

# Multi Variable Calculus

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## Contents

<b>1</b>	<b>Fourier</b>	<b>4</b>
1.1	Fourier Series . . . . .	4
1.2	Fourier Transform . . . . .	4
1.3	Examples . . . . .	4
1.3.1	Example 1: Fourier Series . . . . .	4
1.3.2	Example 2: Fourier Transform . . . . .	6
1.3.3	Example 3: Inverse Fourier Transform . . . . .	6
1.3.4	Example 4: Fourier Transform . . . . .	6
<b>2</b>	<b>Laplace transform</b>	<b>7</b>
2.1	Examples . . . . .	7
2.1.1	Example 1: Laplace Transform . . . . .	7
2.1.2	Example 2: Trabsfer Function . . . . .	7
<b>3</b>	<b>Several-Variables</b>	<b>8</b>
3.1	Examples . . . . .	8
3.1.1	Example 1: Gradient . . . . .	8
3.1.2	Example 2: Jacobian . . . . .	8
3.1.3	Example 3: Chain Rule . . . . .	8
3.1.4	Example 4: Substitution . . . . .	9
3.1.5	Example 5: Partial Differentiation . . . . .	9
<b>4</b>	<b>Double-Integrals</b>	<b>10</b>
4.1	Riemann Sum . . . . .	10
4.2	Double Integrals over General domains . . . . .	10
4.3	Iteration of Double Integrals . . . . .	10
4.4	Double Integrals in Polar Coordinates . . . . .	10
4.4.1	Limits for Polar Coordinates . . . . .	10
4.5	Change of Variables in Double Integrals . . . . .	10
4.6	Examples . . . . .	11
4.6.1	Example 1: Change of Variables . . . . .	11
4.6.2	Example 2: Double integral . . . . .	12
4.6.3	Example 3: By iteration . . . . .	12
4.6.4	Example 4: By iteration . . . . .	13
4.6.5	Example 5: Polar coordinates . . . . .	13
<b>5</b>	<b>Tripple-Integrals</b>	<b>14</b>
5.1	Riemann Sum . . . . .	14
5.2	Tripple Integrals over General domains . . . . .	14
5.3	Change of Variables . . . . .	14

5.4	Cylindrical Coordinates . . . . .	14
5.4.1	Limits for Cylindrical Coordinates . . . . .	14
5.5	Spherical Coordinates . . . . .	14
5.5.1	Limits for Spherical Coordinates . . . . .	15
5.6	Examples . . . . .	15
5.6.1	Example 1: Triple Integral . . . . .	15
5.6.2	Example 2: Spherical Coordinates . . . . .	15
5.6.3	Example 3: Jacobian Transformation . . . . .	16
5.6.4	Example 4: Triple Integral . . . . .	16
<b>6</b>	<b>Fields-Curve</b>	<b>18</b>
6.1	Curve & Parameterization . . . . .	18
6.2	Vector Fields . . . . .	18
6.2.1	Scalar field . . . . .	18
6.2.2	Field lines . . . . .	18
6.2.3	Conservation field . . . . .	18
6.2.4	Vector field in Polar Coordinates . . . . .	19
6.3	Line Integral . . . . .	19
6.3.1	Line integral of a vector field . . . . .	19
6.4	Examples . . . . .	19
6.4.1	Example 1: Conservative vector field and potential . . . . .	19
6.4.2	Example 2: Line integral . . . . .	20
6.4.3	Example 3: Line integral . . . . .	20
6.4.4	Example 4: Line integral vector field . . . . .	20
6.4.5	Example 5: Line integral over specified curve . . . . .	21
6.4.6	Example 6: Parametrize a curve . . . . .	21
<b>7</b>	<b>Surface-Integrals</b>	<b>22</b>
7.1	Parametric Surface . . . . .	22
7.2	Surface Area . . . . .	22
7.3	Oriented Surface . . . . .	22
7.4	Flux . . . . .	23
7.5	Examples . . . . .	23
<b>8</b>	<b>Theorems</b>	<b>24</b>
8.1	Differential Operators . . . . .	24
8.1.1	Gradient . . . . .	24
8.1.2	Divergence . . . . .	24
8.1.3	Curl . . . . .	24
8.2	Green's Theorem . . . . .	24
8.3	Stokes' Theorem . . . . .	24
8.4	Divergence Theorem . . . . .	24
8.5	Examples . . . . .	25
8.5.1	Example 1: Div and Curl . . . . .	25
8.5.2	Example 2: Green's Theorem . . . . .	25
8.5.3	Example 3: Stokes' Theorem . . . . .	26
8.5.4	Example 4: Divergence Theorem . . . . .	26
<b>9</b>	<b>PDE</b>	<b>27</b>
9.1	Classification of PDEs . . . . .	27
9.2	Characteristics of PDEs . . . . .	27
9.3	Important Second-Order PDEs . . . . .	28
9.4	Initial and Boundary Conditions . . . . .	28
9.5	Wave Equation (1D) . . . . .	28
9.5.1	D'Alembert's Solution of the Wave Equation . . . . .	28

9.6	Heat Equation (1D)	29
9.7	Examples	29
9.7.1		29

# 1 Fourier

## 1.1 Fourier Series

A periodic function with period  $2L$  and let  $f(x)$  and  $f'(x)$  be piecewise continuous on the interval  $-L < x < L$

$$S_N(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left( a_n \cos\left(\frac{n\pi x}{L}\right) + b_n \sin\left(\frac{n\pi x}{L}\right) \right) = \sum_{n=-\infty}^{\infty} c_n e^{jn\pi x/L}$$

The coefficients are given by:

$$a_n = \frac{1}{L} \int_{-L}^L f(x) \cos\left(\frac{n\pi x}{L}\right) dx \quad n \geq 0$$

$$b_n = \frac{1}{L} \int_{-L}^L f(x) \sin\left(\frac{n\pi x}{L}\right) dx \quad n > 0$$

$$c_n = \frac{1}{2}(a_n - jb_n) \quad n > 0$$

## 1.2 Fourier Transform

If  $h(t)$  is a periodic function then the Fourier transform is given by:

$$H(\omega) = \int_{-\infty}^{\infty} h(t) e^{-j\omega t} dt$$

Inverse Fourier transformation of  $H(\omega)$ :

$$h(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} H(\omega) e^{j\omega t} d\omega$$

Signal	Fourier Transform
$\delta(t)$	1
$u(t)$	$\frac{1}{j\omega} + \pi\delta(\omega)$
$\delta(t - t_0)$	$e^{-j\omega t_0}$
$\sin(\omega_0 t)$	$-j\pi(\delta(\omega - \omega_0) - \delta(\omega + \omega_0))$
$\cos(\omega_0 t)$	$\pi(\delta(\omega - \omega_0) + \delta(\omega + \omega_0))$
1	$2\pi\delta(\omega)$

## 1.3 Examples

### 1.3.1 Example 1: Fourier Series

Find the Fourier coefficients and Fourier Series for the square wave shown below:

$$f(x) = \begin{cases} 0 & \text{for } -1 \leq x \leq 0 \\ 1 & \text{for } 0 \leq x \leq 1 \end{cases}$$

and

$$f(x+2) = f(x)$$

---

The fourier series is given by:

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left( a_n \cos\left(\frac{n\pi x}{L}\right) + b_n \sin\left(\frac{n\pi x}{L}\right) \right)$$

Find the  $L$  value:

$$2L = 2 \quad \Rightarrow \quad L = 1$$

Find  $a_0$ :

$$\begin{aligned} a_n &= \frac{1}{L} \int_{-L}^L f(x) \cos\left(\frac{n\pi x}{L}\right) dx \quad n \geq 0 \\ a_0 &= \frac{1}{1} \int_{-1}^1 f(x) \cos\left(\frac{0\pi x}{1}\right) dx = \int_{-1}^1 f(x) dx = \int_{-1}^0 0 dx + \int_0^1 1 dx = 1 \end{aligned}$$

Find  $a_n$ :

$$\begin{aligned} a_n &= \frac{1}{L} \int_{-L}^L f(x) \cos\left(\frac{n\pi x}{L}\right) dx \quad n \geq 0 \\ &= \frac{1}{1} \int_{-1}^1 f(x) \cos\left(\frac{n\pi x}{1}\right) dx = \int_{-1}^1 f(x) \cos(n\pi x) dx \\ &= \int_{-1}^0 0 \cos(n\pi x) dx + \int_0^1 1 \cos(n\pi x) dx = 0 + \left[ \frac{\sin(n\pi x)}{n\pi} \right]_0^1 = \frac{\sin(\pi n)}{\pi n} \end{aligned}$$

For all  $n$ :

$$\frac{\sin(\pi n)}{\pi n} = 0$$

Find  $b_n$ :

$$\begin{aligned} b_n &= \frac{1}{L} \int_{-L}^L f(x) \sin\left(\frac{n\pi x}{L}\right) dx \quad n > 0 \\ b_n &= \int_{-1}^1 f(x) \sin\left(\frac{n\pi x}{1}\right) dx = \int_{-1}^0 0 \sin(n\pi x) dx + \int_0^1 1 \sin(n\pi x) dx \\ &= 0 + \left[ \frac{-\cos(n\pi x)}{n\pi} \right]_0^1 = \frac{-\cos(n\pi 1)}{n\pi} - \frac{-\cos(n\pi 0)}{n\pi} \end{aligned}$$

If  $n$  is even the function will cancel out, therefore  $n = 1, 3, 5, \dots$  (odd):

$$= \frac{1}{n\pi} + \frac{1}{n\pi} = \frac{2}{n\pi}$$

Ans:

$$f(x) = \frac{1}{2} + \sum_{n=1,3,5,\dots} \frac{2}{n\pi} \sin(n\pi x)$$

### 1.3.2 Example 2: Fourier Transform

The unit step function is defined as:

$$u(t - a) = \begin{cases} 1 & \text{for } t - a > 0 \\ 0 & \text{for } t - a < 0 \end{cases}$$

is used to define the rectangular pulse function:

$$x(t) = u(t - a) - u(t - b) \quad \text{where } a < b$$

---

$$\begin{aligned} X(\omega) &= \int_{-\infty}^{\infty} x(t) e^{-j\omega t} dt \\ X(\omega) &= \int_{-\infty}^a 0 e^{-j\omega t} dt + \int_a^b 1 e^{-j\omega t} dt + \int_b^{\infty} 0 e^{-j\omega t} dt \\ X(\omega) &= 0 + \left[ \frac{-e^{-j\omega t}}{j\omega} \right]_a^b + 0 \end{aligned}$$

Insert the limits:

$$X(\omega) = \frac{e^{-j\omega a} - e^{-j\omega b}}{j\omega}$$

### 1.3.3 Example 3: Inverse Fourier Transform

Consider the signal:  $X(\omega) = \delta(\omega - \omega_0)$  where  $\omega_0$  is a constant. Find the inverse Fourier Transform of this signal to find  $x(t)$ .

### 1.3.4 Example 4: Fourier Transform

Consider the signal:  $x(\omega) = \delta(\omega - \omega_0)$  where  $\omega_0$  is a constant. Find the inverse Fourier Transform of this signal to find  $x(t)$ . Ans:

$$X(\omega) = -j\pi(\delta(\omega - \omega_0) - \delta(\omega + \omega_0))$$

## 2 Laplace transform

Is a generalisation of the Fourier transform and defined as:

$$H(s) = \mathcal{L}\{h(t)\} = \int_{0^-}^{\infty} h(t)e^{-st} dt \quad s \in \mathbb{C}$$

$s$  is a complex number  $s = \sigma + j\omega$  and is identical with Fourier transform, if  $s$  is set to  $j\omega$ .  
Inverse Laplace tranformation:

$$h(t) = \mathcal{L}^{-1}\{H(t)\} = \frac{1}{2\pi j} \int_{\sigma_c - j\infty}^{\sigma_c + j\infty} H(s)e^{st} ds$$

Signal	Laplace Transform
1	$\frac{1}{s}$
$e^{at}$	$\frac{1}{s-a}$
$\sin(at)$	$\frac{a}{s^2+a^2}$
$\cos(at)$	$\frac{s}{s^2+a^2}$

### 2.1 Examples

#### 2.1.1 Example 1: Laplace Transform

Using the Laplace transform, find the solution for the following equation:

$$\frac{\partial^2}{\partial t^2}y(t) + 2\frac{\partial}{\partial t}y(t) + 2y(t) = 0$$

with initial conditions  $y(0) = 1$  and  $Dy(0) = -1$

#### 2.1.2 Example 2: Trabsfer Function

Consider a mass-spring-damper system with the following differential equation:

$$m\ddot{x} = -kx - b\dot{x} + f$$

Find the transfer function for the system with input  $f$  and output  $x$ .

$$ms^2X(s) = -kX(s) - bsX(s) + F(s)$$

$$ms^2X(s) + kX(s) + bsX(s) = F(s)$$

$$(ms^2 + k + bs)X(s) = F(s)$$

The transfer function is:

$$\frac{X(s)}{F(s)} = \frac{1}{ms^2 + k + bs}$$

## 3 Several-Variables

### 3.1 Examples

#### 3.1.1 Example 1: Gradient

Find the rate of change of  $f(x, y) = y^4 + 2xy^3 + x^2y^2$  at  $(0, 1)$  in each of the following directions:

1.  $\mathbf{i} + 2\mathbf{j}$
2.  $\mathbf{j} - 2\mathbf{i}$
3.  $3\mathbf{i}$
4.  $\mathbf{i} + \mathbf{j}$

#### 3.1.2 Example 2: Jacobian

Find the Jacobian  $Df(1, 0)$  for the transformation from  $\mathbb{R}^2$  to  $\mathbb{R}^3$  given by:

$$\mathbf{f}(x, y) = (xe^y + \cos(\pi y), x^2, x - e^y)$$

#### 3.1.3 Example 3: Chain Rule

If  $z = \sin(x^2y)$  where  $x = st^2$  and  $y = s^2 + \frac{1}{t}$ , find  $\frac{\partial z}{\partial s}$  and  $\frac{\partial z}{\partial t}$  using chain rule.

---

For:

$$\frac{\partial z}{\partial s} = \frac{\partial z}{\partial x} \frac{\partial x}{\partial s} + \frac{\partial z}{\partial y} \frac{\partial y}{\partial s}$$

$$\frac{\partial z}{\partial x} = 2xy \cos(x^2y)$$

$$\frac{\partial x}{\partial s} = t^2$$

$$\frac{\partial z}{\partial y} = x^2 \cos(x^2y)$$

$$\frac{\partial y}{\partial s} = 2s$$

Find:

$$\frac{\partial z}{\partial s} = (2xy \cos(x^2y))t^2 + (x^2 \cos(x^2y))2s$$

Replace  $x$  and  $y$  with  $x = st^2$  and  $y = s^2 + \frac{1}{t}$ :

$$\frac{\partial z}{\partial s} = (4s^3t^4 + 2st^3) \cos(s^4t^4 + s^2t^3)$$

Same principal for:

$$\frac{\partial z}{\partial t} = \frac{\partial z}{\partial y} \frac{\partial y}{\partial t} + \frac{\partial z}{\partial x} \frac{\partial x}{\partial t}$$



### 3.1.4 Example 4: Substitution

If  $z = \sin(x^2y)$  where  $x = st^2$  and  $y = s^2 + \frac{1}{t}$  find  $\frac{\partial z}{\partial s}$  and  $\frac{\partial z}{\partial t}$  using substitution.

---

$$\begin{aligned}z &= \sin\left((st^2)^2s^2 + \frac{1}{t}\right) = \sin\left(s^2t^4(s^2 + \frac{1}{t})\right) = s^4t^4 + s^2t^3 \\ \frac{\partial z}{\partial s} &= \sin(s^4t^4 + s^2t^3) = (4s^3t^4 + 2st^3) \cos(s^4t^4 + s^2t^3) \\ \frac{\partial z}{\partial t} &= \sin(s^4t^4 + s^2t^3) = (s^44t^3 + s^23t^2) \cos(s^4t^4 + s^2t^3)\end{aligned}$$

### 3.1.5 Example 5: Partial Differentiation

Calculate  $f_{223}(x, y, z)$ ,  $f_{232}(x, y, z)$ , and  $f_{322}(x, y, z)$  of the following function:

$$f(x, y, z) = e^{x-2y+3z}$$

Normal Differentiation. For  $f_{223}(x, y, z)$ , start with  $y$ , then  $y$  again, and then  $z$ :

$$\frac{\partial}{\partial z} \frac{\partial}{\partial y} \frac{\partial f(x, y, z)}{\partial y}$$

## 4 Double-Integrals

### 4.1 Riemann Sum

$$\sum_{i=1}^n f(x_i^*, y_i^*) \Delta A_i$$

$$I = \iint_D f(x, y) dA \quad \text{where } D \text{ is a region in } \mathbb{R}^2 \text{ and } dA \text{ is } dxdy$$

### 4.2 Double Integrals over General domains

If  $f(x, y)$  is defined and bounded on domain  $D$ , then  $\hat{f}(x, y)$  is zero outside  $D$ .

$$\iint_D f(x, y) dA = \iint_R \hat{f}(x, y) dA$$

### 4.3 Iteration of Double Integrals

If  $f(x, y)$  is continuous on the bounded y-simple domain  $D$  given by  $a \leq x \leq b$  and  $c(x) \leq y \leq d(x)$ , then:

$$\iint_D f(x, y) dA = \int_a^b dx \int_{c(x)}^{d(x)} f(x, y) dy$$

If  $f(x, y)$  is continuous on the bounded x-simple domain  $D$  given by  $c \leq x \leq d$  and  $a(x) \leq y \leq b(x)$ , then:

$$\iint_D f(x, y) dA = \int_c^d dx \int_{a(x)}^{b(x)} f(x, y) dy$$

### 4.4 Double Integrals in Polar Coordinates

$$dA = dxdy = r drd\theta$$

$$x = r \cos(\theta) \quad r^2 = x^2 + y^2$$

$$y = r \sin(\theta) \quad \tan(\theta) = \frac{y}{x}$$

#### 4.4.1 Limits for Polar Coordinates

$r$  is the radius from origin to the point

$$r \geq 0$$

$\theta$  is the angle in the positive direction of the xy-plane

$$0 \leq \theta \leq 2\pi$$

### 4.5 Change of Variables in Double Integrals

If  $x$  and  $y$  are given as a function of  $u$  and  $v$ :

$$x = x(u, v)$$

$$y = y(u, v)$$

These can be transformed or mapped from points  $(u, v)$  in the  $uv$ -plane to points  $(x, y)$  in the  $xy$ -plane.

The inverse transformation is given by:

$$u = u(x, y)$$

$$v = v(x, y)$$

Scaled area element:

$$dA = dx dy = \left| \frac{\partial(x, y)}{\partial(u, v)} \right| du dv$$

where the Jacobian is:

$$\left| \frac{\partial(x, y)}{\partial(u, v)} \right| = \frac{\partial x}{\partial u} \frac{\partial y}{\partial v} - \frac{\partial x}{\partial v} \frac{\partial y}{\partial u}$$

Let  $x(u, v)$  and  $y(u, v)$  be a one-to-one transformation from a domain  $S$  in the  $uv$ -plane onto a domain  $D$  in the  $xy$ -plane.

Suppose, that function  $x$  and  $y$ , and first partial derivatives with respect to  $u$  and  $v$  are continuous in  $S$ . If  $f(x, y)$  is integrable on  $D$ , then  $g(u, v) = f(x(u, v), y(u, v))$  is integrable on  $S$  and:

$$\iint_D f(x, y) dA = \iint_S g(u, v) \left| \frac{\partial(x, y)}{\partial(u, v)} \right| du dv$$

## 4.6 Examples

### 4.6.1 Example 1: Change of Variables

Evaluate the double integral:

$$\iint (x - 3y) dA$$

where  $R$  is triangular region with vertices  $(0, 0)$ ,  $(2, 1)$ , and  $(1, 2)$  using the transformation:

$$x = 2u + v$$

$$y = u + 2v$$

As  $x$  and  $y$  are dependent on  $u$  and  $v$  the transformation of  $dA$  is given by

$$dA = dx dy = \left| \frac{\partial(x, y)}{\partial(u, v)} \right| du dv$$

Using:

$$\left| \frac{\partial(x, y)}{\partial(u, v)} \right| = \frac{\partial x}{\partial u} \frac{\partial y}{\partial v} - \frac{\partial x}{\partial v} \frac{\partial y}{\partial u}$$

the Jacobian can be calculated:

$$\frac{\partial x}{\partial u} = 2 \quad \frac{\partial y}{\partial v} = 2$$

$$\frac{\partial x}{\partial v} = 1 \quad \frac{\partial y}{\partial u} = 1$$

$$2 \cdot 2 - 1 \cdot 1 = 3$$

Find the boundaries for the double integral

$$y_1 : (0, 0) \rightarrow (2, 1) \text{ is } y = \frac{1}{2}x$$

$$y_2 : (0, 0) \rightarrow (1, 2) \text{ is } y = 2x$$

$$y_3 : (1, 2) \rightarrow (2, 1) \text{ is } y = 3 - x$$

Replace  $x$  and  $y$  with their transformation:

$$\begin{aligned} u + 2v &= \frac{2u+v}{2} & v &= 0 \\ u + 2v &= 4u + 2v & u &= 0 \\ u + 2v &= 3 - 2u - v & u &= 1 - v \end{aligned}$$

Therefore  $0 \leq u \leq 1 - v$  and  $0 \leq v \leq 1$

Now transform the original function  $x - 3y$ :

$$\begin{aligned} x - 3y &= 2u + v - 3(u + 2v) \\ &= 2u - 3u + v - 6v \\ &= -u - 5v \end{aligned}$$

$$\begin{aligned} \int_0^1 \int_0^{1-v} (-u - 5v) \cdot 3 \, du dv &= -3 \int_0^1 \left[ \frac{u^2}{2} + 5uv \right]_0^{1-v} dv \\ &= -\frac{3}{2} \int_0^1 \left( \frac{27v^2}{2} - 12v \right) dv \\ &= \left[ \frac{9v^3}{2} - 6v^2 - \frac{3v}{2} \right]_0^1 \\ &= \boxed{-3} \end{aligned}$$

#### 4.6.2 Example 2: Double integral

Evaluate the double integral by iteration

$$\iint_R (x^2 + y^2) \, dA$$

where  $R$  is the rectangle  $0 \leq x \leq a$ ,  $0 \leq y \leq b$

Insert the limits and solve the integral:

$$\begin{aligned} \int_0^b \int_0^a (x^2 + y^2) dx dy &= \int_0^b \left[ \frac{x^3}{3} + xy^2 \right]_0^a dy \\ &= \int_0^b \left( \frac{a^3}{3} + ay^2 \right) dy \\ &= \boxed{\frac{a^3b}{3} + \frac{ab^3}{3}} \end{aligned}$$

#### 4.6.3 Example 3: By iteration

Evaluate the double integral by iteration:

$$\iint_D x \cos y \, dA$$

where  $D$  is the finite region in the first quadrant bounded by the coordinate axes and the curve  $y = 1 - x^2$ .

Given the region the minimum for  $x$  and  $y$  must be 0 and for  $x$  the maximum is 1:

$$\begin{aligned}
\int_0^1 \int_0^{1-x^2} (x \cos(y)) dy dx &= \int_0^1 x \sin(1-x^2) dx \\
&= \left[ \frac{1}{2} \sin(1) \sin(x^2) + \frac{1}{2} \cos(1) \cos(x^2) \right]_0^1 \\
&= \boxed{\sin^2\left(\frac{1}{2}\right)}
\end{aligned}$$

#### 4.6.4 Example 4: By iteration

Evaluate the double integral by iteration

$$\iint_R xy^2 dA$$

where  $R$  is the finite region in the first quadrant bounded by the curves  $y = x^2$  and  $x = y^2$

$$x = \sqrt{y} \quad x = y^2$$

Since it is bounded in the first quadrant here intercepts in  $(0, 0)$  and  $(1, 1)$ :  $0 \leq y \leq 1$

In this region  $x = \sqrt{y} \geq x = y^2$

Solve the integral:

$$\begin{aligned}
&\int_0^1 \int_{y^2}^{\sqrt{y}} xy^2 dx dy \\
&= \int_0^1 \left[ \frac{x^2 y^2}{2} \right]_{y^2}^{\sqrt{y}} dy = \frac{1}{2} \int_0^1 (\sqrt{y}^2 y^2 - ((y^2)^2 y^2)) dy \\
&= \frac{1}{2} \int_0^1 y^3 - y^6 dy = \left[ \frac{y^4}{4} - \frac{y^7}{7} \right]_0^1 \\
&= \frac{1}{2} \left( \frac{1}{4} - \frac{1}{7} \right) = \frac{1}{2} \cdot \frac{7-4}{28} = \frac{3}{56}
\end{aligned}$$

#### 4.6.5 Example 5: Polar coordinates

## 5 Tripple-Integrals

### 5.1 Riemann Sum

### 5.2 Tripple Integrals over General domains

### 5.3 Change of Variables

$$\begin{aligned}dV &= dx \, dy \, dz = \left| \frac{\partial(x, y, z)}{\partial(u, v, w)} \right| du \, dv \, dw \\ \iiint f(x, y, z) \, dx \, dy \, dz &= \iiint g(u, v, w) \left| \frac{\partial(x, y, z)}{\partial(u, v, w)} \right| du \, dv \, dw \\ \left| \frac{\partial(x, y, z)}{\partial(u, v, w)} \right| &= \begin{vmatrix} \frac{\partial x}{\partial u} & \frac{\partial x}{\partial v} & \frac{\partial x}{\partial w} \\ \frac{\partial y}{\partial u} & \frac{\partial y}{\partial v} & \frac{\partial y}{\partial w} \\ \frac{\partial z}{\partial u} & \frac{\partial z}{\partial v} & \frac{\partial z}{\partial w} \end{vmatrix} \\ &= \frac{\partial x}{\partial u} \left( \frac{\partial y}{\partial v} \frac{\partial z}{\partial w} - \frac{\partial y}{\partial w} \frac{\partial z}{\partial v} \right) - \frac{\partial x}{\partial v} \left( \frac{\partial y}{\partial u} \frac{\partial z}{\partial w} - \frac{\partial y}{\partial w} \frac{\partial z}{\partial u} \right) + \frac{\partial x}{\partial w} \left( \frac{\partial y}{\partial u} \frac{\partial z}{\partial v} - \frac{\partial y}{\partial v} \frac{\partial z}{\partial u} \right)\end{aligned}$$

### 5.4 Cylyndrical Coordinates

$$\begin{aligned}x &= r \cos(\theta) & r^2 &= x^2 + y^2 \\ y &= r \sin(\theta) & \tan \theta &= \left(\frac{y}{x}\right) \\ z &= z\end{aligned}$$

From the Jacobian using change of variables:

$$\begin{aligned}\left| \frac{\partial(x, y, z)}{\partial(r, \theta, z)} \right| &= r \\ dV &= dx \, dy \, dz = r \, dr \, d\theta \, dz\end{aligned}$$

#### 5.4.1 Limits for Cylyndrical Coordinates

$r$  is the radius from origin to the point

$$r \geq 0$$

$\theta$  is the angle in the positive direction of the x-axis

$$0 \leq \theta \leq 2\pi$$

### 5.5 Spherical Coordinates

$$\begin{aligned}x &= \rho \sin(\phi) \cos(\theta) & \rho^2 &= x^2 + y^2 + z^2 \\ y &= \rho \sin(\phi) \sin(\theta) & \cos(\phi) &= \frac{z}{\rho} \\ z &= \rho \cos(\phi) & \tan \theta &= \frac{y}{x} \\ dxdydz &= dV = \rho^2 \sin(\phi) d\rho d\phi d\theta\end{aligned}$$

### 5.5.1 Limits for Spherical Coordinates

$\rho$  is the distance from the origin O to the point P

$$\rho \geq 0$$

$\phi$  is the angle by the radial line OP to the positive direction of the z-axis

$$0 \leq \phi \leq \pi$$

$\theta$  is the angle in the positive direction of the x-axis to the point P in the xy-plane

$$0 \leq \theta \leq 2\pi$$

## 5.6 Examples

### 5.6.1 Example 1: Tripple Integral

Find  $\iiint (x^2 + y^2 + z^2) dV$ , where the region is bounded by  $z = c\sqrt{(x^2 + y^2)}$  and  $x^2 + y^2 + z^2 = a^2$

---

Using Cylyndrical Coordinates:

$$z = c\sqrt{r^2} = cr \quad r^2 + z^2 = a^2 \quad \Rightarrow \quad z = \sqrt{a^2 - r^2}$$

Therefore the region is bounded by:

$$0 \leq r \leq a \quad 0 \leq \theta \leq 2\pi \quad cr \leq z \leq \sqrt{a^2 - r^2}$$

Convert the function:

$$\begin{aligned} x^2 + y^2 + z^2 &\Rightarrow r^2 + z^2 \\ \int_0^{2\pi} \int_0^a \int_{cr}^{\sqrt{a^2 - r^2}} (x^2 + y^2 + z^2) dz dr d\theta \end{aligned}$$

### 5.6.2 Example 2: Sphereical Coordinates

Find the volume of:

$$\iiint \sqrt{x^2 + y^2 + z^2} dx dy dz$$

where the region is bounded by  $x^2 + y^2 + z^2 \leq 1$  in spherical domain.

---

Transform the region:

$$\rho^2 = x^2 + y^2 + z^2 \leq 1 \quad \text{Therefore: } 0 \leq \rho \leq 1$$

For  $\theta$  and  $\phi$  we have:

$$0 \leq \theta \leq 2\pi \quad 0 \leq \phi \leq \pi$$

and for  $dV$ :

$$dV = dx dy dz = \rho^2 \sin \phi d\rho d\phi d\theta$$

Transform the function:

$$\sqrt{x^2 + y^2 + z^2} = \sqrt{\rho^2} = \rho$$

Solve the integral:

$$\begin{aligned}
 \int_0^{2\pi} \int_0^\pi \int_0^1 \rho \cdot \rho^2 \sin(\phi) d\rho d\phi d\theta &= \int_0^{2\pi} \int_0^\pi \left[ \frac{1}{4} \rho^4 \sin(\phi) \right]_0^1 d\phi d\theta \\
 &= \int_0^{2\pi} \int_0^\pi \frac{\sin(\phi)}{4} d\phi d\theta \\
 &= \int_0^{2\pi} \left[ -\frac{\cos(\phi)}{4} \right]_0^\pi d\theta \\
 &= \frac{1}{2} \int_0^{2\pi} d\theta \\
 &= \frac{1}{2} \cdot 2\pi \\
 &= \boxed{\pi}
 \end{aligned}$$

### 5.6.3 Example 3: Jacobian Transformation

Find the Jacobian using change of variables from uv-space to xy-space when:

$$x = 2u + w \quad y = 2u - 2v \quad z = u + v^2 - 2w^2$$

The Jacobian is:

$$\begin{aligned}
 \left| \frac{\partial(x, y, z)}{\partial(u, v, w)} \right| &= \begin{vmatrix} \frac{\partial x}{\partial u} & \frac{\partial x}{\partial v} & \frac{\partial x}{\partial w} \\ \frac{\partial y}{\partial u} & \frac{\partial y}{\partial v} & \frac{\partial y}{\partial w} \\ \frac{\partial z}{\partial u} & \frac{\partial z}{\partial v} & \frac{\partial z}{\partial w} \end{vmatrix} \\
 \begin{vmatrix} 2 & 0 & 1 \\ 2u & -2v & 0 \\ 1 & 2v & -4w \end{vmatrix} &= 2(-2v \cdot -4w - 0 \cdot 2v) - 0 + 1(2u \cdot 2v - 2v \cdot 1) \\
 &= 16vw + 4uv - 2v
 \end{aligned}$$

### 5.6.4 Example 4: Triple Integral

Find the volume of solid bounded by:

$$x^2 + y^2 + z^2 = 9 \quad x^2 + y^2 = 8z$$

Using cylindrical coordinates:

$$r^2 + z^2 = 9 \quad r^2 = 8z$$

This gives two bounds for  $z$ :

$$z = \sqrt{9 - r^2} \quad z = \frac{r^2}{8}$$

Bounds for  $r$  is the intersection:

$$\sqrt{9 - r^2} = z = \frac{r^2}{8} \Rightarrow r = 2\sqrt{2}$$



From the  $r$  bounds we see:

$$z = \underbrace{\sqrt{9-r^2}}_{\text{Upper bound}} \quad z = \underbrace{\frac{r^2}{8}}_{\text{Lower bound}}$$

And for  $\theta$ :

$$0 \leq \theta \leq 2\pi$$

Setup the integral:

$$\begin{aligned} & \int_0^{2\pi} \int_0^{2\sqrt{2}} \int_{r^2/8}^{\sqrt{9-r^2}} r \, dz \, dr \, d\theta \\ &= \int_0^{2\pi} \int_0^{2\sqrt{2}} [rz]_{r^2/8}^{\sqrt{9-r^2}} dr d\theta \\ &= \int_0^{2\pi} \int_0^{2\sqrt{2}} r\sqrt{9-r^2} - r^3/8 dr d\theta \\ &= \int_0^{2\pi} \left( \int_0^{2\sqrt{2}} r\sqrt{9-r^2} dr - \int_0^{2\sqrt{2}} r^3/8 dr \right) d\theta \end{aligned}$$

Using u substitution:

$$\int_0^{2\sqrt{2}} r\sqrt{u} dr \quad u = 9 - r^2 \quad \Rightarrow \quad \frac{du}{dr} = -2r \quad \Rightarrow \quad dr = \frac{du}{-2r}$$

New limits:

$$r = 0 : \quad u = 9 - 0^2 = 9 \quad r = 2\sqrt{2} : \quad u = 9 - (2\sqrt{2})^2 = 1$$

$$\int_9^1 r\sqrt{u} \frac{du}{-2r} = \frac{-1}{2} \int_9^1 \sqrt{u} du = \frac{-1}{2} \left[ \frac{2u^{3/2}}{3} \right]_9^1 = \frac{26}{3}$$

Solve the other integral:

$$= \int_0^{2\sqrt{2}} r^3/8 dr = [r^4/32]_0^{2\sqrt{2}} = 2$$

Insert results:

$$= \int_0^{2\pi} \frac{26}{3} - 2 d\theta = \boxed{\frac{40}{3}\pi}$$

## 6 Fields-Curve

### 6.1 Curve & Parameterization

Representation of a curve in 3 space by using its position vector is given as:

$$r = r(t) = x(t)\mathbf{i} + y(t)\mathbf{j} + z(t)\mathbf{k} \quad \text{where } a \leq t \leq b$$

### 6.2 Vector Fields

$$\mathbf{F}(x, y, z) = \underbrace{f_1(x, y, z)}_{\text{Scaler function}} \mathbf{i} + \underbrace{f_2(x, y, z)}_{\text{Scaler function}} \mathbf{j} + \underbrace{f_3(x, y, z)}_{\text{Scaler function}} \mathbf{k}$$

$$\frac{\partial f}{\partial x} = f_1 = f_x \quad \frac{\partial f}{\partial y} = f_2 = f_y \quad \frac{\partial f}{\partial z} = f_3 = f_z$$

Position vector:

$$r = x\mathbf{i} + y\mathbf{j} + z\mathbf{k}$$

Unit vector with magnitude 1:

$$r = \mathbf{i} + \mathbf{j} + \mathbf{k}$$

#### 6.2.1 Scalar field

$$F(x, y, z) = f_1(x, y, z) + f_2(x, y, z) + f_3(x, y, z)$$

The gradient of a scalar field is a vector field:

$$\nabla f = \text{grad } f(x, y, z) = f_x(x, y, z)\mathbf{i} + f_y(x, y, z)\mathbf{j} + f_z(x, y, z)\mathbf{k}$$

#### 6.2.2 Field lines

$$\frac{dx}{f_1(x, y, z)} = \frac{dy}{f_2(x, y, z)} = \frac{dz}{f_3(x, y, z)}$$

#### 6.2.3 Conervation field

If  $\mathbf{F}(x, y, z) = \nabla\phi(x, y, z)$  in a 3d domain  $D$ , then  $\mathbf{F}$  is a conservative vector field in  $D$  and function  $\phi$  is the potential function.

$$\mathbf{F}(x, y, z) = \nabla\phi(x, y, z) = \phi_x(x, y, z)\mathbf{i} + \phi_y(x, y, z)\mathbf{j} + \phi_z(x, y, z)\mathbf{k}$$

If the vector field is conservative, then all the following equations are true:

$$\begin{aligned} \frac{\partial f_1}{\partial y} &= \frac{\partial f_2}{\partial x} \\ \frac{\partial f_1}{\partial z} &= \frac{\partial f_3}{\partial x} \\ \frac{\partial f_2}{\partial z} &= \frac{\partial f_3}{\partial y} \end{aligned}$$

If  $\mathbf{F}(x, y) = \nabla\phi(x, y)$  in a 2d domain  $D$ , then  $\mathbf{F}$  is a conservative vector field in  $D$  and function  $\phi$  is the potential function.

$$\frac{\partial f_1}{\partial y} = \frac{\partial^2 \phi}{\partial y \partial x} = \frac{\partial^2 \phi}{\partial x \partial y} = \frac{\partial f_2}{\partial x}$$

### 6.2.4 Vector field in Polar Coordinates

$$\mathbf{F} = f(r, \theta) = f_r(r, \theta)\hat{\mathbf{r}} + f_\theta(r, \theta)\hat{\boldsymbol{\theta}}$$

where:

$$\begin{aligned}\hat{\mathbf{r}} &= \cos(\theta)\mathbf{i} + \sin(\theta)\mathbf{j} \\ \hat{\boldsymbol{\theta}} &= -\sin(\theta)\mathbf{i} + \cos(\theta)\mathbf{j}\end{aligned}$$

## 6.3 Line Integral

$$f(x, y)ds = \text{Area (tiny point)}$$

$$\text{Length of } \mathcal{C} = \int_{\mathcal{C}} f(x, y, z) ds = \int_a^b f(r(t)) \left| \frac{dr}{dt} \right| dt$$

### 6.3.1 Line integral of a vector field

$$W = \int_{\mathcal{C}} \mathbf{F} \cdot d\mathbf{r} = \int_{\mathcal{C}} F dr = \int_{\mathcal{C}} f_1(x, y, z)dx + f_2(x, y, z)dy + f_3(x, y, z)dz$$

## 6.4 Examples

### 6.4.1 Example 1: Conservative vector field and potential

Determine whether the given vector field is conservative, and find a potential function if it is:

$$\mathbf{F}(x, y, z) = (2xy - z^2)\mathbf{i} + (2yz + x^2)\mathbf{j} - (2zx - y^2)\mathbf{k}$$

The field is conservative if:

$$\begin{aligned}\frac{\partial f_1}{\partial y} &= \frac{\partial f_2}{\partial x} \\ \frac{\partial f_1}{\partial z} &= \frac{\partial f_3}{\partial x} \\ \frac{\partial f_2}{\partial z} &= \frac{\partial f_3}{\partial y}\end{aligned}$$

$$\begin{aligned}\frac{\partial(2xy - z^2)}{\partial y} &= 2x = \frac{\partial(2yz + x^2)}{\partial x} \\ \frac{\partial(2xy - z^2)}{\partial z} &= -2z = \frac{\partial(-2zx + y^2)}{\partial x} \\ \frac{\partial(2yz + x^2)}{\partial z} &= 2y = \frac{\partial(-2zx + y^2)}{\partial y}\end{aligned}$$

All equations are satisfied! The field is conservative.

Find the potential function  $\phi(x, y, z)$ :

$$\begin{aligned}f_1 = \frac{\partial \phi}{\partial x} &\Rightarrow \phi = \int f_1 dx = x^2 y - z^2 x + c(y, z) \\ \frac{\partial \phi}{\partial y} &= x^2 + \frac{\partial c(y, z)}{\partial y} \\ f_2 = \frac{\partial \phi}{\partial y} &= x^2 + \frac{\partial c(y, z)}{\partial y} = 2yz + x^2 \Rightarrow \frac{\partial c(y, z)}{\partial y} = 2yz\end{aligned}$$

This means  $c$  is a function of  $y$  and  $z$  and can be found by taking the anit-derivative

$$c(y, z) = y^2 z + c(z)$$

Insert  $c(y, z)$ :

$$\begin{aligned} \phi &= x^2 y - z^2 x + y^2 z + c(z) \\ f_3 &= \frac{\partial \phi}{\partial z} = -2zx + y^2 + \frac{\partial c(z)}{\partial z} = -2zx + y^2 \Rightarrow \frac{\partial c(z)}{\partial z} = 0 \end{aligned}$$

A scalar potential function of  $F$ :

$$\phi(x, y, z) = x^2 y - z^2 x + y^2 z$$

#### 6.4.2 Example 2: Line integral

Evaluate  $\oint x^2 y^2 dx + x^3 y dy$  counterclockwise around the square with vertices  $(0, 0)$ ,  $(1, 0)$ ,  $(1, 1)$ , and  $(0, 1)$

---

#### 6.4.3 Example 3: Line integral

Evaluate the line integral for  $f(x, y) = x^2 y^2$  along a straight line from origin to the point  $(2, 1)$

---

The parmeterization of arc length over  $t$ :

$$\begin{aligned} x &= f(t) = t & \frac{df(t)}{dt} &= 1 \\ y &= g(t) = 2t & \frac{dg(t)}{dt} &= 2 \end{aligned}$$

Setup integral with bounds:  $0 \leq t \leq 1$

$$\begin{aligned} \int_0^1 t^2 (2t)^2 \sqrt{f'(t)^2 + g'(t)^2} dt &= \int_0^1 5t^2 \sqrt{5} dt \\ &= \left[ \frac{5t^3 \sqrt{5}}{3} \right]_0^1 = \frac{5\sqrt{5}}{3} \end{aligned}$$

#### 6.4.4 Example 4: Line integral vector field

Evaluate the line integral of the tangential component of the given vector field along the given curve:

$$F(x, y) = xy\mathbf{i} - x^2\mathbf{j}$$


---

For a vector field:

$$W = \int F dr$$

Along the line  $y = x^2$ : Parametrize  $x$  and  $y$ :

$$\begin{aligned} x(t) &= t & y(t) &= t^2 & r(t) &= t\mathbf{i} + t^2\mathbf{j} \\ \frac{dr}{dt} &= \mathbf{i} + 2t\mathbf{j} & \Rightarrow & dr &= (\mathbf{i} + 2t\mathbf{j})dt \end{aligned}$$

Setup integral with bounds:  $0 \leq t \leq 1$

$$\begin{aligned} \int_0^1 (t^3\mathbf{i} - t^2\mathbf{j})(\mathbf{i} + 2t\mathbf{j})dt &= \int_0^1 t^3 - 2t^3 dt = \int_0^1 -t^3 dt \\ &= \left[ -\frac{t^4}{4} \right]_0^1 = -\frac{1}{4} \end{aligned}$$

### 6.4.5 Example 5: Line integral over specified curve

Evaluate the given line integral over the specified curve  $\mathcal{C}$

$$\int_{\mathcal{C}} (x + y) ds \quad \mathbf{r} = at\mathbf{i} + bt\mathbf{j} + ct\mathbf{k} \quad 0 \leq t \leq m$$

---

$$\begin{aligned}\int_{\mathcal{C}} f(x, y, z) ds &= \int_a^b f(r(t)) \left| \frac{dr}{dt} \right| dt = \sqrt{a^2 + b^2 + c^2} dt \\ ds &= \left| \frac{dr}{dt} \right| dt = |a\mathbf{i} + b\mathbf{j} + c\mathbf{k}| dt \\ f(r(t)) &= at + bt\end{aligned}$$

Solve the integral:

$$\begin{aligned}\int_0^m (at + bt) \sqrt{a^2 + b^2 + c^2} dt &= \sqrt{a^2 + b^2 + c^2} \int_0^m (a + b)t dt \\ &= \sqrt{a^2 + b^2 + c^2} \left[ \frac{(a + b)t^2}{2} \right]_0^m = \frac{\sqrt{a^2 + b^2 + c^2}(a + b)m^2}{2}\end{aligned}$$

### 6.4.6 Example 6: Parametrize a curve

Use  $t = y$  to parametrize the part of the line of intersection of the two planes:

Plane 1:  $y = 2x - 4$

Plane 2:  $z = 3x + 1$  from  $(2, 0, 7)$  to  $(3, 2, 10)$

Ans:  $r(t) = \left(\frac{1}{2}(t + 4)\right)\mathbf{i} + (t)\mathbf{j} + \left(\frac{3}{2}t + 7\right)\mathbf{k}$

## 7 Surface-Integrals

### 7.1 Parametric Surface

For curve parametrization:

$$r = r(t) = x(t)\mathbf{i} + y(t)\mathbf{j} + z(t)\mathbf{k} \quad \text{where } a \leq t \leq b$$

For surface parametrization:

$$r = r(u, v) = x(u, v)\mathbf{i} + y(u, v)\mathbf{j} + z(u, v)\mathbf{k} \quad \text{where } a \leq u \leq b, \quad c \leq v \leq d$$

### 7.2 Surface Area

For a surface the area is given by:

$$\iint_S f(x, y, z) dS$$
$$dS = \left| \frac{\partial r}{\partial u} \times \frac{\partial r}{\partial v} \right| du dv = \sqrt{\left( \frac{\partial(y, z)}{\partial(u, v)} \right)^2 + \left( \frac{\partial(z, x)}{\partial(u, v)} \right)^2 + \left( \frac{\partial(x, y)}{\partial(u, v)} \right)^2} du dv$$

For a parametrized surface  $S$  given by  $r = r(u, v)$ , where  $(u, v)$  is in the domain  $D$  in the  $uv$ -plane, the surface area is given by:

$$\iint_S f dS = \iint_D f(r(u, v)) \left| \frac{\partial r}{\partial u} \times \frac{\partial r}{\partial v} \right| du dv$$
$$= \iint_D f(x(u, v), y(u, v), z(u, v)) \sqrt{\left( \frac{\partial(y, z)}{\partial(u, v)} \right)^2 + \left( \frac{\partial(z, x)}{\partial(u, v)} \right)^2 + \left( \frac{\partial(x, y)}{\partial(u, v)} \right)^2} du dv$$

For a surface  $S$  given by  $z = g(x, y)$ , where  $(x, y)$  is in the domain  $D$  in the  $xy$ -plane, the surface area is given by:

$$\iint_S f(x, y, z) dS = \iint_D f(x, y, z(x, y)) \sqrt{1 + \left( \frac{\partial g(x, y)}{\partial x} \right)^2 + \left( \frac{\partial g(x, y)}{\partial y} \right)^2} dx dy$$

The projection of normal vector onto the  $xy$ -plane is given by:

$$\cos(\gamma) = \frac{1}{\sqrt{1 + \left( \frac{\partial g(x, y)}{\partial x} \right)^2 + \left( \frac{\partial g(x, y)}{\partial y} \right)^2}} \quad \text{hence } dS = \frac{1}{\cos(\gamma)} dx dy$$

### 7.3 Oriented Surface

- A smooth surface  $S$  in 3-space is said to be orientable if there exists a unit vector field  $\hat{N}(P)$ .
- $\hat{N}(P)$  defined on  $S$  that varies continuously as  $P$  ranges over  $S$  and that is everywhere normal to  $S$ .
- Any such vector field  $\hat{N}(P)$  determines an orientation of  $S$ .
- The oriented surface must have two sides.
- $\hat{N}(P)$  can have only one value at each point  $P$  with two sides.

## 7.4 Flux

$$\mathbf{F} = f_1(x, y, z)\mathbf{i} + f_2(x, y, z)\mathbf{j} + f_3(x, y, z)\mathbf{k}$$

Given any continuous vector field  $\mathbf{F}$ , flux of  $\mathbf{F}$  across the orientable surface  $S$  is integral of the normal component of  $\mathbf{F}$  over  $S$

$$\iint_S \mathbf{F} \cdot d\mathbf{S} = \iint_S (\mathbf{F} \cdot \hat{\mathbf{N}}) dS$$

If the surface is closed, then the flux is given by:

$$\oiint_S \mathbf{F} \cdot d\mathbf{S} = \oiint_S (\mathbf{F} \cdot \hat{\mathbf{N}}) dS$$

If  $S$  is a parametrized surface given by  $\mathbf{r} = \mathbf{r}(u, v)$ , where  $(u, v)$  is in the domain  $D$  in the  $uv$ -plane, then the flux is given by:

$$\begin{aligned} \iint_S \mathbf{F} \cdot d\mathbf{S} &= \iint_D \mathbf{F} \cdot \left( \frac{\partial \mathbf{r}}{\partial u} \times \frac{\partial \mathbf{r}}{\partial v} \right) du dv \\ &= \iint_D \left( f_1 \frac{\partial(y, z)}{\partial(u, v)} + f_2 \frac{\partial(z, x)}{\partial(u, v)} + f_3 \frac{\partial(x, y)}{\partial(u, v)} \right) du dv \end{aligned}$$

For a surface  $S$  given by  $z = g(x, y)$ , where  $(x, y)$  is in the domain  $D$  in the  $xy$ -plane, the flux is given by:

$$\iint_S \mathbf{F} \cdot d\mathbf{S} = \iint_D \left( -f_1 \frac{\partial z}{\partial x} \mathbf{i} - f_2 \frac{\partial z}{\partial y} \mathbf{j} + f_3 \mathbf{k} \right) dx dy$$

## 7.5 Examples

## 8 Theorems

### 8.1 Differential Operators

#### 8.1.1 Gradient

The gradient of a scalar field is a vector field that points in the direction of the steepest increase of the scalar field.

$$\begin{aligned}\text{grad } f(x, y, z) &= \nabla f(x, y, z) = \frac{\partial f}{\partial x} \mathbf{i} + \frac{\partial f}{\partial y} \mathbf{j} + \frac{\partial f}{\partial z} \mathbf{k} \\ \mathbf{F}(x, y, z) &= f_x(x, y, z) \mathbf{i} + f_y(x, y, z) \mathbf{j} + f_z(x, y, z) \mathbf{k}\end{aligned}$$

#### 8.1.2 Divergence

The divergence of a velocity field represents the net flow of fluid out of a small volume in a scalar field.

$$\text{div } \mathbf{F}(x, y, z) = \nabla \cdot \mathbf{F}(x, y, z) = \frac{\partial f_1}{\partial x} + \frac{\partial f_2}{\partial y} + \frac{\partial f_3}{\partial z}$$

#### 8.1.3 Curl

The curl or field circulation of the electric field gives the rate of change of the magnetic field.

$$\begin{aligned}\text{curl } \mathbf{F}(x, y, z) &= \nabla \times \mathbf{F}(x, y, z) = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ f_x & f_y & f_z \end{vmatrix} \\ &= \left( \frac{\partial f_1}{\partial y} - \frac{\partial f_2}{\partial x} \right) \mathbf{i} + \left( \frac{\partial f_3}{\partial z} - \frac{\partial f_1}{\partial x} \right) \mathbf{j} + \left( \frac{\partial f_2}{\partial x} - \frac{\partial f_1}{\partial y} \right) \mathbf{k}\end{aligned}$$

### 8.2 Green's Theorem

Let  $R$  be a regular, closed region in the  $xy$ -plane whose boundary,  $C$ , consists of one or more piecewise smooth, simple closed curves that are positively oriented (counterclockwise) with respect to  $R$ .

$$\oint_C f_1(x, y) dx + f_2(x, y) dy = \iint_R \left( \frac{\partial f_2}{\partial x} - \frac{\partial f_1}{\partial y} \right) dA$$

### 8.3 Stokes' Theorem

Let  $S$  be a piecewise smooth, oriented surface in 3-space, having unit normal field  $\hat{N}$  and boundary  $C$  consisting of one or more piecewise smooth, closed curves with orientation inherited from  $S$ .

$$\oint_C \mathbf{F} \cdot d\mathbf{r} = \iint_S \text{curl } \mathbf{F} \cdot \hat{N} dS$$

### 8.4 Divergence Theorem

Let  $S$ , be a closed piecewise smooth surface, which is the boundary of  $V$  with normal  $\hat{N}$  pointing outwards.

$$\oint_S (\mathbf{F} \cdot \hat{N}) dS = \iiint_V \text{div } \mathbf{F} dV$$

More variants:

$$\begin{aligned}\iiint_D \text{curl } \mathbf{F} dV &= - \oint_S (\mathbf{F} \times \hat{N}) dS \\ \iiint_D \text{grad } \phi dV &= \oint_S \phi dS\end{aligned}$$



## 8.5 Examples

### 8.5.1 Example 1: Div and Curl

Calculate the divergence and curl of the following vector field:

$$\mathbf{F} = \cos x \mathbf{i} - \sin y \mathbf{j} + z \mathbf{k}.$$

---

**Divergence:**

$$\begin{aligned}\operatorname{div} \mathbf{F}(x, y, z) &= \nabla \cdot \mathbf{F}(x, y, z) = \frac{\partial f_1}{\partial x} + \frac{\partial f_2}{\partial y} + \frac{\partial f_3}{\partial z} \\ \operatorname{div} F &= -\sin(x) - \cos(y) + 1\end{aligned}$$

**Curl:**

$$\begin{aligned}\operatorname{curl} F &= \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ f_x & f_y & f_z \end{vmatrix} \\ &= \left( \frac{\partial f_z}{\partial y} - \frac{\partial f_y}{\partial z} \right) \mathbf{i} + \left( \frac{\partial f_x}{\partial z} - \frac{\partial f_z}{\partial x} \right) \mathbf{j} + \left( \frac{\partial f_y}{\partial x} - \frac{\partial f_x}{\partial y} \right) \mathbf{k} \\ &= (0 - 0)\mathbf{i} + (0 - 0)\mathbf{j} + (0 + 0)\mathbf{k}\end{aligned}$$

### 8.5.2 Example 2: Green's Theorem

Using Green's Theorem evaluate  $\oint_C (x^2 y) dx + (xy^2) dy$ , clockwise bounded of the region:

$$0 \leq y \leq \sqrt{9 - x^2}$$

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$$\begin{aligned}\oint_C f_1(x, y) dx + f_2(x, y) dy &= \iint_R \left( \frac{\partial f_2}{\partial x} - \frac{\partial f_1}{\partial y} \right) dA \\ f_1(x, y) &= x^2 y & f_2 &= xy^2 \\ \frac{\partial f_1}{\partial y} &= x^2 & \frac{\partial f_2}{\partial x} &= y^2 \\ &\iint_R (y^2 - x^2) dA\end{aligned}$$

But since it is clockwise:

$$-\iint_R (y^2 - x^2) dA = \iint_R (x^2 - y^2) dA$$

Using polar coordinates:

$$y^2 = 9 - x^2 \Rightarrow r = 3$$

Since  $y \geq 0$ :

$$0 \leq \theta \leq \pi$$

Convert the function to polar:

$$x^2 = (r \cos(\theta))^2 \quad y^2 = (r \sin(\theta))^2$$

$$\begin{aligned}
\int_0^\pi \int_0^3 (r^2 \cos^2(\theta) - r^2 \sin^2(\theta)) r dr d\theta &= \int_0^\pi \int_0^3 r^3 (\cos^2(\theta) - \sin^2(\theta)) dr d\theta \\
&= \int_0^\pi \left[ \frac{1}{4} r^4 (\cos^2(\theta) - \sin^2(\theta)) \right]_0^3 d\theta \\
&= \frac{81}{4} \int_0^\pi (\cos^2(\theta) - \sin^2(\theta)) d\theta = \frac{81}{4} \int_0^\pi \frac{1 + \cos(2\theta)}{2} - \frac{1 - \cos(2\theta)}{2} d\theta \\
&= \frac{81}{4} \int_0^\pi \frac{1 + \cos(2\theta)}{2} - \frac{1 - \cos(2\theta)}{2} d\theta = \frac{81}{4} \int_0^\pi \cos(2\theta) d\theta \\
&= \frac{81}{4} \left[ \frac{\sin(2\theta)}{2} \right]_0^\pi = 0 - 0 = 0
\end{aligned}$$

### 8.5.3 Example 3: Stokes' Theorem

Evaluate  $\oint F \cdot dr$ , where  $F = -y^3 i + x^3 j - z^3 k$  and  $C$  is the curve of intersection of the cylinder  $x^2 + y^2 \leq 1$  and the plane  $2x + 2y + z = 3$  oriented to have a counterclockwise projection onto the xy-plane.

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### 8.5.4 Example 4: Divergence Theorem

Use the Divergence Theorem to calculate the flux of the given vector field out of the sphere  $s$  with equation  $x^2 + y^2 + z^2 = a^2$ , where  $a > 0$  and

$$\mathbf{F} = (x^2 + y^2)\mathbf{i} + (y^2 - z^2)\mathbf{j} + z\mathbf{k}$$

## 9 PDE

Partial Differential Equations are equations with multiple variables and derivatives. They are used to model many physical phenomena, such as heat, sound, and light. The totality of solutions to a PDE is called its general solution, and there can be a lot.

### 9.1 Classification of PDEs

General representation of a PDE:

$$A \frac{\partial^2 u}{\partial x^2} + B \frac{\partial^2 u}{\partial x \partial y} + C \frac{\partial^2 u}{\partial y^2} + D \frac{\partial u}{\partial x} + E \frac{\partial u}{\partial y} + Fu = G$$

$$Au_{xx} + Bu_{xy} + Cu_{yy} + Du_x + Eu_y + Fu = G$$

Conditions:

**Linear:**  $A, B, C, D, E, F$  are only function of  $x, y$  variables, not  $u$ .

**Quasi-linear:**  $A, B, C, D, E, F$  may be function of  $(x, y, u, u_x, u_y)$

**Fully non-linear:**  $A, B, C, D, E, F$  may be function of  $(x, y, u, u_x, u_y, u_{xx}, u_{yy}, u_{xy})$

### 9.2 Characteristics of PDEs

$B^2 - 4AC > 0$    2 real roots   2 characteristics   **Hyperbolic PDE**

$B^2 - 4AC = 0$    1 real roots   1 characteristics   **Parabolic PDE**

$B^2 - 4AC < 0$    0 real roots   0 characteristics   **Elliptic PDE**

Types of various PDEs:

**Wave Equation:** Hyperbolic PDE

**Heat Equation:** Parabolic PDE

**Laplace Equation:** Elliptic PDE

$B^2 - 4AC > 0$    2 real roots   2 characteristics   **Hyperbolic PDE**

$B^2 - 4AC = 0$    1 real roots   1 characteristics   **Parabolic PDE**

$B^2 - 4AC < 0$    0 real roots   0 characteristics   **Elliptic PDE**

### 9.3 Important Second-Order PDEs

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} \quad \text{One-dimensional wave equation}$$

$$\frac{\partial u}{\partial t} = c^2 \frac{\partial^2 u}{\partial x^2} \quad \text{One-dimensional heat equation}$$

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = 0 \quad \text{Two-dimensional Laplace equation}$$

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = f(x, y) \quad \text{Two-dimensional Poisson equation}$$

$$\frac{\partial^2 u}{\partial t^2} = c^2 \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad \text{Two-dimensional wave equation}$$

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} = 0 \quad \text{Three-dimensional Laplace equation}$$

### 9.4 Initial and Boundary Conditions

#### 9.5 Wave Equation (1D)

One dimensional wave equation is given by:

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} \quad \text{where } c^2 = \left[ \frac{T(x, t)}{\mu_x} \right] \quad (1)$$

With two boundary conditions  $x = 0$  and  $x = L$ :

$$u(0, t) = 0 \quad u(L, t) = 0 \quad \text{For all } t \geq 0$$

And two initial conditions, initial displacement and initial velocity at time  $t = 0$ :

$$u(x, 0) = f(x) \quad \frac{\partial u}{\partial t}(x, 0) = g(x) \quad \text{For all } 0 \leq x \leq L$$

Steps to solve:

1. Method of Separation of Variables  $u(x, t) = X(x)T(t)$
2. Satisfy the Boundary Conditions test
3. Fourier Series Validation

#### 9.5.1 D'Alembert's Solution of the Wave Equation

His solution is given by eq. (1) but extended to two variables:

$$v = (x - ct) \quad w = (x + ct) \quad (2)$$

I.e.  $u(v, w)$ . Partial derivatives from chain rule:

$$u_x = u_v \cdot v_x + u_w \cdot w_x = u_v + u_w$$

For double derivatives:

$$u_{xx} = (u_v + u_w)_x = (u_v + u_w)_v v_x + (u_v + u_w)_w w_x = u_{vv} + 2u_{vw} + u_{ww}$$

With respect to  $t$ :

$$u_{tt} = c^2 u_{xx} = c^2(u_{vv} + 2u_{vw} + u_{ww})$$

From eq. (1) and eq. (2):

$$u_{vw} = \frac{\partial^2 u}{\partial w \partial v} = 0$$

This can be solved by integrating with respect to  $v$  and  $w$ :

$$\frac{\partial u}{\partial v} = h(v) \text{ and } u = \int h(v) dv + \psi(w)$$

Here,  $h(v)$  and  $\psi(w)$  are arbitrary functions of  $v$  and  $w$ , respectively. The solution in term for  $x$ :

$$u = \phi(v) + \psi(w)$$

This is d'Alembert's solution, which is the general solution to the wave equation.

$$u(x, t) = \phi(x + ct) + \psi(x - ct)$$

This solution satisfies the wave equation and the initial conditions:

## 9.6 Heat Equation (1D)

$$\frac{\partial u}{\partial t} = c^2 \frac{\partial^2 u}{\partial x^2} \quad (3)$$

Conditions:

- PDE is linear and homogeneous.
- Boundary conditions are linear and homogeneous. The two for  $u(x, t)$  is  $u(0, t) = 0$  and  $u(L, t) = 0$  for all  $t > 0$ .
- One initial condition at time ( $t = 0$ ):  $u(x, 0) = f(x)$ .

Solve the

Solution:

$$u(x, t) = \sum_{n=1}^{\infty} B_n \sin\left(\frac{n\pi x}{L}\right) e^{-\lambda_n^2 t}$$

where

$$\lambda_n = \frac{cn\pi}{L}$$

and

$$B_n = \frac{2}{L} \int_0^L f(x) \sin\left(\frac{n\pi x}{L}\right) dx \quad \text{for } n = 1, 2, 3, \dots$$

## 9.7 Examples

### 9.7.1