
(+)	$2$	$e^x$
	$0$	

## Particular Solutions

In many applications of integrations, we are given enough information to determine a particular solution. To do this, we need to know the value of  $F(x)$  for one value of  $x$ . This information is called an initial condition.

### Example

Solve the differential equation:  $y' = te^t$  that satisfies  $y(0) = 2$

#### Solution

$$y = \int te^t dt$$

$$\text{Integration by part: } \int u dv = uv - \int v du$$

$$\begin{cases} u = t \Rightarrow du = dt \\ dv = e^t dt \Rightarrow v = e^t \end{cases}$$

$$y = te^t - \int e^t dt$$

$$= te^t - e^t + C$$

$$y(0) = (0)e^0 - e^0 + C = 2$$

$$-1 + C = 2$$

$$C = 3$$

$$\underline{y(t) = e^t(t-1) + 3}$$

### Example

Solve the differential equation:  $y' = \frac{1}{x}$  that satisfies  $y(1) = 3$

#### Solution

$$y = \int \frac{1}{x} dx$$

$$= \ln|x| + C$$

$$y(1) = \ln|1| + C = 3$$

$$\boxed{C = 3}$$

$$\underline{y(x) = \ln x + 3} \quad \text{with } x > 0$$

### ***Example***

Suppose a ball thrown into the air with initial velocity  $v_0 = 20 \text{ ft/sec}$ . Assuming the ball thrown from a height of  $x_0 = 6 \text{ ft}$ , how long does it take for the ball to hit the ground?

### **Solution**

$$\frac{dv}{dt} = -g \Rightarrow dv = -gdt$$

$$v(t) = -gt + C_1$$

$$v(t=0) = -g(0) + C_1 = 20$$

$$C_1 = 20$$

$$v(t) = -32t + 20$$

$$\frac{dx}{dt} = v \Rightarrow dx = vdt$$

$$\int dx = \int vdt$$

$$x(t) = \int (-32t + 20)dt$$

$$= -16t^2 + 20t + C_2$$

$$x(t=0) = -16(0)^2 + 20(0) + C_2 = 6$$

$$C_2 = 6$$

$$\underline{x(t) = -16t^2 + 20t + 6}$$



## ***Theorem*** – The Fundamental Theorem of Calculus, P-2

If  $f$  is continuous at every point in  $[a, b]$ , then  $F$  is any antiderivative of  $f$  on  $[a, b]$ , then

$$\boxed{\int_a^b f(x) dx = F(b) - F(a)}$$

### ***Example***

$$\begin{aligned} a) \quad \int_0^{\pi} \cos x \, dx &= \sin x \Big|_0^{\pi} \\ &= \sin \pi - \sin 0 \\ &= \underline{0} \end{aligned}$$

$$\begin{aligned} b) \quad \int_{-\frac{\pi}{4}}^0 \sec x \tan x \, dx &= \sec x \Big|_{-\frac{\pi}{4}}^0 \\ &= \sec 0 - \sec\left(-\frac{\pi}{4}\right) \\ &= \underline{1 - \sqrt{2}} \end{aligned}$$

$$\begin{aligned} c) \quad \int_1^4 \left( \frac{3}{2} \sqrt{x} - \frac{4}{x^2} \right) dx &= \left[ x^{3/2} + \frac{4}{x} \right]_1^4 \\ &= \left( (4)^{3/2} + \frac{4}{4} \right) - \left( (1)^{3/2} + \frac{4}{1} \right) \\ &= (9) - (5) \\ &= \underline{4} \end{aligned}$$

## Exercises Section R.2 – Integration

Find each indefinite integral.

1.  $\int \frac{x+2}{\sqrt{x}} dx$

2.  $\int 4y^{-3} dy$

3.  $\int (x^3 - 4x + 2) dx$

4.  $\int \left( \sqrt[4]{x^3} + 1 \right) dx$

5.  $\int \sqrt{x}(x+1) dx$

6.  $\int (1+3t)t^2 dt$

7.  $\int \frac{x^2-5}{x^2} dx$

8.  $\int (-40x + 250) dx$

9.  $\int (7-3x-3x^2)(2x+1) dx$

10.  $\int xe^{2x} dx$

11.  $\int x \ln x dx$

12.  $\int (x^2 - 2x + 1)e^{2x} dx$

13.  $\int e^{2x} \cos 3x dx$

Find the general solution of the differential equation

14.  $y' = 2t + 3$

15.  $y' = 3t^2 + 2t + 3$

16.  $y' = \sin 2t + 2 \cos 3t$

17.  $y' = x^3(3x^4 + 1)^2$

18.  $y' = 5x\sqrt{x^2 - 1}$

19.  $y' = x\sqrt{x^2 + 4}$

20.  $y' = (2x + 1)e^{x^2 + x}$

21.  $y' = \frac{1}{6x-5}$

22.  $y' = \frac{x^2 + 2x + 3}{x^3 + 3x^2 + 9x + 1}$

23.  $y' = \frac{1}{x(\ln x)^2}$

Evaluate the integrals

24.  $\int_{-2}^2 (x^3 - 2x + 3) dx$

25.  $\int_0^1 (x^2 + \sqrt{x}) dx$

26.  $\int_0^{\pi/3} 4 \sec u \tan u du$

27.  $\int_{\pi/4}^{3\pi/4} \csc \theta \cot \theta d\theta$

28.  $\int_{-\pi/3}^{-\pi/4} \left( 4 \sec^2 t + \frac{\pi}{t^2} \right) dt$

29.  $\int_{-3}^{-1} \frac{y^5 - 2y}{y^3} dy$

30.  $\int_1^8 \frac{(x^{1/3} + 1)(2 - x^{2/3})}{x^{1/3}} dx$

31.  $\int_0^1 (2t + 3)^3 dt$

32.  $\int_{-1}^1 r\sqrt{1-r^2} dr$

33. Find the general solution of  $F'(x) = 4x + 2$ , and find the particular solution that satisfies the initial condition  $F(1) = 8$ .
34. Find the general solution of the differential equation:  $y' = t \cos 3t$
35. A ball is thrown into the air from an initial height of  $6\text{ m}$  with an initial velocity of  $120\text{ m/s}$ . What will be the maximum height of the ball and at what time will this event occur?
36. Derive the position function if a ball is thrown upward with initial velocity of  $32\text{ ft per second}$  from an initial height of  $48\text{ ft}$ . When does the ball hit the ground? With what velocity does the ball hit the ground?