Multivariable Calculus
(following “J. R. Stewart, Calculus, 8th Ed.”)

Lectures on YouTube:
https://www.youtube.com/channel/UCmRbK4vlGDht-joOQ5g0J2Q

Seongjai Kim

Department of Mathematics and Statistics
Mississippi State University
Mississippi State, MS 39762 USA
Email: skim@math.msstate.edu

Updated: June 17, 2022
Seongjai Kim, Professor of Mathematics, Department of Mathematics and Statistics, Mississippi State University, Mississippi State, MS 39762 USA. Email: skim@math.msstate.edu.
Prologue

This lecture note is closely following the part of multivariable calculus in Stewart’s book [7]. In organizing this lecture note, I am indebted by Cedar Crest College Calculus IV Lecture Notes, Dr. James Hammer [1].

Two projects are included for students to experience computer algebra. Computer algebra (also called symbolic computation) is a scientific area that refers to the study and development of algorithms and software for manipulating mathematical expressions and other mathematical objects; it emphasizes exact computation with expressions containing variables that have no given value and are manipulated as symbols. In practice, you can use computer algebra to effectively handle complex math equations and problems that would be simply too complicated/time-consuming to do by hand. The projects are organized using Maple.

Through the lecture note, I tried to make figures using Maple. Also added are some of programming scripts written in Maple. The end of each section includes exercise problems. For problems indicated by the Computer Algebra System (CAS) sign, you are recommended to use a CAS to solve the problem.

Currently the lecture note is not fully grown up; other useful techniques and interesting examples would be soon incorporated. Any questions, suggestions, comments will be deeply appreciated.

Seongjai Kim
June 17, 2022
# Contents

Title ii

Prologue iii

Table of Contents vii

12 Vectors and the Geometry of Space 1
   12.1. Vector Operations .................................................. 2
      12.1.1. 3D coordinate systems ...................................... 2
      12.1.2. Vectors and vector operations ......................... 4
   12.2. Equations in the 3D Space ................................... 10
   12.3. Cylinders and Quadric Surfaces ............................... 14

14 Partial Derivatives 17
   14.1. Functions of Several Variables ............................... 18
      14.1.1. Domain and range ............................................. 18
      14.1.2. Graphs ........................................................... 19
      14.1.3. Level curves .................................................. 20
      14.1.4. Functions of three or more variables ................. 23
   14.2. Limits and Continuity .......................................... 25
   14.3. Partial Derivatives .............................................. 32
      14.3.1. First-order partial derivatives ....................... 32
      14.3.2. Higher-order partial derivatives ..................... 37
   14.4. Tangent Planes & Linear Approximations .................... 40
   14.5. The Chain Rule .................................................. 45
      14.5.1. Chain rule .................................................... 45
      14.5.2. Implicit differentiation ................................. 48
   14.6. Directional Derivatives and the Gradient Vector ........... 51
   14.7. Maximum and Minimum Values .................................. 59
      14.7.1. Local extrema ............................................... 59
      14.7.2. Absolute extrema .......................................... 63
   14.8. Lagrange Multipliers ......................................... 65
R.14. Review Problems for Ch. 14 .................................... 70
Project 1. Linear and Quadratic Approximations .................... 72
   P.1.1. Newton's method .............................................. 75
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>P.1.2. Estimation of critical points</td>
<td>76</td>
</tr>
<tr>
<td>P.1.3. Quadratic approximations</td>
<td>77</td>
</tr>
<tr>
<td><strong>15 Multiple Integrals</strong></td>
<td>79</td>
</tr>
<tr>
<td>15.1. Double Integrals over Rectangles</td>
<td>80</td>
</tr>
<tr>
<td>15.1.1. Volumes as double integrals</td>
<td>81</td>
</tr>
<tr>
<td>15.1.2. Iterated integrals</td>
<td>83</td>
</tr>
<tr>
<td>15.2. Double Integrals over General Regions</td>
<td>89</td>
</tr>
<tr>
<td>15.3. Double Integrals in Polar Coordinates</td>
<td>97</td>
</tr>
<tr>
<td>15.4. Applications of Double Integrals</td>
<td>106</td>
</tr>
<tr>
<td>15.5. Surface Area</td>
<td>112</td>
</tr>
<tr>
<td>15.6. Triple Integrals</td>
<td>116</td>
</tr>
<tr>
<td>15.7. Triple Integrals in Cylindrical Coordinates</td>
<td>123</td>
</tr>
<tr>
<td>15.8. Triple Integrals in Spherical Coordinates</td>
<td>127</td>
</tr>
<tr>
<td>15.9. Change of Variables in Multiple Integrals</td>
<td>132</td>
</tr>
<tr>
<td>R.15. Review Problems for Ch. 15</td>
<td>141</td>
</tr>
<tr>
<td>Project 2. The Volume of the Unit Ball in $n$-Dimensions</td>
<td>143</td>
</tr>
<tr>
<td><strong>16 Vector Calculus</strong></td>
<td>147</td>
</tr>
<tr>
<td>16.1. Vector Fields</td>
<td>148</td>
</tr>
<tr>
<td>16.1.1. Definitions</td>
<td>148</td>
</tr>
<tr>
<td>16.1.2. Gradient fields and potential functions</td>
<td>151</td>
</tr>
<tr>
<td>16.2. Line Integrals</td>
<td>156</td>
</tr>
<tr>
<td>16.2.1. Line integrals for scalar functions in the plane</td>
<td>157</td>
</tr>
<tr>
<td>16.2.2. Line integrals in space</td>
<td>164</td>
</tr>
<tr>
<td>16.2.3. Line integrals of vector fields</td>
<td>166</td>
</tr>
<tr>
<td>16.3. The Fundamental Theorem for Line Integrals</td>
<td>170</td>
</tr>
<tr>
<td>16.3.1. Conservative vector fields</td>
<td>170</td>
</tr>
<tr>
<td>16.3.2. Independence of path</td>
<td>172</td>
</tr>
<tr>
<td>16.3.3. Potential functions</td>
<td>177</td>
</tr>
<tr>
<td>16.4. Green's Theorem</td>
<td>182</td>
</tr>
<tr>
<td>16.4.1. Application to area computation</td>
<td>184</td>
</tr>
<tr>
<td>16.4.2. Generalization of Green's Theorem</td>
<td>187</td>
</tr>
<tr>
<td>16.5. Curl and Divergence</td>
<td>192</td>
</tr>
<tr>
<td>16.5.1. Curl</td>
<td>192</td>
</tr>
<tr>
<td>16.5.2. Divergence</td>
<td>195</td>
</tr>
<tr>
<td>16.5.3. Vector forms of Green's Theorem</td>
<td>196</td>
</tr>
<tr>
<td>16.6. Parametric Surfaces and Their Areas</td>
<td>199</td>
</tr>
<tr>
<td>16.6.1. Parametric surfaces</td>
<td>199</td>
</tr>
<tr>
<td>16.6.2. Tangent planes</td>
<td>205</td>
</tr>
<tr>
<td>16.6.3. Surface area</td>
<td>207</td>
</tr>
<tr>
<td>16.7. Surface Integrals</td>
<td>213</td>
</tr>
</tbody>
</table>
CHAPTER 12

Vectors and the Geometry of Space

In this chapter, we study vectors and equations in the 3-dimensional (3D) space. In particular, you will learn

- vectors
- dot product
- cross product
- equations of lines and planes, and
- cylinders and quadric surfaces

Contents of Chapter 12

12.1. Vector Operations ................................................................. 2
12.2. Equations in the 3D Space ...................................................... 10
12.3. Cylinders and Quadric Surfaces ............................................ 14

This chapter corresponds to Chapter 12 in STEWART, Calculus (8th Ed.), 2015.
12.1. Vector Operations

There exists a lot to cover in the class of multivariable calculus; however, it is important to have a good foundation before we trudge forward. In that vein, let’s review vectors and their geometry in space ($\mathbb{R}^3$) briefly.

12.1.1. 3D coordinate systems

**Recall:** Let $P = (x_1, y_1)$ and $Q = (x_2, y_2)$ be points in $\mathbb{R}^2$. Then the **distance** from $P$ to $Q$ is

$$|PQ| = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}.$$  \hfill (12.1)

**Definition** 12.1. Let $P = (x_1, y_1, z_1)$ and $Q = (x_2, y_2, z_2)$ be points in $\mathbb{R}^3$. Then the **distance** from $P$ to $Q$ is

$$|PQ| = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}.$$  \hfill (12.2)

**Problem** 12.2. Find the distance between $P(-3, 2, 7)$ and $Q(-1, 0, 6)$.

**Solution.**

Ans: 3
Recall: A circle in $\mathbb{R}^2$ is defined to be all of the points in the plane ($\mathbb{R}^2$) that are equidistant from a central point $C(a, b)$.

\[(x - a)^2 + (y - b)^2 = r^2.\] (12.3)

A natural generalization of this to 3-D space would be to say that a sphere is defined to be all of the points in $\mathbb{R}^3$ that are equidistant from a central point $C$. This is exactly what the following definition does!

**Definition 12.3.** Let $C(h, k, l)$ be a point in $\mathbb{R}^3$. Then the **sphere** centered at $C$ with radius $r$ is defined by the equation

\[(x - h)^2 + (y - k)^2 + (z - l)^2 = r^2.\] (12.4)

That is to say that this defines all points $(x, y, z) \in \mathbb{R}^3$ that are at the same distance $r$ from the center $C(h, k, l)$.

**Problem 12.4.** Show that $x^2 + y^2 + z^2 - 4x + 2y - 6z + 10 = 0$ is the equation of a sphere, and find its center and radius.

**Solution.**

*Ans: $C(2, -1, 3)$ and $r = 2$*
12.1.2. Vectors and vector operations

**Definition 12.5.** A vector is a mathematical object that stores both length (which we will often call magnitude) and direction.

Let \( P = (x_1, y_1, z_1) \) and \( Q = (x_2, y_2, z_2) \). Then the vector with initial point \( P \) and terminal point \( Q \) (denoted \( \vec{PQ} \)) is defined by

\[
\vec{PQ} = (x_2 - x_1, y_2 - y_1, z_2 - z_1) = \vec{OQ} - \vec{OP},
\]

where \( O \) is the origin, \( O = (0, 0, 0) \). The vector \( \vec{OP} \) is called the position vector of the point \( P \). For convenience, we use bold-faced lower-case letters to denote vectors. For example, \( \mathbf{v} = <v_1, v_2, v_3> \) is a (position) vector in \( \mathbb{R}^3 \) associated with the point \( (v_1, v_2, v_3) \).

**Definition 12.6.** Two vectors are said to be equal if and only if they have the same length and direction, regardless of their position in \( \mathbb{R}^3 \). That is to say that a vector can be moved (with no change) anywhere in space as long as the magnitude and direction are preserved.

**Definition 12.7.** Let \( \mathbf{v} = <v_1, v_2, v_3> \). Then the magnitude (a.k.a. length or norm) of \( \mathbf{v} \) (denoted \( |\mathbf{v}| \) or sometimes \( ||\mathbf{v}|| \)) is defined by

\[
|\mathbf{v}| = \sqrt{v_1^2 + v_2^2 + v_3^2}. \tag{12.5}
\]

**Definition 12.8.** (Vector addition) Let \( \mathbf{u} = <u_1, u_2, u_3> \) and \( \mathbf{v} = <v_1, v_2, v_3> \). Then

\[
\mathbf{u} + \mathbf{v} = <u_1 + v_1, u_2 + v_2, u_3 + v_3>.
\]
12.1. Vector Operations

**Definition 12.9.** (Scalar multiplication) Let $v = < v_1, v_2, v_3 >$ and $k \in \mathbb{R}$. Then

$$k \, v = < kv_1, kv_2, kv_3 >.$$

**Problem 12.10.** If $a = < 0, 3, 4 >$ and $b = < 1, 5, 2 >$, find $|a|$, $2a - 3b$, and $|2a - 3b|$.

**Solution.**

Ans: $|a| = 5$; $2a - 3b = < -3, -9, 2 >$; $|2a - 3b| = \sqrt{94}$

**Definition 12.11.** A **unit vector** is a vector whose magnitude is 1. Note that given a vector $v$, we can form a unit vector (of the same direction) by dividing by its magnitude. That is, let $v = < v_1, v_2, v_3 >$. Then

$$u = \frac{v}{|v|}$$

is a unit vector in the direction of $v$.

**Definition 12.12.** Any vector can be denoted as the linear combination of the standard unit vectors

$$i = < 1, 0, 0 >, \quad j = < 0, 1, 0 >, \quad k = < 0, 0, 1 >.$$ 

So given a vector $v = < v_1, v_2, v_3 >$, one can express it with respect to the standard unit vectors as

$$v = < v_1, v_2, v_3 > = v_1 \, i + v_2 \, j + v_3 \, k. \quad (12.7)$$

This text, however, will more often than not use the angle brace notation.
Definition 12.13. Let \( u = \langle u_1, u_2, u_3 \rangle \) and \( v = \langle v_1, v_2, v_3 \rangle \). Then the dot product is
\[
\mathbf{u} \cdot \mathbf{v} = u_1 v_1 + u_2 v_2 + u_3 v_3, \tag{12.8}
\]
which is sometimes referred as the Euclidean inner product. Note that \( \mathbf{v} \cdot \mathbf{v} = |\mathbf{v}|^2 \).

Theorem 12.14. Let \( \theta \) be the angle between \( \mathbf{u} \) and \( \mathbf{v} \) (so \( 0 \leq \theta \leq \pi \)). Then
\[
\mathbf{u} \cdot \mathbf{v} = |\mathbf{u}| |\mathbf{v}| \cos(\theta). \tag{12.9}
\]

Corollary 12.15. Two vectors \( \mathbf{u} \) and \( \mathbf{v} \) are orthogonal if and only if \( \mathbf{u} \cdot \mathbf{v} = 0 \).

Problem 12.16. Find the angle between the vectors \( \mathbf{a} = \langle 2, 2, 1 \rangle \) and \( \mathbf{b} = \langle 3, 0, 3 \rangle \).

Solution. 

\textit{Ans}: \( \pi/4 \) (= 45°)
12.1. Vector Operations

**Definition 12.17.** Let \( u = < u_1, u_2, u_3 > \) and \( v = < v_1, v_2, v_3 > \). Then the cross product is the determinant of the following matrix:

\[
\begin{align*}
\mathbf{u} \times \mathbf{v} &= \det \begin{bmatrix}
i & j & k \\
u_1 & u_2 & u_3 \\
v_1 & v_2 & v_3 
\end{bmatrix} \\
&= \det \begin{bmatrix} u_2 & u_3 \\
v_2 & v_3 \end{bmatrix} i - \det \begin{bmatrix} u_1 & u_3 \\
v_1 & v_3 \end{bmatrix} j + \det \begin{bmatrix} u_1 & u_2 \\
v_1 & v_2 \end{bmatrix} k \\
&= < u_2 v_3 - u_3 v_2, u_3 v_1 - u_1 v_3, u_1 v_2 - u_2 v_1 >.
\end{align*}
\]

**Problem 12.18.** Find the cross product \( a \times b \), when \( a = < 1, 3, 4 > \) and \( b = < 3, -1, -2 > \).

**Solution.**

\[
\text{Ans: } < -2, 14, -10 >
\]

**Theorem 12.19.** The vector \( a \times b \) is orthogonal to both \( a \) and \( b \).

**Theorem 12.20.** Let \( \theta \) be the angle between \( a \) and \( b \) (so \( 0 \leq \theta \leq \pi \)). Then

\[
|a \times b| = |a||b| \sin(\theta).
\]

(12.11)
[Claim] 12.21. The length of the cross product $a \times b$ is equal to the area of the parallelogram determined by $a$ and $b$.

![Diagram of cross product](image)

Figure 12.1

[Problem] 12.22. Prove that two nonzero vectors $a$ and $b$ are parallel if and only if $a \times b = 0$.

Solution.

The cross product $a \times b$ is defined as a vector that is perpendicular (orthogonal) to both $a$ and $b$, with a direction given by the **right-hand rule** and a magnitude equal to the area of the parallelogram that the vectors span.

If the fingers of your right hand curl in the direction of a rotation (through an angle less than $180^\circ$) from $a$ to $b$, then the thumb points in the direction of $a \times b$. See Figure 12.2.
Exercises 12.1

1. Find the cross product $a \times b$ and verify that it is orthogonal to both $a$ and $b$.

   (a) $a = \langle 1, 2, -1 \rangle$, $b = \langle 2, 0, -3 \rangle$
   (b) $a = \langle 1, t, 1/t \rangle$, $b = \langle t^2, t, 1 \rangle$

2. Find $|u \times v|$ and determine whether $u \times v$ is directed into the page or out of the page.

3. (i) Find a nonzero vector orthogonal to the plane through the points $P$, $Q$, and $R$, and (ii) find the area of the triangle $PQR$.

   (a) $P(1, 0, 1)$, $Q(2, 1, 3)$, $R(-3, 2, 5)$
   $\text{Ans: } \langle 0, -12, 6 \rangle$, $3\sqrt{5}$

   (b) $P(1, -1, 0)$, $Q(-3, 1, 2)$, $R(0, 3, -1)$
   $\text{Ans: } \langle -10, -6, -14 \rangle$, $\sqrt{83}$

4. Find the angle between $a$ and $b$, when $a \cdot b = -\sqrt{3}$ and $a \times b = \langle 2, 2, 1 \rangle$.
   $\text{Ans: } 120^\circ$

Note: Exercise problems are added for your homework; answers would be provided for some of them. However, you have to verify them, by showing solutions in detail.
Parametrization of a Line. Let \( P_0 = (x_0, y_0, z_0) \) be a point in \( \mathbb{R}^3 \), and \( v = \langle a, b, c \rangle \) be a vector in \( \mathbb{R}^3 \). Then the line through \( P_0 \) parallel to \( v \) is
\[
r = P_0 + t v, \quad t \in \mathbb{R}.
\] (12.12)

This can also be written as
\[
x = x_0 + at, \quad y = y_0 + bt, \quad z = z_0 + ct; \quad t \in \mathbb{R}.
\] (12.13)

or as the symmetric equation
\[
\frac{x - x_0}{a} = \frac{y - y_0}{b} = \frac{z - z_0}{c}.
\] (12.14)

Parametrization of a Line Segment. Let \( P \) and \( Q \) be respectively the initial and terminal points of a line segment. Then the line segment \( PQ \) can be parametrized as
\[
r(t) = (1 - t) \overrightarrow{OP} + t \overrightarrow{OQ}, \quad 0 \leq t \leq 1.
\] (12.15)
\textbf{Problem 12.23.} Find a vector equation and parametric equation for the line that passes through the point \((5, 1, 3)\) and is parallel to \(\langle 1, 4, -2 \rangle\).

\textbf{Solution.}

\textit{Ans:} \(x = 5 + t, \ y = 1 + 4t, \ z = 3 - 2t\)

\textbf{Problem 12.24.} Find the parametric equation of the line segment from \((2, 4, -3)\) to \((3, -1, 1)\).

\textbf{Solution.}

\textit{Ans:} \(r(t) = \langle 2 + t, 4 - 5t, -3 + 4t \rangle, \ 0 \leq t \leq 1\).
Planes. Let \( x_0 = (x_0, y_0, z_0) \) be a point in the plane and \( n = \langle a, b, c \rangle \) be a vector normal to the plane. Then the equation of the plane is

\[
n \cdot (x - x_0) = a(x - x_0) + b(y - y_0) + c(z - z_0) = 0. \tag{12.16}
\]

Problem 12.25. Find an equation of the plane that passes through the points \( P(1, 2, 3) \), \( Q(3, 2, 4) \), and \( R(1, 5, 2) \).

Solution.

\[
\text{Ans: } -3(x - 1) + 2(y - 2) + 6(z - 3) = 0.
\]
12.2. Equations in the 3D Space

Exercises 12.2

1. Find an equation of the line which passes through $(1, 0, 3)$ and perpendicular to the plane 
   $x - 3y + 2z = 4$.

2. Find the line of the intersection of planes $x + 2y + 3z = 6$ and $x - y + z = 1$. (Hint: The 
   intersection is a line; consider how the direction of the line is related to the normal vectors of 
   the planes.)
   \[ \text{Ans: } r = P_0 + tv = <1, 1, 1> + t <5, 2, -3> \]

3. Find the vector equation for the line segment from $P(1, 2, -4)$ to $Q(5, 6, 0)$.

4. Find an equation of the plane.
   
   (a) The plane through the point $(0, 1, 2)$ and parallel to the plane $x - y + 2z = 4$.
   (b) The plane through the points $P(1, -2, 2)$, $Q(3, -4, 0)$, and $R(-3, -2, -1)$.
   \[ \text{Ans: } 3(x - 1) + 7(y + 2) - 4(z - 2) = 0. \]

5. Use intercepts to help sketch the plane $2x + y + 5z = 10$. 
12.3. Cylinders and Quadric Surfaces

**Objective:** To visualize surfaces, given their equations.

**Definition 12.26.** A **cylinder** is a surface that consists of all lines that are parallel to a given line and pass through a given plane curve.

**Problem 12.27.** Sketch $z = x^2$ in $\mathbb{R}^3$.

**Problem 12.28.** Sketch $x^2 + y^2 = 1$ in $\mathbb{R}^3$.

**Problem 12.29.** Sketch $y^2 + z^2 = 1$ in $\mathbb{R}^3$. 
Definition 12.30. A **quadric surface** is the graph of a second-degree equation in three variables \( x, y, \) and \( z \). By translation and rotation, we can write the standard form of a quadric surface as

\[
Ax^2 + By^2 + Cz^2 + J = 0 \quad \text{or} \quad Ax^2 + By^2 + Iz = 0. \quad (12.17)
\]

Definition 12.31. The **trace** of a surface in \( \mathbb{R}^3 \) is the graph in \( \mathbb{R}^2 \) obtained by allowing one of the variables to be a specific real number. For example, \( x = a \).

Problem 12.32. Use the traces to sketch \( x^2 + \frac{y^2}{9} + \frac{z^2}{4} = 1 \).
Problem 12.33. Use the traces to sketch \( z = 4x^2 + y^2 \).

Exercises 12.3

1. Sketch the surface.
   
   (a) \( x^2 + y^2 = 1 \)
   (b) \( x^2 + y^2 - 2y = 0 \)
   (c) \( z = \sin x \)

2. Use traces to sketch and identify the surface.
   
   (a) \( z = y^2 - x^2 \)
   (b) \( 4y^2 + 9z^2 = x^2 + 36 \)

3. Sketch the region bounded by the surfaces \( z = \sqrt{x^2 + y^2} \) and \( z = 2 - x^2 - y^2 \).

4. Sketch the surface obtained by rotating the line \( r(t) = (0, 1, 3)t \) about the \( z \)-axis; find an equation of it. (**Hint:** The line can be expressed as \( \{z = 3y, \ x = 0\} \).)  
   
   \( \text{Ans: } |z| = 3\sqrt{x^2 + y^2} \text{ or } z^2 = 9(x^2 + y^2) \)
CHAPTER 14

Partial Derivatives

In mathematics, a **partial derivative** of a function of several variables is its derivative with respect to one of those variables, with the others held constant. In this chapter, you will learn about the partial derivatives and their applications.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limits and continuity</td>
<td></td>
</tr>
<tr>
<td>Partial derivatives</td>
<td></td>
</tr>
<tr>
<td>Tangent planes &amp; linear approximations</td>
<td></td>
</tr>
<tr>
<td>Chain rule</td>
<td></td>
</tr>
<tr>
<td>Directional derivatives and the Gradient Vector</td>
<td></td>
</tr>
<tr>
<td>Maximum and minimum values</td>
<td></td>
</tr>
<tr>
<td>Method of Lagrange multipliers</td>
<td></td>
</tr>
</tbody>
</table>

**Contents of Chapter 14**

14.1. Functions of Several Variables ................................................. 18
14.2. Limits and Continuity ................................................................. 25
14.3. Partial Derivatives ...................................................................... 32
14.4. Tangent Planes & Linear Approximations ......................................... 40
14.5. The Chain Rule ................................................................................. 45
14.6. Directional Derivatives and the Gradient Vector ................................ 51
14.7. Maximum and Minimum Values ........................................................... 59
14.8. Lagrange Multipliers ......................................................................... 65
R.14. Review Problems for Ch. 14 .............................................................. 70
Project 1. Linear and Quadratic Approximations ......................................... 72

This chapter corresponds to Chapter 14 in Stewart, *Calculus* (8th Ed.), 2015.
14.1. Functions of Several Variables

14.1.1. Domain and range

**Definition 14.1.** A function of two variables, \( f \), is a rule that assigns each ordered pair of real numbers \((x, y)\) in a set \( D \subset \mathbb{R}^2 \) a unique real number denoted by \( f(x, y) \). The set \( D \) is called the **domain** of \( f \) and its **range** is the set of values that \( f \) takes on, that is, \( \{ f(x, y) : (x, y) \in D \} \).

**Definition 14.2.** Let \( f \) be a function of two variables, and \( z = f(x, y) \). Then \( x \) and \( y \) are called **independent variables** and \( z \) is called a **dependent variable**.

**Problem 14.3.** Let \( f(x, y) = \frac{\sqrt{x + y + 1}}{x - 1} \). Evaluate \( f(3, 2) \) and give its domain.

**Ans:** \( f(3, 2) = \sqrt{6}/2; \) \( D = \{ (x, y) : x + y + 1 \geq 0, \; x \neq 1 \} \)

**Problem 14.4.** Find the domain of \( f(x, y) = x \ln(y^2 - x) \).
Problem 14.5. Find the domain and the range of
\[ f(x, y) = \sqrt{9 - x^2 - y^2}. \]

14.1.2. Graphs

Definition 14.6. If \( f \) is a function of two variables with domain \( D \), then the graph of \( f \) is the set of all points \((x, y, z) \in \mathbb{R}^3\) such that \( z = f(x, y) \) for all \((x, y) \in D\).

Problem 14.7. Sketch the graph of \( f(x, y) = 6 - 3x - 2y \).

Solution. The graph of \( f \) has the equation \( z = 6 - 3x - 2y \), or \( 3x + 2y + z = 6 \), which is a plane. Now, we can find intercepts to graph the plane.

Problem 14.8. Sketch the graph of \( g(x, y) = \sqrt{9 - x^2 - y^2} \).

Solution. The graph of \( g \) has the equation \( z = \sqrt{9 - x^2 - y^2} \), or \( x^2 + y^2 + z^2 = 9 \), \( z \geq 0 \), which is a upper hemi-sphere.
14.1.3. Level curves

**Definition 14.9.** The level curves of a function of two variables, $f$, are the curves with equations $f(x, y) = k$, for $k \in K \subset \text{Range}(f)$.

Figure 14.1: Level curves: (left) the graph of a function vs. level curves and (right) a topographic map of a mountainous region. Level curves are often considered for an effective visualization.

**Problem 14.10.** Sketch the level curves of $f(x, y) = 6 - 3x - 2y$ for $k \in \{-6, 0, 6, 12\}$.
Problem 14.11. Sketch the level curves of \( g(x, y) = \sqrt{9 - x^2 - y^2} \) for \( k \in \{0, 1, 2, 3\} \).

Problem 14.12. Sketch the level curves of \( h(x, y) = 4x^2 + y^2 + 1 \).
Chapter 14. Partial Derivatives

Function visualization is now easy with e.g., Mathematica, Maple, and Matlab, as shown in Figure 14.3.¹

¹For plotting with Maple, you may exploit plot, plot3d, contourplot3d, and contourplot, which are available from the plots package. Maple can include packages with the with command, as in Figure 14.3.
14.1.4. Functions of three or more variables

Definition 14.13. A function of three variables, \( f \), is a rule that assigns each ordered pair of real numbers \((x, y, z)\) in a set \( D \subset \mathbb{R}^3 \) a unique real number denoted by \( f(x, y, z) \).

Problem 14.14. Find the domain of \( f \) if \( f(x, y, z) = \ln(z - y) + xy \sin z \).

Problem 14.15. Find the level surfaces \((= f(x, y, z) = k)\) of \( f(x, y, z) = x^2 + y^2 + z^2 \).

Solution.

Note: A level surface is the surface where the function values are all the same as \( k \). Thus the outer normal is the fastest increasing direction of \( f \).
Exercises 14.1

1. Find and sketch the domain of the function

(a) \( f(x, y) = \ln(9 - 9x^2 - y^2) \)

(b) \( g(x, y) = \frac{\sqrt{x - y^2}}{1 - y^2} \)

2. Let \( f(x, y) = \sqrt{4 - x^2 - 4y^2} \).

(a) Find the domain of \( f \).
(b) Find the range of \( f \).
(c) Sketch the graph of the function.

3. Match the function with its contour plot (labeled I–VI). Give reasons for your choices.

(a) \( f(x, y) = x^2 - y^2 \)  
(b) \( f(x, y) = x^2 + y^2 \)  
(c) \( f(x, y) = 3 - |x| - |y| \)  
(d) \( f(x, y) = |xy| \)  
(e) \( f(x, y) = \frac{1}{1 + x^2 + y^2} \)  
(f) \( f(x, y) = \frac{1}{1 + x^2 y^2} \)

4. Describe the level surfaces of the function \( f(x, y, z) = x^2 + y^2 - z^2 \).
14.2. Limits and Continuity

Limits

Recall: For \( y = f(x) \), then we say that the limit of \( f(x) \), as \( x \to a \), is \( L \), if

\[
\lim_{x \to a^-} f(x) = \lim_{x \to a^+} f(x) = L
\]

or, equivalently, if \( \forall \epsilon > 0 \), there exists \( \delta = \delta(\epsilon) > 0 \) such that

\[
\text{if } 0 < |x - a| < \delta \text{ then } |f(x) - L| < \epsilon,
\]

which is called the \( \epsilon\)-\( \delta \) argument. In this case, we write

\[
\lim_{x \to a} f(x) = L. \tag{14.1}
\]

**Definition 14.16.** Let \( f \) be a function of two variables whose domain \( D \) includes points arbitrarily close to \((a, b)\). Then we say that the limit of \( f(x, y) \), as \((x, y)\) approaches \((a, b)\), is \( L \):

\[
\lim_{(x,y) \to (a,b)} f(x,y) = L, \tag{14.2}
\]

if \( \forall \epsilon > 0 \), there exists \( \delta = \delta(\epsilon) > 0 \) such that

\[
\text{if } (x,y) \in D \text{ and } 0 < \sqrt{(x-a)^2 + (y-b)^2} < \delta \text{ then } |f(x,y) - L| < \epsilon.
\]

**Arc length of** \( f(B_\delta(a,b)) \) **→ 0, as** \( \delta \rightarrow 0. \)

Figure 14.4: Plots of \( z = \sin x + \sin y \) (left) and \( z = \frac{xy}{x^2 + y^2} \) (right).
Chapter 14. Partial Derivatives

Claim 14.17. If \( f(x, y) \to L_1 \) as \( (x, y) \to (a, b) \) along a path \( C_1 \) and \( f(x, y) \to L_2 \) as \( (x, y) \to (a, b) \) along a path \( C_2 \), where \( L_1 \neq L_2 \), then \( \lim_{(x,y) \to (a,b)} f(x, y) \) does not exist.

Problem 14.18. Show that \( \lim_{(x,y) \to (0,0)} \frac{x^2 - y^2}{x^2 + y^2} \) does not exist.

Solution. Consider two paths: e.g., \( C_1 : \{ y = 0 \} \) and \( C_2 : \{ x = 0 \} \).

Problem 14.19. Does \( \lim_{(x,y) \to (0,0)} \frac{2xy}{x^2 + y^2} \) exist?

Solution. Consider a path \( C : \{ x = y \} \) with another.

Ans: no
Problem 14.20. Does \( \lim_{(x,y) \to (1,1)} \frac{2xy}{x^2 + y^2} \) exist?

Solution.

\[ \text{Ans: yes: } L = 1 \]

Problem 14.21. Does \( \lim_{(x,y) \to (0,0)} \frac{xy^2}{x^2 + y^4} \) exist?

Solution. Consider a path \( C : \{x = y^2\} \) with another.

\[ \text{Ans: no. See Figure 14.6 on p. 31 below.} \]
Problem 14.22. Use the squeeze theorem to show
\[
\lim_{{(x,y) \to (0,0)}} \frac{3x^2y}{x^2 + y^2} = 0.
\]
Solution.

Continuity

Recall: A function (of a single variable) \( f \) is continuous at \( x = a \) if
\[
\lim_{{x \to a}} f(x) = f(a).
\]
The above means that
1. the limit on the left side exists,
2. \( f(a) \) is defined, and
3. they are the same.

Definition 14.23. A function of two variables \( f \) is called continuous at point \( (a,b) \in \mathbb{R}^2 \) if
\[
\lim_{{(x,y) \to (a,b)}} f(x,y) = f(a,b). \tag{14.3}
\]

If \( f \) is continuous at every point \( (x,y) \) in a region \( D \subset \mathbb{R}^2 \), then we say that \( f \) is continuous on \( D \).

Problem 14.24. Is \( f(x,y) = \frac{2xy}{x^2+y^2} \) continuous at \((0,0)\)? What about at \((1,1)\)? Why?

Ans: no; yes
14.2. Limits and Continuity

**Problem 14.25.** Is the following function continuous at \((0,0)\)? What about at elsewhere?

\[ g(x, y) = \begin{cases} 
\frac{3x^2y}{x^2+y^2} & \text{if } (x, y) \neq (0,0) \\
0 & \text{if } (x, y) = (0,0) 
\end{cases} \]  

(14.4)

**Solution.** See Problem 14.22.

**Ans:** It is continuous everywhere.

**Problem 14.26.** Find the limit: \( \lim_{(x,y) \to (0,0)} (x^2 + y^2) \ln(x^2 + y^2) \).

**Solution.** Consider \( \lim_{x \to 0} x \ln x \) and introduce a new variable \( s = x^2 + y^2 \).

**Ans:** \( L = 0 \)
Exercises 14.2

1. Find the limit, if it exists, or show that the limit does not exist.

   \( (a) \lim_{(x,y) \to (\pi,\pi/2)} x \cos(x - y) \)
   \( \text{Ans: 0} \)

   \( (b) \lim_{(x,y) \to (0,0)} \frac{x}{\sqrt{x^2 + y^2}} \)

   \( (c) \lim_{(x,y) \to (0,0)} \frac{xy}{\sqrt{x^2 + y^2}} \)
   \( \text{Ans: 0} \)

2. Use polar coordinates to find the limit.

   \( (a) \lim_{(x,y) \to (0,0)} \frac{\sin(x^2 + y^2)}{x^2 + y^2} \)
   \( \text{Ans: (a) 1; (b) 4} \)

   \( (b) \lim_{(x,y) \to (0,0)} \frac{x^2 + y^2}{\sqrt{4 + x^2 + y^2} - 2} \)

3. \( \text{CAS} \) Use a computer graph of the function to explain why the limit does not exist.\(^2\)

   \( \lim_{(x,y) \to (0,0)} \frac{x^2 + 2xy + 4y^2}{3x^2 + y^2} \)

4. Determine and verify whether the following functions are continuous at \((0,0)\) or not.

   \( (a) \ f(x, y) = \begin{cases} 
   \frac{x^4 \sin y}{x^4 + y^4}, & \text{if } (x, y) \neq (0,0), \\
   0, & \text{if } (x, y) = (0,0).
   \end{cases} \)
   \( \text{Ans: continuous} \)

   \( (b) \ g(x, y) = \begin{cases} 
   \frac{xy}{x^2 + xy + y^2}, & \text{if } (x, y) \neq (0,0), \\
   0, & \text{if } (x, y) = (0,0).
   \end{cases} \)
   \( \text{Ans: discontinuous} \)

---

\(^2\)You have to perform a computer implementation for problems indicated by the Computer Algebra System sign \( \text{CAS} \). Of course, you must print hard copies of your computer work to be attached.
In computational mathematics, **computer algebra** (also called **symbolic computation**) is a scientific area that refers to the study and development of algorithms and software for manipulating mathematical expressions and other mathematical objects; it emphasizes **exact computation** with expressions containing variables that have no given value and are manipulated as symbols.

There have been about 40 computer algebra systems available; search “List of computer algebra systems" in Wikipedia. Popular ones in computational mathematics are Maple, Mathematica, and Matlab.

```matlab
syms x y
f = x*y^2/(x^2+y^4);
ezsurf(f,[-1,1,-1,1])
view(-45,45)
print('-r100','-dpng','matlab_ezsurf.png');
```

The above Matlab script results in Figure 14.6. Line 1 declares symbolic variables \(x\) and \(y\); line 3 defines the function \(f\); line 4 plots a figure over the rectangular domain \([-1, 1] \times [-1, 1]\); line 5 changes the view angle to \((-45^\circ, 45^\circ)\) in the horizontal and vertical directions, respectively; and the final line saves the figure to `matlab_ezsurf.png` with the resolution level of 100.
14.3. Partial Derivatives

14.3.1. First-order partial derivatives

Recall: A function \( y = f(x) \) is **differentiable** at \( a \) if

\[
f'(a) = \lim_{h \to 0} \frac{f(a + h) - f(a)}{h} \quad \text{exists.}
\]

Let \( f \) be a function of two variables \((x, y)\). Suppose we let only \( x \) vary while keeping \( y \) fixed, say \( y = b \). Then \( g(x) := f(x, b) \) is a function of a single variable. If \( g \) is differentiable at \( a \), then we call it the **partial derivative of \( f \) with respect to \( x \) at \((a, b)\)** and denoted by \( f_x(a, b) \).

\[
g'(a) = \lim_{h \to 0} \frac{g(a + h) - g(a)}{h}
= \lim_{h \to 0} \frac{f(a + h, b) - f(a, b)}{h} =: f_x(a, b). \tag{14.5}
\]
Similarly, the **partial derivative of $f$ with respect to $y$ at $(a, b)$**, denoted by $f_y(a, b)$, is obtained keeping $x$ fixed, say $\tilde{x} \equiv \tilde{a}$, and finding the ordinary derivative at $b$ of $G(y) := f(a, y)$:

$$G'(b) = \lim_{h \to 0} \frac{G(b + h) - G(b)}{h}$$

$$= \lim_{h \to 0} \frac{f(a, b + h) - f(a, b)}{h} =: f_y(a, b).$$

**Problem 14.27.** Find $f_x(0, 0)$, when $f(x, y) = \sqrt[3]{x^3 + y^3}$.

**Solution.** Using the definition,

$$f_x(0, 0) = \lim_{h \to 0} \frac{f(h, 0) - f(0, 0)}{h}$$

**Ans:** 1

**Definition 14.28.** *If $f$ is a function of two variables, its **partial derivatives** are the functions $f_x = \frac{\partial f}{\partial x}$ and $f_y = \frac{\partial f}{\partial y}$ defined by:

\[
\begin{align*}
    f_x(x, y) &= \lim_{h \to 0} \frac{f(x + h, y) - f(x, y)}{h} \\
    f_y(x, y) &= \lim_{h \to 0} \frac{f(x, y + h) - f(x, y)}{h}
\end{align*}
\]  

and* (14.7)
Chapter 14. Partial Derivatives

Observation 14.29. The partial derivative with respect to $x$ represents the slope of the tangent lines to the curve that are parallel to the $xz$-plane (i.e. in the direction of $\langle 1, 0, \cdot \rangle$). Similarly, the partial derivative with respect to $y$ represents the slope of the tangent lines to the curve that are parallel to the $yz$-plane (i.e. in the direction of $\langle 0, 1, \cdot \rangle$).

Rule for finding Partial Derivatives of $z = f(x, y)$

- To find $f_x$, regard $y$ as a constant and differentiate $f$ w.r.t. $x$.
- To find $f_y$, regard $x$ as a constant and differentiate $f$ w.r.t. $y$.

Problem 14.30. If $f(x, y) = x^3 + x^2y^3 - 2y^2$, find $f_x(2, 1)$ and $f_y(2, 1)$.

Solution.

An: $f_x(2, 1) = 16; f_y(2, 1) = 8$

Problem 14.31. Let $f(x, y) = \sin \left( \frac{x}{1 + y} \right)$. Find the first partial derivatives of $f(x, y)$.

Solution.
14.3. Partial Derivatives

**Problem** 14.32. Find the first partial derivatives of \( f(x, y) = x^y \).

**Solution.** Use \( \frac{d}{dx} a^x = a^x \ln a \).

Recall: (Implicit differentiation). When \( y = y(x) \) and \( x^2 + y^3 = 3 \), you have \( 2x + 3y^2 y' = 0 \) so that \( y' = -\frac{2x}{3y^2} \).

**Problem** 14.33. Find \( \partial z/\partial x \) and \( \partial z/\partial y \) if 
\( z \) is defined implicitly as a function of \( x \) and \( y \) by 
\[ x^3 + y^3 + z^3 + 6xyz = 1. \]

Figure 14.8: implicitplot3d in Maple: a plot of surface defined in Problem 14.33.
Problem 14.34. (Revisit of Problem 14.27). Find $f_x(x, y)$, when $f(x, y) = \sqrt[3]{x^3 + y^3}$. Can you evaluate $f_x(0, 0)$ easily?

Solution.

Functions of more than two variables

Problem 14.35. Let $f(x, y, z) = e^{xy} \ln z$. Find $f_x$, $f_y$, and $f_z$.

Solution.
14.3.2. Higher-order partial derivatives

Second partial derivatives of \( z = f(x, y) \)

\[
\begin{align*}
(f_x)_x &= f_{xx} = \frac{\partial}{\partial x} \left( \frac{\partial f}{\partial x} \right) = \frac{\partial^2 f}{\partial x^2} = f_{11} \\
(f_x)_y &= f_{xy} = \frac{\partial}{\partial y} \left( \frac{\partial f}{\partial x} \right) = \frac{\partial^2 f}{\partial y \partial x} = f_{12} \\
(f_y)_x &= f_{yx} = \frac{\partial}{\partial x} \left( \frac{\partial f}{\partial y} \right) = \frac{\partial^2 f}{\partial x \partial y} = f_{21} \\
(f_y)_y &= f_{yy} = \frac{\partial}{\partial y} \left( \frac{\partial f}{\partial y} \right) = \frac{\partial^2 f}{\partial y^2} = f_{22}
\end{align*}
\]

**Problem 14.36.** Find the second partial derivatives of \( f(x, y) = x^3 + x^2y^3 - 2y^2 \).

**Solution.**

**Theorem 14.37. (Clairaut’s theorem)** Suppose \( f \) is defined on a disk \( D \subset \mathbb{R}^2 \) that contains the point \((a, b)\). If both \( f_{xy} \) and \( f_{yx} \) are continuous on \( D \), then

\[
f_{xy}(a, b) = f_{yx}(a, b).
\]  

(14.8)

**Claim 14.38.** It can be shown that \( f_{xyy} = f_{yxy} = f_{yxx} \) if these functions are continuous.
Problem 14.39. Verify Clairaut’s theorem for \( f(x, y) = xye^y \).

Problem 14.40. Calculate \( f_{yxx}(x, y, z) \), given \( f(x, y, z) = \sin (3x + yz) \).

Solution.
14.3. Partial Derivatives

Exercises 14.3

1. The temperature $T$ (in °F) at a location in the Northern Hemisphere depends on the longitude $x$, latitude $y$, and time $t$; so we can write $T = f(x, y, t)$. Let’s measure time in hours from the beginning of January.

(a) What do the partial derivatives $\partial T/\partial x$, $\partial T/\partial y$, and $\partial T/\partial t$ mean?

(b) Mississippi State University (MSU) has longitude 88.8°W and latitude 33.5°N. Suppose that at noon on January first, the wind is blowing warm air to northeast, so the air to the west and south is warmer than that in the north and east. Would you expect $f_x(88.8, 33.5, 12)$, $f_y(88.8, 33.5, 12)$, and $f_t(88.8, 33.5, 12)$ to be positive or negative? Explain.

2. The following surfaces, labeled $a$, $b$, and $c$, are graphs of a function $f$ and its partial derivatives $f_x$ and $f_y$. Identify each surface and give reasons for your choices.

3. Find the partial derivatives of the function.

(a) $z = y \cos(xy)$

(b) $f(u, v) = (uv - v^3)^2$

(c) $w = \ln(x^2 + 2y + 3z)$

(d) $u = \sin(x^2 + y^2 + \cdots + x_n^2)$

Ans: (d) $\partial u/\partial x_i = 2x_i \cos(x_1^2 + x_2^2 + \cdots + x_n^2)$

4. Let $f(x, y, z) = xy^2z^3 + \arccos(x\sqrt{y}) + \sqrt{1 + x^2}$. Find $f_{xyz}$, by using a different order of differentiation for each term.

Ans: $6yz^2$

5. Show that each of the following functions is a solution of the wave equation $u_{tt} = a^2 u_{xx}$.

(a) $u = \sin(kx) \sin(akt)$

(b) $u = (x + at)^3 + (x - at)^6$

(c) $u = \sin(x + at) + \ln(x - at)$

(d) $u = f(x + at) + g(x - at)$

where $f$ and $g$ are twice differentiable functions.

---

3MSU, the land-grant research university, has an elevation of 118 meters, or 387 feet.
40

Chapter 14. Partial Derivatives

14.4. Tangent Planes & Linear Approximations

Recall: As one zooms into a curve \( y = f(x) \), the more the curve resembles a line. More specifically, the curve looks more and more like the tangent line. It is the same for surface: the surface looks more and more like the tangent plane. Some functions are difficult to evaluate at a point; so, the equation of the tangent plane (which is much simpler) is used to approximate the value of that curve at a given point.

![Figure 14.9: A tangent line and a tangent plane.](image)

**Tangent plane for** \( z = f(x, y) \) **at** \((x_0, y_0, z_0)\): Any tangent plane passing through \( P(x_0, y_0, z_0) \), \( z_0 = f(x_0, y_0) \), has an equation of the form

\[
A(x - x_0) + B(y - y_0) + C(z - z_0) = 0, \quad \mathbf{n} = <A, B, C>.
\]

By dividing the equation by \( C \neq 0 \) and letting \( a = -A/C \) and \( b = -B/C \), we can write it in the form

\[
z - z_0 = a(x - x_0) + b(y - y_0).
\] (14.9)

Then, the intersection of the plane with \( y = y_0 \) must be the \( x\)-directional tangent line at \((x_0, y_0, z_0)\), having the slope of \( f_x(x_0, y_0) \):

\[
\begin{align*}
z - z_0 &= a(x - x_0), \quad \text{where} \quad y = y_0; \\
\end{align*}
\]

Therefore \[a = f_x(x_0, y_0)\]. Similarly, we can conclude \[b = f_y(x_0, y_0)\].
14.4. Tangent Planes & Linear Approximations

Summary

14.41. Suppose that $f(x, y)$ has continuous partial derivatives. An equation of the tangent plane (equivalently, the linear approximation) to the surface $z = f(x, y)$ at the point $P(x_0, y_0, z_0)$ is

$$z - z_0 = f_x(x_0, y_0)(x - x_0) + f_y(x_0, y_0)(y - y_0), \quad (14.10)$$

where $z_0 = f(x_0, y_0)$.

Problem

14.42. Find an equation for the tangent plane to the elliptic paraboloid $z = 2x^2 + y^2$ at the point $(1, 1, 3)$.

Solution.

\[
\text{Ans: } z = 4x + 2y - 3
\]

Linear approximation (linearization) of $f$ at $(a, b)$:

$$f(x, y) \approx L(x, y) := f(a, b) + f_x(a, b)(x - a) + f_y(a, b)(y - b). \quad (14.11)$$

Problem

14.43. Give the linear approximation of $f(x, y) = xe^{xy}$ at $(1, 0)$. Then use this to approximate $f(1.1, -0.1)$.

Solution.

\[
\text{Ans: } L(x, y) = x + y; L(1.1, -0.1) = 1, \text{ while } f(1.1, -0.1) = 0.9854 \cdots.
\]
Differentiability for functions of multiple variables:

Recall: A function \( y = f(x) \) is **differentiable** at \( a \) if

\[
\lim_{\Delta x \to 0} \frac{f(a + \Delta x) - f(a)}{\Delta x} \text{ exists. (} =: f'(a)\text{)}
\]

Thus, if \( f \) is differentiable at \( a \), then

\[
\frac{f(a + \Delta x) - f(a)}{\Delta x} = f'(a) + \varepsilon \quad \text{and} \quad \Delta y \equiv f(a + \Delta x) - f(a) = f'(a)\Delta x + \varepsilon\Delta x,
\]

where \( \varepsilon \to 0 \) as \( \Delta x \to 0 \).

Now, for \( z = f(x,y) \), suppose that \((x,y)\) changes from \((a,b)\) to \((a + \Delta x, b + \Delta y)\). Then the corresponding change of \( z \) is

\[
\Delta z = f(a + \Delta x, b + \Delta y) - f(a, b).
\]

**Definition** 14.44. A function \( z = f(x,y) \) is **differentiable** at \((a,b)\) if \( \Delta z \) can be expressed in the form

\[
\Delta z = f_x(a,b)\Delta x + f_y(a,b)\Delta y + \varepsilon_1\Delta x + \varepsilon_2\Delta y,
\]

where \( \varepsilon_1, \varepsilon_2 \to 0 \) as \((\Delta x, \Delta y) \to (0,0)\).

It is sometimes hard to use Definition 14.44 directly to check the differentiability of a function.

**Theorem** 14.45. If \( f_x \) and \( f_y \) exist near \((a,b)\) and are **continuous** at \((a,b)\), then \( z = f(x,y) \) is differentiable at \((a,b)\).

**Note:** The above theorem implies that if partial derivatives of \( f \) are continuous, then the slope of \( f \) exists for all directions.

**Problem** 14.46. Let \( f(x,y) = y + \sin(x/y) \). Explain why the function is differentiable at \((0,3)\).
Differentials

**Recall:** For \( y = f(x) \), let \( dx \) be the differential of \( x \) (an independent variable). The **differential** of \( y \) is then defined as

\[
dy = f'(x) \, dx.
\]  

**(14.14)**

**Note:** \( \Delta y \) represents the change in height of the curve \( y = f(x) \), while \( dy \) represents the **change in height of the tangent line**; when \( x \) changes by \( \Delta x = dx \).

**Definition 14.47.** For \( z = f(x,y) \), we define **differentials** \( dx \) and \( dy \) to be independent variables. Then the **differential** \( dz \) is defined by

\[
dz = f_x(x,y) \, dx + f_y(x,y) \, dy,
\]  

**(14.15)**

which is also called the **total differential**.

**Problem 14.48.** Let \( z = f(x,y) = x^2 + 3xy - y^2 \).

(a) Find the differential \( dz \).

(b) If \((x,y)\) changes from \((2,3)\) to \((2.1, 2.9)\), compare the values of \( \Delta z \) and \( dz \).

**Solution.**

\[
\text{Ans: (a) } dz = (2x + 3y)dx + (3x - 2y)dy; \text{ (b) } dz = 1.3, \Delta z = 1.27
\]
Problem 14.49. Use differentials to estimate the amount of metal in a closed cylindrical can that is 10 cm high and 4 cm in diameter, if the metal in the top and bottom is 0.1 cm thick and the metal in the side is 0.05 cm thick.

Solution. \( V(r, z) = \pi r^2 z \). Therefore

\[
dV = V_r \, dr + V_z \, dz = 2\pi rz \, dr + \pi r^2 \, dz,
\]

where \( dr = 0.05 \) and \( dz = 2 \cdot 0.1 = 0.2 \).

\[
\text{Ans: } dV = 2.8\pi = 8.796459431 \cdots \quad (\Delta V = 9.0022337 \cdots)
\]

Exercises 14.4

1. Find an equation of the tangent plane to the given surface at the specified point.

   (a) \( z = \sin(2x + 3y) \), \((-3, 2, 0)\)

   (b) \( z = x^2 + 2y^2 - 3y \), \((1, -1, 6)\)

2. Explain why the function is differentiable at the given point. Then, find the linearization \( L(x, y) \) of the function at that point.

   (a) \( f(x, y) = 5 + x \ln(xy - 1) \), \((1, 2)\)

   (b) \( f(x, y) = xy + \sin(y/x) \), \((2, 0)\)

3. Given that \( f \) is a differentiable function with \( f(5, 2) = 4 \), \( f_x(5, 2) = 1 \), and \( f_y(5, 2) = -1 \), use a linear approximation to estimate \( f(4.9, 2.2) \).

   \[
   \text{Ans: } 3.7
   \]

4. Use differentials to estimate the amount of tin in a closed tin can with diameter 8 cm and height 16 cm if the tin is 0.05 cm thick.

   \[
   \text{Ans: } 8\pi
   \]
14.5. The Chain Rule

14.5.1. Chain rule

Recall: Chain Rule for functions of a single variable: If $y = f(x)$ and $x = g(t)$, where $f$ and $g$ are differentiable, then $y$ is a differentiable function of $t$ and

$$\frac{dy}{dt} = \frac{dy}{dx} \cdot \frac{dx}{dt}.$$  

(14.16)

Theorem 14.50. The Chain Rule (Case 1). Suppose that $z = f(x, y)$ is a differentiable function, where $x = g(t)$ and $y = h(t)$ are both differentiable functions of $t$. Then $z$ is a differentiable function of $t$ and

$$\frac{dz}{dt} = \frac{\partial f}{\partial x} \frac{dx}{dt} + \frac{\partial f}{\partial y} \frac{dy}{dt}.$$  

(14.17)

Observation: Let $z = f(x, y) = xy$ and $x$ and $y$ be functions of $t$:

$$z = f(x, y) = x y = x(t) y(t).$$

Then

$$\frac{dz}{dt} = x'(t) y(t) + x(t) y'(t), \quad \text{(product rule)}$$

$$\frac{\partial f}{\partial x} \frac{dx}{dt} + \frac{\partial f}{\partial y} \frac{dy}{dt} = y x'(t) + x y'(t).$$

Problem 14.51. If $z = x^2 y + xy^3$, where $x = \cos t$ and $y = \sin t$, find $dz/dt$ at $t = 0$.

Solution.

Ans: 1
Chapter 14. Partial Derivatives

Now, we will solve the above problem using the following script in Maple.

```maple
z := x*y^3+x^2*y:
x := cos(t): y := sin(t):
zt := diff(z, t)
simplify(zt)
eval(zt, t = 0)
```

Lines 4, 6, and 8 are answers from Maple.

**Theorem 14.52. The Chain Rule (Case 2).** Suppose that $z = f(x, y)$ is a differentiable function, where $x = g(s, t)$ and $y = h(s, t)$ are both differentiable functions of $s$ and $t$. Then

$$
\frac{\partial z}{\partial s} = \frac{\partial z}{\partial x} \frac{\partial x}{\partial s} + \frac{\partial z}{\partial y} \frac{\partial y}{\partial s}, \quad \frac{\partial z}{\partial t} = \frac{\partial z}{\partial x} \frac{\partial x}{\partial t} + \frac{\partial z}{\partial y} \frac{\partial y}{\partial t}.
$$

(14.18)

**Problem 14.53.** If $z = e^x \sin(y)$, where $x = st^2$ and $y = s^2 t$, find $\frac{\partial z}{\partial s}$ and $\frac{\partial z}{\partial t}$.

**Solution.**

\[
\begin{align*}
z_s &= t^2 e^{st^2} \sin{(s^2 t)} + 2 e^{st^2} s t \cos{(s^2 t)} \\
z_t &= 2 s e^{st^2} \sin{(s^2 t)} + e^{st^2} s^2 \cos{(s^2 t)}
\end{align*}
\]
14.5. The Chain Rule

Functions of three and more variables:

**Theorem 14.54. The Chain Rule (General Version).** Suppose that $u$ is a differentiable function of $n$ variables, $x_1, x_2, \ldots, x_n$, each of which has $m$ variables, $t_1, t_2, \ldots, t_m$. Then for each $i \in \{1, 2, \ldots, m\}$,

$$\frac{\partial u}{\partial t_i} = \frac{\partial u}{\partial x_1} \frac{\partial x_1}{\partial t_i} + \frac{\partial u}{\partial x_2} \frac{\partial x_2}{\partial t_i} + \cdots + \frac{\partial u}{\partial x_n} \frac{\partial x_n}{\partial t_i}.$$ 

**Problem 14.55.** Write the chain rule for $w = f(x, y, z, t)$, where $x = x(u, v), y = y(u, v), z = z(u, v)$, and $t = t(u, v)$. That is, find $\frac{\partial w}{\partial u}$ and $\frac{\partial w}{\partial v}$.

**Problem 14.56.** If $g(s, t) = f(s^2 - t^2, t^2 - s^2)$ and $f$ is differentiable, show that $g$ satisfies the equation

$$t \frac{\partial g}{\partial s} + s \frac{\partial g}{\partial t} = 0.$$ 

**Solution.** Let $x = s^2 - t^2$ and $y = t^2 - s^2$.

Then $g_s = f_x x_s + f_y y_s$ and $g_t = f_x x_t + f_y y_t$. 

**Problem 14.57.** If \( z = x^3 + x^2y \), where \( x = s + 2t - u \) and \( y = stu \), find the values of \( z_s \), \( z_t \), and \( z_u \), when \( s = 2, t = 0, u = 1 \).

**Solution.**

\[
\text{Ans: } z_s = 3, z_t = 8, \text{ and } z_u = -3
\]

### 14.5.2. Implicit differentiation

Consider \( F(x, y) = 0 \), where \( y \) is a function of \( x \), i.e., \( y = f(x) \). Then,

\[
F_x \frac{dx}{dx} + F_y \frac{dy}{dx} = 0.
\]

Thus, we have

\[
y' = -\frac{F_x}{F_y}.
\] 

**Problem 14.58.** Find \( y' \) if \( x^3 + y^3 = 6xy \).

**Solution.** Let \( F = x^3 + y^3 - 6xy \). Then, use (14.19).

\[
\text{Ans: } y' = -(x^2 - 2y)/(y^2 - 2x)
\]
**Note:** You can solve the above problem using the technique you learned earlier in Calculus I. That is, applying \textit{x-derivative} to \(x^3 + y^3 = 6xy\) reads

\[
3x^2 + 3y^2 \frac{dy}{dx} = 6y + 6x \frac{dy}{dx}.
\]

Thus

\[
3y^2 \frac{dy}{dx} - 6x \frac{dy}{dx} = -3x^2 + 6y \quad \Rightarrow \quad \frac{dy}{dx} = -\frac{3x^2 - 6y}{3y^2 - 6x}.
\]

**Claim 14.59.** Let \(z = f(x, y)\) and \(F(x, y, z) = 0\). Then \(F_x \frac{\partial x}{\partial x} + F_y \frac{\partial y}{\partial x} + F_z \frac{\partial z}{\partial x} = 0\) and \(F_x \frac{\partial x}{\partial y} + F_y \frac{\partial y}{\partial y} + F_z \frac{\partial z}{\partial y} = 0\). Thus

\[
\frac{\partial z}{\partial x} = -\frac{F_x}{F_z} \quad \text{and} \quad \frac{\partial z}{\partial y} = -\frac{F_y}{F_z}.
\]  \hspace{1cm} (14.20)

**Problem 14.60.** Find \(\frac{\partial z}{\partial x}\) and \(\frac{\partial z}{\partial y}\), if

\[
x^3 + y^3 + z^3 + 6xyz = 1.
\]  \hspace{1cm} (14.21)

**Solution.**

\[
\text{Ans: } z_x = -\frac{3x^2 + 6yz}{3z^2 + 6xy} = -\frac{x^2 + 2yz}{2z + 2xy}.
\]  See Figure 14.8, p. 35, for a figure of (14.21).
Exercises 14.5

1. Use the Chain Rule to find $dz/dt$ or $dw/dt$.

   (a) $z = \cos x \sin y;\ y = 1/t$
   (b) $w = (x + y^2 + z^2)^2;\ x = 1 + 2t,\ y = -2t,\ z = t^2$

2. Suppose $f$ is a differentiable function of $x$ and $y$, and $g(u, v) = f(u + \cos v, u^2 + 1 + \sin v)$.
   Use the table of values to find $g_u(0, 0)$ and $g_v(0, 0)$.

<table>
<thead>
<tr>
<th></th>
<th>$f$</th>
<th>$g$</th>
<th>$f_x$</th>
<th>$f_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0, 0)</td>
<td>1</td>
<td>2</td>
<td>-1</td>
<td>10</td>
</tr>
<tr>
<td>(0, 1)</td>
<td>3</td>
<td>5</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>(1, 1)</td>
<td>2</td>
<td>7</td>
<td>20</td>
<td>2</td>
</tr>
</tbody>
</table>

   $g_u(0, 0) = 20$ & $g_v(0, 0) = 2$

3. Use the Chain Rule to find the indicated partial derivatives.

   (a) $z = x^2 + y^4;\ x = s + 2t - 3u,\ y = stu$; \[ \frac{\partial z}{\partial s}, \frac{\partial z}{\partial t}, \frac{\partial z}{\partial u}\]
   when $s = 3,\ t = 1,\ and\ u = 1$

   \[\text{Ans: } z_s(3, 1, 1) = 112 \text{ & } z_u(3, 1, 1) = 312\]

   (b) $w = xy + yz + zx;\ x = r \cos \theta,\ y = r \sin \theta$; \[ \frac{\partial w}{\partial r}, \frac{\partial w}{\partial \theta}, \frac{\partial w}{\partial z}\]
   when $r = 2,\ \theta = \pi/2,\ and\ z = 1$

   $w_z = 2$

4. Use the formulas in (14.20) to find $\partial z/\partial x$ and $\partial z/\partial y$, where $z$ is function of $(x, y)$.

   (a) $x^2 + 2y^2 + 3z^2 - 4 = 0$
   (b) $e^z = xy + z$

   $\text{Ans: (b) } z_x = y/(e^z - 1)$
14.6. Directional Derivatives and the Gradient Vector

Recall: If \( z = f(x, y) \), then the partial derivatives \( f_x \) and \( f_y \) represent the rates of change of \( z \) in the \( x \)- and \( y \)-directions, that is, in the directions of the unit vectors \( i \) and \( j \).

Note: It would be nice to be able to find the slope of the tangent line to a surface \( S \) in the direction of an arbitrary unit vector \( u = \langle a, b \rangle \).

**Definition 14.61.** The **directional derivative** of \( f \) at \((x_0, y_0)\) in the direction of a unit vector \( u = \langle a, b \rangle \) is

\[
D_u f(x_0, y_0) = \lim_{h \to 0} \frac{f(x_0 + ha, y_0 + hb) - f(x_0, y_0)}{h},
\]

if the limit exists.

Note that

\[
f(x_0 + ha, y_0 + hb) - f(x_0, y_0) = f(x_0 + ha, y_0 + hb) - f(x_0, y_0 + hb) + f(x_0, y_0 + hb) - f(x_0, y_0)
\]

Thus

\[
\frac{f(x_0 + ha, y_0 + hb) - f(x_0, y_0)}{h} = a \frac{f(x_0 + ha, y_0 + hb) - f(x_0, y_0 + hb)}{ha} + b \frac{f(x_0, y_0 + hb) - f(x_0, y_0)}{hb},
\]

which converges to “\( a f_x(x_0, y_0) + b f_y(x_0, y_0) \)” as \( h \to 0 \).
**Theorem 14.62**. If \( f \) is a differentiable function of \( x \) and \( y \), then \( f \) has a **directional derivative** in the direction of any unit vector \( u = \langle a, b \rangle \) and

\[
D_u f(x, y) = f_x(x, y) a + f_y(x, y) b \\
= \langle f_x(x, y), f_y(x, y) \rangle \cdot \langle a, b \rangle \\
= \langle f_x(x, y), f_y(x, y) \rangle \cdot u.
\]

\( (14.23) \)

**Problem 14.63**. Find the directional derivative \( D_u f(x, y) \), if \( f(x, y) = x^3 + 2xy + y^4 \) and \( u \) is the unit vector given by the angle \( \theta = \frac{\pi}{4} \). What is \( D_u f(2, 3) \)?

**Solution**. \( u = \langle \cos(\pi/4), \sin(\pi/4) \rangle = \langle 1/\sqrt{2}, 1/\sqrt{2} \rangle \).

**Ans**: \( 65\sqrt{2} \)
Note: 1. The only reason we are restricting the directional derivative to the unit vector is because we care about the rate of change in \( f \) per unit distance. Otherwise, the magnitude is irrelevant.
2. If the unit vector \( \mathbf{u} \) makes an angle \( \theta \) with the positive \( x \)-axis, then \( \mathbf{u} = \langle \cos \theta, \sin \theta \rangle \). Thus

\[
D_{\mathbf{u}}f(x, y) = f_x(x, y) \cos \theta + f_y(x, y) \sin \theta.
\] (14.24)

Self-study 14.64. Find the directional derivative of \( f(x, y) = x + \sin(xy) \) at the point \((1, 0)\) in the direction given by the angle \( \theta = \pi/3 \).

Solution.

\[
\text{Ans: } (1 + \sqrt{3})/2
\]

Problem 14.65. If \( f(x, y, z) = x^2 - 2y^2 + z^4 \), find the directional derivative of \( f \) at \((1, 3, 1)\) in the direction of \( \mathbf{v} = \langle 2, -2, -1 \rangle \).

Solution.

\[
\text{Ans: } 8
\]
Gradient Vector

**Definition 14.66.** Let $f$ be a differentiable function of two variables $x$ and $y$. Then the gradient of $f$ is the vector function

$$
\nabla f(x, y) = \langle f_x(x, y), f_y(x, y) \rangle = \frac{\partial f}{\partial x} \mathbf{i} + \frac{\partial f}{\partial y} \mathbf{j}.
$$

(14.25)

**Problem 14.67.** If $f(x, y) = \sin(x) + e^{xy}$, find $\nabla f(x, y)$ and $\nabla f(0,1)$.

**Solution.**

Ans: $\langle 2, 0 \rangle$

**Note:** With this notation of the gradient vector, we can rewrite

$$
D_uf(x, y) = \nabla f(x, y) \cdot u = f_x(x, y)a + f_y(x, y)b, \text{ where } u = \langle a, b \rangle.
$$

(14.26)

**Problem 14.68.** Find the directional derivative of $f(x, y) = x^2y^3 - 4y$ at the point $(2, -1)$ and in the direction of the vector $\mathbf{v} = \langle 3, 4 \rangle$.

**Solution.**

Ans: $4$
Maximizing the Directional Derivative

Note that

\[ D_u f = \nabla f \cdot u = |\nabla f| |u| \cos \theta = |\nabla f| \cos \theta, \]

where \( \theta \) is the angle between \( \nabla f \) and \( u \); the maximum occurs when \( \theta = 0 \).

**Theorem 14.69.** Let \( f \) be a differentiable function of two or three variables. Then

\[ \max_u D_u f(x) = |\nabla f(x)| \] (14.27)

and it occurs when \( u \) has the same direction as \( \nabla f(x) \).

**Problem 14.70.** Let \( f(x, y) = xe^y \).

(a) Find the rate of change of \( f \) at \( P(1, 0) \) in the direction from \( P \) to \( Q(-1, 2) \).
(b) In what direction does \( f \) have the maximum rate of change? What is the maximum rate of change?

**Solution.**

\[ \text{Ans: (a) } 0; \text{ (b) } \sqrt{2} \]

**Remark 14.71.** Let \( u = \frac{\nabla f(x)}{|\nabla f(x)|} \), the unit vector in the gradient direction. Then

\[ D_u f(x) = \nabla f(x) \cdot u = \nabla f(x) \cdot \frac{\nabla f(x)}{|\nabla f(x)|} = |\nabla f(x)|. \] (14.28)

This implies that the directional derivative is maximized in the gradient direction.

**Claim 14.72.** The gradient direction is the direction where the function changes fastest, more precisely, increases fastest!
Suppose $S$ is a surface with equation

$$F(x, y, z) = k$$

and $P(x_0, y_0, z_0) \in S$. Let $C$ be any curve that lies on the surface $S$, passes through $P$, and is described by a continuous vector function

$$r(t) = (x(t), y(t), z(t)).$$

Then, any point $(x(t), y(t), z(t))$ must satisfy

$$F(x(t), y(t), z(t)) = k. \quad (14.30)$$

Apply the Chain Rule to have

$$\frac{d}{dt}F = F_x \frac{dx}{dt} + F_y \frac{dy}{dt} + F_z \frac{dz}{dt} = \nabla F \cdot r'(t) = 0.$$

In particular, letting $t = t_0$ be such that $r(t_0) = (x_0, y_0, z_0)$,

$$\nabla F(x_0, y_0, z_0) \cdot r'(t_0) = 0, \quad (14.31)$$

where $r'(t_0)$ is the tangent vector at $P(x_0, y_0, z_0)$.

---

**Summary 14.73. (Gradient Vector).** Given a level surface $F(x, y, z) = k$, the gradient vector $\nabla F(x, y, z)$ is normal to the surface and pointing the fastest increasing direction.
Tangent Plane to a Level Surface

Suppose \( S \) is a surface given as \( F(x, y, z) = k \) and \( x_0 = (x_0, y_0, z_0) \) is on \( S \).
Then the tangent plane to \( S \) at \( x_0 \) is

\[
\nabla F(x_0) \cdot (x - x_0) = F_x(x_0)(x - x_0) + F_y(x_0)(y - y_0) + F_z(x_0)(z - z_0) = 0. \tag{14.32}
\]

The normal line to \( S \) at \( x_0 \) is

\[
\frac{x - x_0}{F_x(x_0)} = \frac{y - y_0}{F_y(x_0)} = \frac{z - z_0}{F_z(x_0)}. \tag{14.33}
\]

**Problem 14.74.** Find the equations of the tangent plane and the normal line at \( P(-1, 1, 2) \) to the ellipsoid

\[
x^2 + y^2 + \frac{z^2}{4} = 3.
\]

**Solution.**

\[
\text{Ans: } -2x - 6 + 2y + z = 0; \quad \frac{x+1}{2} = \frac{y-1}{2} = \frac{z-2}{1}
\]
Chapter 14. Partial Derivatives

Exercises 14.6

1. Find the directional derivative of $f$ at the point $P$ in the direction indicated by either the angle $\theta$ or a vector $v$.

(a) $f(x,y) = x \sin(xy)$, $P(0,1)$, $\theta = \pi/4$
(b) $f(x,y,z) = y^2 e^{xyz}$, $P(0,1,-1)$, $v = <-1,2,2>$

Ans: (b) $5/3$

2. Find the maximum rate of change of $f$ at the given point and the direction in which it occurs.

(a) $f(x,y) = \sin(xy)$, $(0,1)$
(b) $f(x,y,z) = \frac{z}{x+y}$, $(1,1,4)$

Ans: (b) $|\nabla f(1,1,4)| = 3/2$, $\nabla f(1,1,4) = <-1,-1,1/2>$

Note: We know that a differentiable function $f$ increases most rapidly in the direction of $\nabla f$. Thus, it is natural to claim that the function decreases most rapidly in the direction opposite to the gradient vector, that is, $-\nabla f$.

3. Find the direction in which the function $f(x,y,z) = x^2 + y^2 + z^2$ decreases fastest at the point $(1,1,1)$.

4. Find directions (unit vectors) in which the directional derivative of $f(x,y) = x^2 + xy^2$ at the point $(1,2)$ has value 0.

Ans: $u = \pm \frac{2,-3}{\sqrt{13}}$

5. Find the equations of (i) the tangent plane and (ii) the normal line to the given surface at the specified point.

(a) $(x - 1)^2 + (y - 2)^2 + (z - 3)^2 = 3$, $(2,1,4)$
(b) $xy + yz + zx - 5 = 0$, $(1,1,2)$

Ans: (b) $3(x-1) + 3(y-1) + 2(z-2) = 0$ & $\frac{x-1}{3} = \frac{y-1}{3} = \frac{z-2}{2}$
14.7. Maximum and Minimum Values

**Recall:** To find the **absolute maximum and minimum values** of a continuous function \( f \) on a closed interval \( [a, b] \):

1. Find values of \( f \) at the critical points of \( f \) in \((a, b)\).
2. Find values of \( f \) at the end points of the interval.
3. The largest is the absolute maximum value; the smallest is the absolute minimum value.

**Recall:** *(Second Derivative Test for \( y = f(x) \)) Suppose \( f'' \) is continuous near \( c \).

(a) If \( f'(c) = 0 \) and \( f''(c) > 0 \), then \( f \) has a **local minimum** at \( c \).
(b) If \( f'(c) = 0 \) and \( f''(c) < 0 \), then \( f \) has a **local maximum** at \( c \).

14.7.1. Local extrema

**Definition** 14.75. Let \( f \) be a function of two variables \( x \) and \( y \).

- **It has a local minimum** at \((a, b)\) if \( f(x, y) \geq f(a, b) \) when \((x, y)\) is near \((a, b)\).
- **It has a local maximum** at \((a, b)\) if \( f(x, y) \leq f(a, b) \) when \((x, y)\) is near \((a, b)\).

**Theorem** 14.76. *(First Derivative Test)*. If \( f \) has a local extreme at \((a, b)\) and the first order partial derivatives exist, then \( f_x(a, b) = 0 \) and \( f_y(a, b) = 0 \), that is, \( \nabla f(a, b) = 0 \).

**Problem** 14.77. Find the **critical points** of

\[ f(x, y) = 2x^3 - 3x^2 + y^2 + 4y + 1. \]

**Ans:** \((0, -2), (1, -2)\)
**Theorem 14.78. (Second Derivative Test).** Suppose that the second order partial derivatives of $f$ are continuous near $(a, b)$ and suppose that $\nabla f(a, b) = 0$. Let

$$D = D(a, b) = f_{xx}(a, b)f_{yy}(a, b) - [f_{xy}(a, b)]^2.$$ 

- If $D > 0$ and $f_{xx}(a, b) > 0$, then $f(a, b)$ is a local minimum.
- If $D > 0$ and $f_{xx}(a, b) < 0$, then $f(a, b)$ is a local maximum.
- If $D < 0$, then $f(a, b)$ is a saddle point.

**Note:**
1. If $D = 0$, then no conclusion can be drawn from this test.
2. $D = \det \begin{bmatrix} f_{xx} & f_{xy} \\ f_{yx} & f_{yy} \end{bmatrix} = f_{xx}f_{yy} - f_{xy}f_{yx} = f_{xx}f_{yy} - (f_{xy})^2$
3. Let $D > 0$. Then, $f_{xx}(a, b) \geq 0$ is equivalent to $f_{yy}(a, b) \geq 0$.

**Problem 14.79.** Find all local extrema of $f(x, y) = x^4 + y^4 - 4xy + 1$.

**Solution.**

![Figure 14.14](image)

Ans: local min: $(\pm 1, \pm 1)$; saddle point: $(0, 0)$
**Problem 14.80.** Find the shortest distance from the point \((1, 0, 2)\) to the plane \(2x + 2y - z + 2 = 0\).

**Solution.** (a) You may use the formula \(d = \frac{|ax_0 + by_0 + cz_0 + d|}{\sqrt{a^2 + b^2 + c^2}}\).
(b) Let \(d\) be the distance. Then

\[
f(x, y) = d^2 = (x - 1)^2 + (y - 0)^2 + (z - 2)^2 = (x - 1)^2 + y^2 + (2x + 2y)^2
\]

*Ans: 2/3*
**Problem 14.81.** Find the volume of the largest rectangular box in the first octant with three faces in the coordinate planes and one vertex on the plane $3x + 2y + z = 6$.

**Hint:** Maximize $V = xyz$, subject to $3x + 2y + z = 6$. Thus $V = xy(6 - 3x - 2y)$. Try to find the maximum by setting $\nabla V = 0$.

**Solution.**

**Ans:** $(x, y, z) = (2/3, 1, 2); V = xyz = 4/3$
14.7.2. Absolute extrema

**Theorem 14.82. (Existence).** If \( f \) is continuous on a closed and bounded set \( D \subset \mathbb{R}^2 \), then \( f \) attains an **absolute minimum value** \( f(x_0, y_0) \) and an **absolute maximum value** \( f(x_1, y_1) \) at some points \((x_i, y_i) \in D, i = 0, 1\).

**Strategy 14.83.** To find absolute extrema,
1. Find critical points and values of \( f \) at those critical points.
2. Find the extreme values that occur on the boundary.
3. Compare all of those values for the largest and smallest values.

**Problem 14.84.** Find the absolute extrema of \( f(x, y) = x^2 - 2xy + 2y \) on the rectangle \( R = \{(x,y) | 0 \leq x \leq 3, 0 \leq y \leq 2 \} \).

**Solution.**

![Graph of the region R]

Figure 14.15: \( R = [0, 3] \times [0, 2] \)

*Ans: abs.min=0; abs.max=9*
Exercises 14.7

1. (i) Find the local maxima and minima and saddle points of the function.
   (ii) Use Maple’s plot3d and contourplot functions to verify them.
   
   (a) \( f(x, y) = x^3 - 3xy^2 \)
   
   (b) \( f(x, y) = (2x^2 + y^2)e^{-x^2-y^2} \)

   (Note: You may use Mathematica, if you want.)

2. Find the absolute maximum and minimum values of \( f \) on \( D \).
   
   (a) \( f(x, y) = x^2 + y^2 - 2x; \ D \) is the closed triangular region with vertices \((2, 0), (0, 2), \) and \((0, -2)\).
   
   Ans: max: \( f(0, \pm 2) = 4 \); min: \( f(1, 0) = -1 \)
   
   (b) \( f(x, y) = 4x^2 + y^4; \ D = \{(x, y)|x^2 + y^2 \leq 1\} \).
   
   Ans: max: \( f(\pm 1, 0) = 4 \); min: \( f(0, 0) = 0 \)

3. Find three positive numbers whose sum is 60 and whose product is maximum.
   Hint: The problem can read: \( \text{max } xyz, \) subject to \( x + y + z = 60 \). Thus for example it can be reformulated as: \( \text{max } xy(60 - x - y), \) with each component being positive. From this, you may conclude \( x = y \).

4. Find the volume of the largest rectangular box in the first octant with three faces in the coordinate planes and one vertex in the plane \( 2x + 5y + z = 30 \). Clue: Try to use the hint given for Problem 14.81.
14.8. Lagrange Multipliers

In Problem 14.81, on p. 62, we maximized a volume function \( V = xyz \) subject to the constraint \( 3x + 2y + z = 6 \), which was the plane having a vertex of the rectangular box.

In this section, we consider Lagrange’s method to solve the problem of the form

\[
\max_x f(x) \quad \text{subj.to} \quad g(x) = c. \quad (14.34)
\]

Figure 14.16: The method of Lagrange multipliers in \( \mathbb{R}^2 \): \( \nabla f \parallel \nabla g \), at maximum.

**Strategy 14.85.** (Method of Lagrange multipliers). For the maximum and minimum values of \( f(x, y, z) \) subject to \( g(x, y, z) = c \),

(a) Find all values of \( (x, y, z) \) and \( \lambda \) such that

\[
\nabla f(x, y, z) = \lambda \nabla g(x, y, z) \quad \text{and} \quad g(x, y, z) = c.
\quad (14.35)
\]

(b) Evaluate \( f \) at all these points, to find the maximum and minimum.
Problem 14.86. (Revisit of Problem 14.81, p. 62). Find the volume of the largest rectangular box in the first octant with three faces in the coordinate planes and one vertex on the plane $3x + 2y + z = 6$, using the method of Lagrange multipliers.

Solution.

Ans: $\frac{4}{3}$

Problem 14.87. A topless rectangular box is made from $12m^2$ of cardboard. Find the dimensions of the box that maximizes the volume of the box.

Solution. Maximize $V = xyz$ subj.to $2xz + 2yz + xy = 12$.

Ans: $4 (x = y = 2z = 2)$
14.8. Lagrange Multipliers

**Problem 14.88.** Find the extreme values of \( f(x, y) = x^2 + 2y^2 \) on the circle \( x^2 + y^2 = 1 \).

**Solution.** \( \nabla f = \lambda \nabla g \implies \begin{bmatrix} 2x \\ 4y \end{bmatrix} = \lambda \begin{bmatrix} 2x \\ 2y \end{bmatrix} \). Therefore, \( \begin{cases} 2x = 2x \lambda \\ 4y = 2y \lambda \\ x^2 + y^2 = 1 \end{cases} \)

From (1), \( x = 0 \) or \( \lambda = 1 \).

**Ans:** \( \text{min: } f(\pm 1, 0) = 1; \text{max: } f(0, \pm 1) = 2 \)

**Problem 14.89.** Find the extreme values of \( f(x, y) = x^2 + 2y^2 \) on the disk \( x^2 + y^2 \leq 1 \).

**Solution.** **Hint:** You may use Lagrange multipliers when \( x^2 + y^2 = 1 \).

**Ans:** \( \text{min: } f(0, 0) = 0; \text{max: } f(0, \pm 1) = 2 \)
Two Constraints

Consider the problem of the form

\[ \max_x f(x) \quad \text{subj.to} \quad g(x) = c \quad \text{and} \quad h(x) = d. \quad (14.36) \]

Then, at extrema we must have

\[ \nabla f \in \text{Plane}(\nabla g, \nabla h) := \{c_1 \nabla g + c_2 \nabla h\}. \quad (14.37) \]

Thus (14.36) can be solved by finding all values of \((x, y, z)\) and \((\lambda, \mu)\) such that

\[
\begin{align*}
\nabla f(x, y, z) &= \lambda \nabla g(x, y, z) + \mu \nabla h(x, y, z) \\
g(x, y, z) &= c \\
h(x, y, z) &= d
\end{align*}
\]

(14.38)

**Problem 14.90.** Find the maximum value of the function \(f(x, y, z) = z\) on the curve of the intersection of the cone \(2x^2 + 2y^2 = z^2\) and the plane \(x + y + z = 4\).

**Solution.** Letting \(g = 2x^2 + 2y^2 - z^2 = 0\) \(4\) and \(h = x + y + z = 4\) \(5\), we have

\[
\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \lambda \begin{bmatrix} 4x \\ 4y \\ -2z \end{bmatrix} + \mu \begin{bmatrix} 1 \\ 1 \end{bmatrix} \implies \begin{cases} 0 = 4\lambda x + \mu & (1) \\ 0 = 4\lambda y + \mu & (2) \\ 1 = -2\lambda z + \mu & (3) \end{cases}
\]

From \(1\) and \(2\), we conclude \(x = y\); using \(4\), we have \(z = \pm 2x\).

**Ans:** 2
Exercises 14.8

1. Use Lagrange multipliers to find extreme values of the function subject to the given constraint.

(a) \( f(x, y) = xy; \quad x^2 + 4y^2 = 2 \)
(b) \( f(x, y) = x + y + 2z; \quad x^2 + y^2 + z^2 = 6 \)

Ans: max: \( f(1, 1, 2) = 6 \); min: \( f(-1, -1, -2) = -6 \)

2. Find extreme values of \( f \) subject to both constraint.

\[
\begin{align*}
\quad & x^2 + y^2 + z^2; \quad x - y = 3, \quad x^2 - z^2 = 1.
\end{align*}
\]

Ans: \( f(1, -2, 0) = 5 \)

Note: The value just found for Problem 2 is the minimum. Why? See the figure below.

Figure 14.17: implicitplot3d. red: \( x - y = 3 \); green: \( x^2 - z^2 = 1 \); blue: \( f(x, y, z) = 5 \).

3. Use Lagrange multipliers to solve Problem 3 in Exercise 14.7. (See p. 64.)

4. Use Lagrange multipliers to solve Problem 4 in Exercise 14.7.
R.14. Review Problems for Ch. 14

1. Let \( f(x, y) = \sqrt{4 - x^2 - 4y^2} \).
   
   (a) Find the **domain** of \( f \).
   (b) Sketch the **graph** of the function.

   \text{Ans:} \{ (x, y) \mid x^2 + 4y^2 \leq 4 \}

2. **Determine and verify** whether the following functions are continuous at \((0, 0)\) or not.

   (a) \( f(x, y) = \begin{cases} \frac{xy^2}{x^2 + y^2}, & \text{if } (x, y) \neq (0, 0), \\ 0, & \text{if } (x, y) = (0, 0). \end{cases} \)  
   \text{Circle: continuous discontinuous}

   (b) \( g(x, y) = \begin{cases} \frac{\sin(x^2 + y^2)}{x^2 + y^2}, & \text{if } (x, y) \neq (0, 0), \\ 0, & \text{if } (x, y) = (0, 0). \end{cases} \)  
   \text{Circle: continuous discontinuous}

   \text{Ans:} (a) continuous; (b) discontinuous

3. Let \( f(x, y) = \sin(2x - 3y) \).
   
   (a) Find \( f_x(3, 2) \) and \( f_y(3, 2) \).
   (b) Find \( f_{xyx}(3, 2) \) and \( f_{yxx}(3, 2) \).

   \text{Ans:} (a) 2, -3; (b) 12, 12

4. Let \( f(x, y) = 1 + x \ln(xy - 5) \).
   
   (a) Explain why \( f \) is **differentiable** at \((2, 3)\).
   (b) Find the **linearization** \( L(x, y) \) of \( f \) at \((2, 3)\).

   \text{Ans:} (a): \( f_x = \ln(xy - 5) + \frac{xy}{xy - 5} \) and \( f_y = \frac{x^2}{xy - 5} \) are continuous near \((2, 3)\).
   \text{(b)} \( L(x, y) = 1 + 6(x - 2) + 4(y - 3) \).

5. Suppose \( f \) is a differentiable function of \( x \) and \( y \), and \( g(u, v) = f(u + e^v + \cos v, u^2 + \sin v) \). Use the table of values to find \( g_u(0, 0) \) and \( g_v(0, 0) \).

\[
\begin{array}{|c|c|c|c|}
\hline
(x, y) & f & g & f_x & f_y \\
\hline
(0, 0) & 2000 & 2 & 100 & 9 \\
(2, 0) & 3 & 4 & 9 & 12 \\
\hline
\end{array}
\]
6. Let \( f(x, y) = x + \sin(xy) \) and \( P(1, 0) \).

(a) Find the **directional derivative** of \( f \) at \( P \) in the direction given by the angle \( \theta = \pi/3 \).

(b) Determine \( \max_u D_u f(P) \), where \( u \) is a unit vector.

Ans: (a) \( <1, 1> \cdot <\cos(\pi/3), \sin(\pi/3)> = (1 + \sqrt{3})/2 \).  
(b) \( \sqrt{2} \)

7. Consider the ellipsoid \( \frac{x^2}{4} + y^2 + \frac{z^2}{9} = 3 \). Find the **tangent plane** to it at point \( (2, 1, -3) \).

Ans: \( (x - 2) + 2(y - 1) - \frac{2}{3}(z + 3) = 0 \)

8. Find the **absolute maximum and minimum values** of \( f \) over \( D \):
\[
f(x, y) = 3x^2 + y^2, \quad D = \{(x, y) \mid x^2 + y^2 \leq 1\}.
\]

Ans: min:0, max:3

9. Use the **method of Lagrange multipliers** to find the maximum and minimum values of \( f \) subject to the given constraint:
\[
f(x, y) = x^2 - y^2; \quad x^2 + y^2 = 1
\]

**Hint**: \( \nabla f = \lambda \nabla g \Rightarrow \begin{cases} 2x = \lambda \cdot 2x \\ -2y = \lambda \cdot 2y \\ x^2 + y^2 = 1 \end{cases} \)  
Then, it follows from 1 and 2 that \( \lambda = \pm 1 \). When \( \lambda = -1 \), for example, \( x = 0 \) from 1, with which 3 makes \( y = \pm 1 \).

Ans: min: -1, max: 1

10. Use the **method of Lagrange multipliers** to find three positive numbers whose sum is 15 and the sum of whose squares is as small as possible.

**Clue**: \( \min x^2 + y^2 + z^2 \), subject to \( x + y + z = 15 \).

Ans: \( x = y = z = 5 \)
Chapter 14. Partial Derivatives

Project 1. Linear and Quadratic Approximations

This project is designed for students to experience computer algebra, while solving some calculus problems with computer coding. Although it includes examples written in Maple only, students can finish the project using Maple, Mathematica, or MathCad.

Getting familiar with Computer Algebra (CAS)

For a smooth function of one variable, \( f \), its Taylor series about \( a \) is given as

\[
f(x) \sim \sum_{k=0}^{\infty} \frac{f^{(k)}(a)}{k!}(x-a)^k = f(a) + \frac{f'(a)}{1!}(x-a) + \frac{f''(a)}{2!}(x-a)^2 + \cdots . \tag{14.39}
\]

As with any convergent series, \( f(x) \) is the limit of the sequence of partial sums. That is,

\[
f(x) = \lim_{n \to \infty} T_n(x), \tag{14.40}
\]

where \( T_n(x) \) is called the Taylor polynomial of degree \( n \):

\[
T_n(x) = \sum_{k=0}^{n} \frac{f^{(k)}(a)}{k!}(x-a)^k.
\]

Example 14.91. Let

\[
f(x) = \arctan(x) - \frac{1}{3}. \tag{14.41}
\]

Then, when it is expanded about \( a = 1/2 \), \( T_n(x) \) can be obtained using Maple:

\[
\begin{align*}
a & := 1/2; \\
T_n & := x \rightarrow \text{convert(taylor(f(x),x=a,n+1),polynom)};
\end{align*}
\]

See Figure 14.18 (p. 73). For the function in (14.41),

\[
\begin{align*}
T_1(x) &= \arctan \left( \frac{1}{2} \right) - \frac{1}{3} + \frac{4}{5} \left( x - \frac{1}{2} \right), \\
T_2(x) &= \arctan \left( \frac{1}{2} \right) - \frac{1}{3} + \frac{4}{5} \left( x - \frac{1}{2} \right) - \frac{8}{25} \left( x - \frac{1}{2} \right)^2.
\end{align*} \tag{14.42}
\]

\(^4\)In Maple, \texttt{taylor(f(x),x=a,n+1)} returns a polynomial of \((n+1)\) terms plus the remainder, \( T_n(x) + O((x-a)^{n+1}) \); while the command \texttt{convert(g,polynom)} converts \( g \) into a polynomial form, which is \( T_n(x) \). In Mathematica, \texttt{Series[f[x],x,a,n]} produces the same result as for \texttt{taylor(f(x),x=a,n+1)} in Maple. Now, the Mathematica-command \texttt{Normal} can be used to convert the result into normal expressions of polynomials.
14.8. Lagrange Multipliers

Figure 14.18: Screen-shot of Maple window, which plots linear and quadratic approximations of $f(x) = \arctan(x) - \frac{1}{3}$ about $a = 1/2$. 

```maple
restart: with(plots):
f := x -> arctan(x) - 1/3:
a := 1/2: taylor(f(x), x = a, 3)

\[
\arctan\left(\frac{1}{2}\right) - \frac{1}{3} + \frac{4}{5} \left(x - \frac{1}{2}\right) - \frac{8}{25} \left(x - \frac{1}{2}\right)^2 + O\left(\left(x - \frac{1}{2}\right)^3\right)
\]
(1)

T1 := x -> convert(taylor(f(x), x = a, 2), polynom):
T2 := x -> convert(taylor(f(x), x = a, 3), polynom):

p1 := plot([[f(a)], [f(a)]], style = point, symbol = solidcircle, symbolsize = 15, color = black):
p2 := plot([f(x), T1(x), T2(x)], x = -2 .. 3, color = [black, blue, red], linestyle = [solid, dot, dash], thickness = 2, legend = [y = f(x), "T1(x)", "T2(x)"], legendstyle = [font = ["HELVETICA", 12], location = bottom]):
display({p1, p2}, labels = [x, y], labelfont = ["HELVETICA", "bold", 12])
```
Maple: 3D Plots

First load the plots package, along with other frequently used packages, using the entry:

```maple
with(plots): with(plottools):
with(VectorCalculus): with(Student[MultivariateCalculus]):
```

1. Plot $z = f(x, y)$ in **Cartesian coordinates**, using

```maple
plot3d( f(x, y), x = a..b, y = c..d, options)
```

Consider the options
(a) **style = patchcontour** Puts contour curves on the surface.
(b) **axes = boxed** Puts the axes on the edges of a box enclosing the surface.
(c) **scaling = constrained** Makes the scale on the three axes the same.
(d) **orientation = [40, 70]** Orients the viewpoint so it is closer to what you see in your text.

2. Plot $F(x, y, z) = 0$ in **Cartesian coordinates**, using

```maple
implicitplot3d( F(x, y, z) = 0, x = a..b, y = c..d, z = s..t, options)
```

Consider the options listed above along with the following.
(a) **grid = [m, n, k]** Where $m, n, k$ are positive integers, try $[30, 30, 30]$ for example. This plots 30 points in each direction for a smoother surface.
(b) **axes = framed** Puts axes along the edges of a frame around the plot.
(c) **orientation = [-50, 60]** Another nice viewing angle.

3. Plot $r = f(\theta, z)$ in **cylindrical coordinates**, using

```maple
plot3d( f(\theta, z), \theta = a..b, z = s..t, coords = cylindrical, options)
```

To plot $z = g(r, \theta)$, use

```maple
plot3d([r, \theta, g(r, \theta)], r = a..b, \theta = \alpha..\beta, coords = cylindrical, options)
```

Options are more or less the same as the above.

4. Plot $\rho = f(\theta, \phi)$ in **spherical coordinates**, using

```maple
plot3d( f(\theta, \phi), \theta = \alpha..\beta, \phi = \gamma..\delta, coords = spherical, options)
```

5. Implicit plots can also be made in **cylindrical or spherical coordinates**. For example, to plot the equation $r^2 + 2z^2 = r \cos \theta$ in cylindrical coordinates, use

```maple
implicitplot3d(r^2 + 2z^2 = r \cos(\theta), r = a..b, \theta = \alpha..\beta, z = s..t, coords = cylindrical, options)
```

6. **(Contour plots in 2D).** For $z = f(x, y)$, use

```maple
contourplot(f(x, y), x = a..b, y = c..d, options)
```
14.8. Lagrange Multipliers

P.1.1. Newton’s method

As one can see from Figure 14.18, the first-degree Taylor series $T_1(x)$ is the tangent line to the curve $y = f(x)$ at the point $(a, f(a))$. One of popular applications exploiting the tangent line is Newton’s method for the problem of root-finding.

Given a differentiable function $f(x)$, find $r$ such that $f(r) = 0$, \hspace{1cm} (14.43)

where $r$ is an $x$-intercept of the curve $y = f(x)$.

The idea behind Newton’s method:

- The tangent line is close to the curve and so its $x$-intercept must be close to the $x$-intercept of the curve.
- Let $x_0$ be the initial approximation close to $r$. Then, the tangent line at $(x_0, f(x_0))$ reads

$$L(x) = f'(x_0)(x - x_0) + f(x_0).$$ \hspace{1cm} (14.44)

Let $x_1$ be the $x$-intercept of $y = L(x)$. Then,

$$0 = f'(x_0)(x_1 - x_0) + f(x_0).$$

Solving the above equation for $x_1$ becomes

$$x_1 = x_0 - \frac{f(x_0)}{f'(x_0)},$$ \hspace{1cm} (14.45)

which hopefully is a better approximation for the root $r$.
- Repeat the above till the convergence.

Algorithm 14.92. (Newton’s method for solving $f(x) = 0$). For $x_0$ chosen close to a root $r$, compute $\{x_n\}$ repeatedly satisfying

$$x_n = x_{n-1} - \frac{f(x_{n-1})}{f'(x_{n-1})}, \hspace{1cm} n \geq 1.$$ \hspace{1cm} (14.46)

Problem 14.93. Consider the function $f(x) = \arctan(x) - \frac{1}{3}$ in (14.41).

1. Implement a code for Newton’s method to approximate a root of $f(x) = 0$.
   (You can use Maple, Mathematica, or MathCad.)
2. Run a few iterations, starting from $x_0 = 0.5$, and measure how the error decreases as the iteration count grows.
(Note that the exact root $r = \tan(1/3) \approx 0.34625354951057549103$.)

P.1.2. Estimation of critical points

The second part of the project involves a min-max analysis of a function in $(x, y)$ that is based on each student’s ID number, so that each student has his/her own function to work with. If a student’s ID number is 123-45-6789, then he/she will study the behavior of the function

$$f(x, y) = 1 \sin(x - 2) + 3 \cos(y - 4) + 5x^2 - 6xy + 7y^2 - 8x + 9y, \quad (14.47)$$

where the alternating signs are used to create a little more “action”. We will call such a function the ID function.

![Contour plot of $f(x, y)$ in (14.47).](image)

**Problem 14.94.** Create your ID function. Then,

1. Include a variety of surface plots with different views and contour plots with different windows to provide a good picture of the behavior of your ID function.\(^5\)

\(^5\)In Maple, you can use the commands `plot3d` and `contourplot`. In Mathematica, `Plot3D` and `ContourPlot` are available.
2. Label the figures and refer to them in your write-up, as you discuss the kinds of critical points you observe. (If you have no or one critical point, change the signs and/or shuffle the digits in your ID function to get more action.)

3. Zoom in sufficiently so that you can estimate the coordinates of each of the critical points.

P.1.3. Quadratic approximations

We have discussed the linear approximation (or, linearization) of a function \( f \) of two variables at a point \((a, b)\):

\[
L(x, y) = f(a, b) + f_x(a, b)(x - a) + f_y(a, b)(y - b),
\]

(14.48)

which is also called the \textbf{first-degree Taylor polynomial} of \( f \) at \((a, b)\). If \( f \) has continuous second-order partial derivatives at \((a, b)\), then the \textbf{second-degree Taylor polynomial} of \( f \) at \((a, b)\) is

\[
Q(x, y) = f(a, b) + f_x(a, b)(x - a) + f_y(a, b)(y - b) + \frac{1}{2}f_{xx}(a, b)(x - a)^2 + f_{xy}(a, b)(x - a)(y - b) + \frac{1}{2}f_{yy}(a, b)(y - b)^2,
\]

(14.49)

and the approximation \( f(x, y) \approx Q(x, y) \) is called the \textit{quadratic approximation} of \( f \) at \((a, b)\).

\textbf{Problem 14.95.} Answer the following.

1. Verify that the quadratic approximation \( Q \) has the same first- and second-order partial derivatives as \( f \) at \((a, b)\). (This is the only portion of the project that you can finish without using computer implementation.) \textit{Hint}: The partial derivatives evaluated at \((a, b)\), appeared in \( Q \), are all constant.

2. Use computer algebra to find the first- and second-degree Taylor polynomials \( L \) and \( Q \) for your ID function \( f \) at a critical point \( C(x_0, y_0) \) that you estimated from Problem 14.94.

3. Compare the values of \( f \), \( L \), and \( Q \) at \((x_0 + 0.1, y_0 - 0.1)\).
4. Graph $f$, $L$, and $Q$; comment on how well $L$ and $Q$ approximate $f$.

**Report.** Submit hard copies of your experiences.
- Solve Problems 14.93, 14.94, and 14.95, using computer programming.
- Make hard copies of your work, and **collect them in order**.
- Attach a “summary” or “conclusion” page at the beginning of report.

You may work in a small group; however, you must report individually.
CHAPTER 15

Multiple Integrals

The multiple integral is a definite integral of a function of more than one real variable, for example, \( f(x, y) \) or \( f(x, y, z) \). Integrals of a function of two variables over a region in \( \mathbb{R}^2 \) are called double integrals, and integrals of a function of three variables over a region of \( \mathbb{R}^3 \) are called triple integrals.

In this chapter, you will learn double integrals and triple integrals in rectangular coordinates, polar coordinates, cylindrical coordinates, and spherical coordinates. Also, you will learn how to perform integration by changing variables between or inside coordinates.

Contents of Chapter 15

15.1. Double Integrals over Rectangles ................................................. 80
15.2. Double Integrals over General Regions ..................................... 89
15.3. Double Integrals in Polar Coordinates ..................................... 97
15.4. Applications of Double Integrals ............................................. 106
15.5. Surface Area ........................................................................... 112
15.6. Triple Integrals ....................................................................... 116
15.7. Triple Integrals in Cylindrical Coordinates .............................. 123
15.8. Triple Integrals in Spherical Coordinates ................................. 127
15.9. Change of Variables in Multiple Integrals ............................... 132
R.15. Review Problems for Ch. 15 ................................................. 141
Project 2. The Volume of the Unit Ball in \( n \)-Dimensions ............. 143

This chapter corresponds to Chapter 15 in Stewart, *Calculus* (8th Ed.), 2015.
Recall: (Review on Definite Integrals). We know the following:

- We defined the integral in terms of Riemann Sum.
- That is, we found the area underneath the curve $y = f(x)$ by dividing the area into rectangles. We then added up their areas to get the area under the curve.
- We then found the exact area of this by evaluating
  \[ \int_{a}^{b} f(x) \, dx = \lim_{n \to \infty} \sum_{i=1}^{n} f(x_i^*) \Delta x, \quad \Delta x = \frac{b - a}{n}. \]
- We could also get it using the Fundamental Theorem of Calculus (Part 2):
  \[ \int_{a}^{b} f(x) \, dx = F(b) - F(a), \quad (15.1) \]
  where $F$ is a function such that $F' = f$ (antiderivative).
15.1. Double Integrals over Rectangles

15.1.1. Volumes as double integrals

Let \( R = [a, b] \times [c, d] \subset \mathbb{R}^2 \) be a rectangle. Define
\[
\Delta x = (b - a)/m, \quad \Delta y = (d - c)/n,
\]
for some \( m, n > 0 \). Let
\[
\begin{align*}
x_i &= a + i\Delta x, \quad i = 0, 1, \ldots, m, \\
y_j &= c + j\Delta y, \quad j = 0, 1, \ldots, n,
\end{align*}
\]
and
\[
R_{ij} = [x_{i-1}, x_i] \times [y_{j-1}, y_j].
\]

Let \( S_R = \{(x, y, z) \mid 0 \leq z \leq f(x, y), (x, y) \in R\} \) define the solid that lies above \( R \). Let \( \Delta A = \Delta x \Delta y \) denote the area of each \( R_{ij} \). Then we can express this volume of \( S_R \) as
\[
V \approx \sum_{i=1}^{m} \sum_{j=1}^{n} f(x^*_ij, y^*_ij) \Delta A,
\]
where \( (x^*_ij, y^*_ij) \) is a sample point in each division \( R_{ij} \).

**Definition** 15.1. The **double integral** of \( f \) over the rectangle \( R \) is
\[
\iint_R f(x, y) \, dA = \lim_{m,n \to \infty} \sum_{i=1}^{m} \sum_{j=1}^{n} f(x^*_ij, y^*_ij) \Delta A.
\]

We can simplify this if we choose each sample point to be the point in the upper right corner of each sub-rectangle, \( (x^*_ij, y^*_ij) = (x_i, y_j) \):
\[
\iint_R f(x, y) \, dA = \lim_{m,n \to \infty} \sum_{i=1}^{m} \sum_{j=1}^{n} f(x_i, y_j) \Delta A.
\]
Problem 15.2. Estimate the volume of the solid that lies above the square $R = [0, 2] \times [0, 2]$ and below the elliptic paraboloid $z = 16 - x^2 - 2y^2$. Divide $R$ into four equal squares and choose the sample point to be the upper right corner of each square $R_{ij}$. Approximate the Volume.

Solution.

Ans: 34

Problem 15.3. (Midpoint rule). Estimate the volume of the solid that lies above the square $R = [0, 2] \times [1, 2]$ and below the function $f(x, y) = 5x^2 - 4y$. Divide $R$ into four equal rectangles and choose the sample point to be the midpoint of each rectangle $R_{ij}$. Approximate the volume.

Solution.

Ans: 1
15.1.2. Iterated integrals

Okay; so, taking these Riemann Sums is a bit of a pain.

Recall: Earlier in Calculus, we equated these Riemann sums to the definition of an integral. We will attempt to do the same here; however, we will use two partial integrals.

Suppose that $f$ is a function of two variables that is integrable on the rectangle $R = [a, b] \times [c, d]$.

\begin{definition}
We define
\[ A(x) = \int_{c}^{d} f(x, y) \, dy \] (15.5)
\end{definition}

as the partial integral with respect to $y$. We evaluate this integral by treating $x$ as a constant, and integrate $f(x, y)$ with respect to $y$.

\begin{definition}
We define
\[ B(y) = \int_{a}^{b} f(x, y) \, dx \] (15.6)
\end{definition}

as the partial integral with respect to $x$. We evaluate this integral by treating $y$ as a constant, and integrate $f(x, y)$ with respect to $x$.

Note: The Fundamental Theorem of Calculus, Part 2, Equation (15.1) on p. 80, can be used to evaluate the partial integrals.
Chapter 15. Multiple Integrals

**Definition 15.6.** The *iterated integral* is defined as follows:

\[
\int_a^b \int_c^d f(x, y) \, dy \, dx = \int_a^b \left[ \int_c^d f(x, y) \, dy \right] \, dx = \int_a^b A(x) \, dx. \tag{15.7}
\]

In other words, we work this integral **from the inside out**.

**Problem 15.7.** Evaluate the integrals

(a) \( \int_0^3 \int_1^2 x^2 y \, dy \, dx \)
   and
(b) \( \int_1^2 \int_0^3 x^2 y \, dx \, dy \).

**Solution.** \( R = [0, 3] \times [1, 2] \).

**Theorem 15.8. (Fubini’s Theorem).** If \( f \) is continuous on the rectangle \( R = \{ (x, y) \in \mathbb{R}^2 \mid a \leq x \leq b, c \leq y \leq d \} \), then

\[
\int_R f(x, y) \, dA = \int_a^b \int_c^d f(x, y) \, dy \, dx = \int_c^d \int_a^b f(x, y) \, dx \, dy. \tag{15.8}
\]
15.9. (Revisit of Problem 15.3). Evaluate the double integral
\[ \iint_{R} (5x^2 - 4y) \, dA, \text{ where } R = \{(x, y) \in \mathbb{R}^2 \mid 0 \leq x \leq 2, 1 \leq y \leq 2\}. \]

Solution.

\[ \text{Ans: } \frac{4}{3} \]

15.10. Evaluate \[ \iint_{R} y \sin(xy) \, dA, \text{ where } R = [1, 2] \times [0, \pi]. \]

Solution. Let’s try the iterated integrals with \(x\)-first and \(y\)-first.

\[ \text{Ans: } 0 \]
Separable functions \( f(x, y) = g(x) \, h(y) \):

Let \( R = [a, b] \times [c, d] \). Then

\[
\iint_R f(x, y) \, dA = \int_c^d \int_a^b f(x, y) \, dx \, dy = \int_c^d \left( \int_a^b g(x) \, h(y) \, dx \right) \, dy \\
= \int_c^d h(y) \left( \int_a^b g(x) \, dx \right) \, dy \\
= \left( \int_a^b g(x) \, dx \right) \int_c^d h(y) \, dy,
\]

where the underlined (in maroon) are treated as constants.

\[
\iint_R g(x)h(y) \, dA = \int_a^b g(x) \, dx \cdot \int_c^d h(y) \, dy, \quad R = [a, b] \times [c, d]. \tag{15.9}
\]

**Problem 15.11.** Evaluate \( \iint_R e^{x+3y} \, dA \), where \( R = [0, 3] \times [0, 1] \).

**Solution.**

Ans: \((e^3 - 1)^2/3\)
Average Value

**Recall**: The average value of a function \( f \) of one variable defined on an interval \([a, b]\) is
\[
 f_{\text{ave}} = \frac{1}{b - a} \int_{a}^{b} f(x) \, dx.
\]

**Definition** 15.12. In a similar fashion, we define the average value of \( f \) of two variables defined on \( R \) to be
\[
 f_{\text{ave}} = \frac{1}{A(R)} \iint_{R} f(x, y) \, dA,
\]
where \( A(R) \) is the area of \( R \).

**Problem** 15.13. Find the average value of \( f(x, y) = x^2 + \sin(2y) \) over \( R = [0, 3] \times [0, \pi] \).

**Solution**. Use symmetry, for a simpler calculation!

Ans: 3
Exercises 15.1

1. Estimate the volume of the solid that lies below the surface $z = x^2 + y$ and above the rectangle

   $$ R = \{ (x, y) \mid 0 \leq x \leq 4, \ 0 \leq y \leq 6 \}.$$

   Use a Riemann sum with $m = 2$, $n = 3$, and the Midpoint Rule.

   Ans: $48 \cdot 4 = 192$

2. Let $V$ be the volume of the solid that lies under the surface $z = 30 - 4x - y^2$ and above the rectangle $R = \{ (x, y) \mid 2 \leq x \leq 6, \ 0 \leq y \leq 2 \}$. Use the lines $x = 4$ and $y = 1$ to divide $R$ into four subrectangles. Let $L$ and $U$ be the Riemann sums computed respectively using lower left corners and upper right corners. Without using the actual numbers $V$, $L$, and $U$, arrange them in increasing order and describe your reasoning.

3. Evaluate the double integral by first identifying it as the volume of a solid.

   (a) $\int \int_R (x + 1) \, dA, \quad R = \{ (x, y) \mid 0 \leq x \leq 2, \ 0 \leq y \leq 2 \}$

   (b) $\int \int_R (4 - 2y) \, dA, \quad R = [0, 1] \times [0, 1]$

4. Calculate the iterated integral.

   (a) $\int_1^3 \int_0^2 (6xy^2 - 12x^2) \, dx \, dy$

   (b) $\int_0^2 \int_1^3 (6xy^2 - 12x^2) \, dy \, dx$

   (c) $\int_0^1 \int_0^2 2\pi xy \sin(\pi xy^2) \, dy \, dx$

   (d) $\int_0^2 \int_0^1 2\pi xy \sin(\pi xy^2) \, dx \, dy$

   Ans: (a) 40, (c) 1

5. Calculate the double integral.

   (a) $\int \int_R y \sec^2(x) \, dA, \quad R = [0, \pi/4] \times [0, 4]$

   (b) $\int \int_R xe^{-xy} \, dA, \quad R = [0, 2] \times [0, 1]$

   Ans: (a) 8; (b) $1 - e^{-2}$

6. Find the volume of the solid in the first octant bounded by the cylinder $z = 9 - y^2$ and the plane $x = 2$.

   Ans: 36
15.2. Double Integrals over General Regions

Okay. So, now we know how to find the volume of the solid under a surface, when the projection of the solid down to the $xy$-plane is a rectangular region.

Let $D \subset \mathbb{R}^2$ be a bounded region of general shape as in Figure 15.4. For a bounded function $f$ defined over $D$, define

$$ F(x, y) = \begin{cases} f(x, y) & \text{if } (x, y) \in D \\ 0 & \text{if } (x, y) \notin D. \end{cases} $$

Then,

$$ \int\int_D f(x, y) \, dA = \int\int_R F(x, y) \, dA, \quad (15.11) $$

which implies the following.

- The integral $\int\int_D f(x, y) \, dA$ exists.
- The **iterated integral** can be applied to get the double integral over general regions.
Quesiton. What if the region $D$ is not rectangular but defined as the boundary between two functions?

![Diagram of D1 and D2]

Figure 15.5: General regions $D$: Type 1 (left) and Type 2 (right).

Let the region $D$ be given as

$$D_1 = \{(x, y) \in \mathbb{R}^2 \mid a \leq x \leq b, g_1(x) \leq y \leq g_2(x)\}$$

$$D_2 = \{(x, y) \in \mathbb{R}^2 \mid h_1(y) \leq x \leq h_2(y), c \leq y \leq d\},$$

Then

$$\iint_{D_1} f(x, y) \, dA = \int_{a}^{b} \int_{g_1(x)}^{g_2(x)} f(x, y) \, dy \, dx$$

$$\iint_{D_2} f(x, y) \, dA = \int_{c}^{d} \int_{h_1(y)}^{h_2(y)} f(x, y) \, dx \, dy \quad (15.12)$$

Strategy. 15.14. Double integral over general regions $D$:

1. Visualize to recognize the region.
2. Decide the order of integration.
3. If the calculation becomes complicated, try the other order.
Problem 15.15. Evaluate $\int\int_D (x + 2y) \, dA$, where $D$ is the region bounded by the parabolas $y = 2x^2$ and $y = 1 + x^2$.

Solution. First, visualize the region.

Ans: $\frac{32}{15}$
Problem 15.16. Find the volume of the solid that lies under the plane $z = 1 + 2y$ and above the region $D$ in the $xy$-plane bounded by the line $y = 2x$ and the parabola $y = x^2$.

Solution. Try for both orders.

Note: Here, the main concern is how to access the domain $D$; the iterated integration must access points in $D$, once-and-only-once.
15.2. Double Integrals over General Regions

**Problem 15.17.** Evaluate \( \iint_D 2xy \, dA \), where \( D \) is the region bounded by the line \( y = x - 2 \) and the parabola \( x = y^2 \).

**Solution.**

\[ \text{Ans: } \frac{45}{4} \]
Problem 15.18. Evaluate \( \int_0^1 \int_x^1 \sin(y^2) \, dy \, dx \).

Solution. Visualize the region and try to change the order of integration.

Ans: \( (1 - \cos 1)/2 \)

Proposition 15.19. (Properties of double integrals). Let \( f \) and \( g \) be continuous functions defined in \( D \) and \( c \in \mathbb{R} \). Then

1. \( \iint_D [f(x, y) + g(x, y)] \, dA = \iint_D f(x, y) \, dA + \iint_D g(x, y) \, dA \)
2. \( \iint_D c f(x, y) \, dA = c \iint_D f(x, y) \, dA \)
3. \( \iint_D f(x, y) \, dA \geq \iint_D g(x, y) \, dA, \quad \text{if} \quad f(x, y) \geq g(x, y), \quad \forall (x, y) \in D \)
4. \( \iint_D f(x, y) \, dA = \iint_{D_1} f(x, y) \, dA + \iint_{D_2} f(x, y) \, dA, \quad \text{when} \quad D = D_1 \cup D_2 \)
5. \( \iint_D 1 \, dA = A(D) \)
6. \( m \cdot A(D) \leq \iint_D f(x, y) \, dA \leq M \cdot A(D), \quad \text{if} \quad m \leq f(x, y) \leq M, \quad \forall (x, y) \in D \)

Problem 15.20. Show that \( \iint_D 1 \, dA = A(D) \), where \( A(D) \) denotes the area of the region \( D \).

Hint: Consider a solid cylinder whose base is \( D \) and whose height is 1.
Problem 15.21. Use Property 6 in Proposition 15.19 to estimate the integral
\[ I = \iint_D e^{\sin x \cos y} \, dA, \]
where \( D \) is the disk with center the origin and radius 2.

**Solution.**

\[ \text{Ans: } 4\pi/e \leq I \leq 4\pi e \]

Problem 15.22. Evaluate the integral
\[ \int_0^1 \int_x^1 2e^{x/y} \, dy \, dx \]
by reverting the order of integration.

**Solution.**

\[ \text{Ans: } e - 1 \]
Chapter 15. Multiple Integrals

Exercises 15.2

1. Evaluate the double integral, by setting up an iterated integral in the easier order.

(a) \( \int_D 2e^{-x^2} \, dA \), \( D = \{(x,y) \mid 0 \leq x \leq 2, \ 0 \leq y \leq x\} \)

(b) \( \int_D x \, dA \), \( D \) is bounded by \( y = x + 2 \) and \( y = x^2 \)

(c) \( \int_D y \sin \pi x \, dA \), \( D \) is bounded by \( x = 0, x = y^2, \) and \( y = 2 \)

Ans: (a) \( 1 - e^{-4} \); (c) \( 2/\pi \)

2. Evaluate the volume of the solid that lies under the surface \( z = x(y + 2) \) and above the triangle with vertices \( P(1,1), Q(3,1), \) and \( R(1,3) \).

Ans: 12

3. Sketch the region of the integral and change the order of integration.

(a) \( \int_0^1 \int_0^{y^2} f(x,y) \, dx \, dy \) 

(b) \( \int_0^1 \int_0^{\ln x} f(x,y) \, dy \, dx \)

Ans: (b) \( \int_0^1 \int_{e^y}^e f(x,y) \, dx \, dy \)

4. Evaluate the integral by reversing the order of integration:

(a) \( \int_0^1 \int_0^1 \sqrt{y} \cos(y^2) \, dy \, dx \)

(b) \( \int_0^4 \int_0^{\sqrt{4-y}} e^{12x-x^3} \, dx \, dy \)

Ans: (a) \( \sin 1 \)

5. In evaluating a double integral over a region \( D \), a sum of iterated integrals was obtained as follows:

\[ \iint_D f(x,y) \, dA = \int_0^1 \int_0^y f(x,y) \, dx \, dy + \int_1^2 \int_0^{2-y} f(x,y) \, dx \, dy. \]

(a) Sketch the region \( D \).

(b) Express the double integral as a single iterated integral with reversed order of integration.
15.3. Double Integrals in Polar Coordinates

We have spent most of our lives in the Cartesian/Rectangular coordinate system, which was invented by none other than René Descartes, who was because he thought. Sometimes, however, functions (and consequently integrals) become simpler when expressed in different coordinate systems. There are many different coordinate systems. Here, we will focus on one that was invented by Sir Isaac Newton – the **polar coordinate system**.

**Definition 15.23. (Polar point).** Points in polar coordinate system are defined by two parameters \((r, \theta)\), where \(r\) is the distance the point is from the origin and \(\theta\) is the angle between the polar axis (positive \(x\)-axis) and the line that connects the point to the origin.

Since a picture is worth a thousand words, here is a picture describing what was just described:

![Figure 15.6: Point in Rectangular/Cartesian and Polar coordinates.](image)

Naturally, there is a conversion from the Polar Coordinates to the Rectangular Coordinate system and vice versa. That conversion looks like:

\[
\begin{align*}
(x, y)_R & \leftarrow (r, \theta)_P & (r, \theta)_P & \leftarrow (x, y)_R \\
\begin{aligned}
x & = r \cos \theta \\
y & = r \sin \theta
\end{aligned} & \quad \begin{aligned}
r^2 & = x^2 + y^2 \\
\tan \theta & = \frac{y}{x}
\end{aligned}
\]

(15.13)
Frequently used trigonometric formulas

\[
\begin{align*}
\sin^2 x + \cos^2 x &= 1 \\
\sin 2x &= 2 \sin x \cos x \\
\sin^2 x &= \frac{1 - \cos 2x}{2} \\
1 + \tan^2 x &= \sec^2 x \\
\cos 2x &= \cos^2 x - \sin^2 x \\
\cos^2 x &= \frac{1 + \cos 2x}{2}
\end{align*}
\]  

(15.14)

Sectors: arc length and area

Arc length:  \( \ell = r\theta \)  

Area:  \( A = \frac{1}{2} r \ell = \frac{1}{2} r^2 \theta \)  

(15.15)

More study on trigonometry and sectors

Figure 15.7

Figure 15.8
Double integrals with polar coordinates

Polar rectangle:

\[ R = \{(r, \theta) \mid a \leq r \leq b, \ \alpha \leq \theta \leq \beta\} \]

Let \( \Delta r = (b - a)/m \) and \( \Delta \theta = (\beta - \alpha)/n \), for some \( m, n \), and

\[ r_i = a + i\Delta r, \quad i = 0, 1, \ldots, m, \]
\[ \theta_j = \alpha + j\Delta \theta, \quad j = 0, 1, \ldots, n. \]

The area of \( R_{ij} \) is

\[
\Delta A_{ij} = \frac{1}{2} r_i^2 \Delta \theta - \frac{1}{2} r_{i-1}^2 \Delta \theta = \frac{1}{2} (r_i + r_{i-1})(r_i - r_{i-1}) \Delta \theta = r_i^* \Delta r \Delta \theta, \quad (15.16)
\]

where \( r_i^* = (r_i + r_{i-1})/2 \).

**Theorem 15.24. (Polar version of iterated integral).** If \( f \) is continuous on the polar rectangle \( R \) given by \( 0 \leq a \leq r \leq b, \alpha \leq \theta \leq \beta \), where \( 0 \leq \beta - \alpha \leq 2\pi \), then

\[
\iint_R f(x, y) \, dA = \int_{\alpha}^{\beta} \int_{a}^{b} f(r \cos(\theta), r \sin(\theta)) \, r \, dr \, d\theta. \quad (15.17)
\]

**Note:**

1. Do not forget the “\( r \)” before the \( dr \, d\theta \)!
2. It follows from Figure 15.9 that \( \Delta A_{ij} \approx \Delta r \cdot r_j \Delta \theta = r_j \Delta r \Delta \theta \).
Problem 15.25. Evaluate \( \int \int_R (3x + 4y^2) \, dA \), where \( R \) is the region in the upper half-plane bounded by the circles \( x^2 + y^2 = 1 \) and \( x^2 + y^2 = 4 \).

Solution.

Ans: \( \frac{15\pi}{2} \)

Problem 15.26. Find the volume of the solid bounded by the plane \( z = 0 \) and the paraboloid \( z = 1 - x^2 - y^2 \).

Solution. Volume \( V = \int \int_D (1 - x^2 - y^2) \, dA \), where \( D = \{(x, y) \mid x^2 + y^2 \leq 1\} \).

Ans: \( \frac{\pi}{2} \)
15.3. Double Integrals in Polar Coordinates

**Theorem** 15.27. (Polar version of **(15.12), p. 90**). If \( f \) is continuous on a polar region of the form \( D = \{(r, \theta) \mid \alpha \leq \theta \leq \beta, h_1(\theta) \leq r \leq h_2(\theta)\} \), then

\[
\iint_D f(x, y) \, dA = \int_{\alpha}^{\beta} \int_{h_1(\theta)}^{h_2(\theta)} f(r \cos(\theta), r \sin(\theta)) \, r \, dr \, d\theta.
\] (15.18)

---

**Problem** 15.28. Use a double integral to find the area enclosed by one loop of the four-leaved rose \( r = \cos(2\theta) \).

**Solution.** \( A(D) = \iint_D dA = \int_{-\pi/4}^{\pi/4} \int_0^{\cos 2\theta} r \, dr \, d\theta \).

*Ans: \( \pi/8 \)*
Problem 15.29. Find the volume of the solid that lies under the paraboloid \( z = x^2 + y^2 \), above the \( xy \)-plane, and inside the cylinder \( x^2 + y^2 = 2x \).

\[ \text{Hint.} \]
- First, find what the “polar region” looks like.
- That is to say, translate \( x^2 + y^2 = 2x \) into polar coordinates and see what that region looks like. (Also, you may refer to \((x - 1)^2 + y^2 = 1\).)
- Then, look at \( z = x^2 + y^2 \) as a polar function and use it as your integrand.
- Evaluate.
- Don’t forget the \( r \) in “\( r \, dr \, d\theta \)!"

Solution.

\[ \text{Ans: } \frac{3}{2} \pi \]
15.3. Double Integrals in Polar Coordinates

Problem 15.30. (A variant of Problem 15.29). Evaluate the double integral \( \int_0^2 \int_0^{\sqrt{2x-x^2}} \sqrt{x^2+y^2} \, dy \, dx \), by recognizing the region and converting it to polar coordinates.

Solution. Hint: \( D = \{ \theta = 0..\pi/2, \quad r = 0..2\cos \theta \} \)

Ans: 16/9
**Volume of $n$-Ball**: The **unit interval** $[-1, 1]$ can be rewritten as

$$B_1 \overset{\text{def}}{=} \{ x \mid x^2 \leq 1 \} \subset \mathbb{R}. \quad (15.19)$$

Similarly, the **unit circle** and the **unit sphere** (of radius 1) read

$$B_2 \overset{\text{def}}{=} \{ (x, y) \mid x^2 + y^2 \leq 1 \} \subset \mathbb{R}^2 \text{ and } B_3 \overset{\text{def}}{=} \{ (x, y, z) \mid x^2 + y^2 + z^2 \leq 1 \} \subset \mathbb{R}^3. \quad (15.20)$$

In general, an **$n$-dimensional ball** (or **$n$-Ball**) of radius $r$ is defined as

$$B_{n,r} = \{ (x_1, x_2, \ldots, x_n) \mid x_1^2 + x_2^2 + \cdots + x_n^2 \leq r^2 \} \subset \mathbb{R}^n. \quad (15.21)$$

It is possible to define **volume of $n$-Ball of radius** $r$, $V_{n,r}$; in $\mathbb{R}$ it is **length**, in $\mathbb{R}^2$ it is **area**, in $\mathbb{R}^3$ it is **ordinary volume**, and in $\mathbb{R}^n$, $n \geq 4$, it is called a **hypervolume**. For example,

$$V_{1,r} = V(B_{1,r}) = 2r, \quad V_{2,r} = V(B_{2,r}) = \pi r^2, \quad V_{3,r} = V(B_{3,r}) = \frac{4}{3}\pi r^3. \quad (15.22)$$

Note that $V_{n,r} = V_{n,1} \cdot r^n$, $n \geq 1$.

**Challenge 15.31.** Let $B_n = B_{n,1}$ and $V_n = V(B_{n,1})$. Use **polar coordinates** to find $V_n$, the volume of the unit $n$-Ball $B_n$, $n \geq 4$.

**Solution.** See Figure 15.11. Then,

$$V_n = \int_0^{2\pi} \int_0^1 \left( V_{n-2} \left( \sqrt{1 - r^2} \right)^{n-2} \right) r \, dr \, d\theta$$

Figure 15.11: The unit $n$-Ball, $B_{n,1}$.

Ans: $V_n = \frac{2\pi}{n} V_{n-2}$. (You will solve this problem differently in Project 2, p. 143.)
15.3. Double Integrals in Polar Coordinates

Exercises 15.3

1. Use polar coordinates to evaluate the double integral, or the volume of the solid.

(a) \[ \iint_D e^{x^2+y^2} \, dA, \]
where \( D \) is the region bounded by the semi-circle \( x = \sqrt{1-y^2} \) and the \( y \)-axis.

(b) The solid that lies above the cone \( z = \sqrt{x^2+y^2} \) and below the sphere \( x^2+y^2+z^2 = 8 \).

Ans: (a) \( (e-1)\pi/2 \); (b) \( \frac{32(\sqrt{2}-1)\pi}{3} \)

2. A swimming pool is circular with 60–ft diameter. The depth is constant along east-west lines and increases linearly from 2 ft at the east end to 8 ft at the west end. Find the volume of water in the pool, using a double integral in polar coordinates. **Hint:** \( V = \iint_D (5 + \frac{x}{10}) \, dA \), where \( D \) is the circle of radius 30 and centered at the origin.

3. Use polar coordinates to evaluate

\[ \iint_{D_a} e^{-x^2-y^2} \, dA, \quad (15.23) \]

where \( D_a \) is the disk of radius \( a \) centered at the origin.

Ans: \( \pi(1-e^{-a^2}) \)

4. We may define the improper integral (over the entire plane \( \mathbb{R}^2 \))

\[ I := \iint_{\mathbb{R}^2} e^{-x^2-y^2} \, dA = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{-x^2-y^2} \, dx \, dy = \lim_{a \to \infty} \iint_{D_a} e^{-x^2-y^2} \, dA. \quad (15.24) \]

(a) Use the result from the previous problem (Problem 3, Exercises 15.3) to conclude

\[ \int_{-\infty}^{\infty} e^{-x^2} \, dx = \sqrt{\pi}. \quad (15.25) \]

(b) Let \( \sigma > 0 \). Use the change of variable \( x = \sigma t \) to evaluate

\[ \int_{-\infty}^{\infty} e^{-x^2/\sigma^2} \, dx. \quad (15.26) \]
15.4. Applications of Double Integrals

Objectives. Find the mass and center of mass of a planar lamina and moments of inertia, using double integrals. Then, apply them for probability and mean values.

Density and Mass

Figure 15.12

Let a lamina occupy a region $D$ in $xy$-plane. Then its density is defined as

$$\rho(x, y) = \lim_{\Delta A \to 0} \frac{\Delta m}{\Delta A},$$

(15.27)

where $\Delta m$ and $\Delta A$ the mass and the area of a small rectangle that contains $(x, y)$. Thus, the mass of the lamina over $D$ approximates

$$m = \sum_{i=1}^{m} \sum_{j=1}^{n} \rho(x_{ij}^*, y_{ij}^*) \Delta A.$$

By increasing the number of subrectangles, we obtain the total mass of the lamina

$$m = \lim_{m,n \to \infty} \sum_{i=1}^{m} \sum_{j=1}^{n} \rho(x_{ij}^*, y_{ij}^*) \Delta A = \int\int_{D} \rho(x, y) \, dA.$$  

(15.28)
Problem 15.32. Find the mass of the triangular lamina with vertices (0, 0), (2, 2), and (0, 4), given that the density at (x, y) is \( \rho(x, y) = 2x + y \).

Solution.

Ans: 40/3

Definition 15.33. The moment of a particle about an axis is the product of its mass and its directed distance from the axis. Say, \( M_x = m \cdot y \), \( M_y = m \cdot x \).

Theorem 15.34. The moments (first moments) of the entire lamina about x- and y-axes:

\[
M_x = \iint_D y \rho(x, y) \, dA, \quad M_y = \iint_D x \rho(x, y) \, dA. \tag{15.29}
\]

When we define the center of mass \((\bar{x}, \bar{y})\) so that \( m \bar{x} = M_y \) and \( m \bar{y} = M_x \), then

\[
\bar{x} = \frac{M_y}{m} = \frac{1}{m} \iint_D x \rho(x, y) \, dA, \quad \bar{y} = \frac{M_x}{m} = \frac{1}{m} \iint_D y \rho(x, y) \, dA. \tag{15.30}
\]
108

Chapter 15. Multiple Integrals

Problem 15.35. (Revisit of Problem 15.32). Find the center of mass for the triangular lamina with vertices $(0, 0)$, $(2, 2)$, and $(0, 4)$, given that the density at $(x, y)$ is $\rho(x, y) = 2x + y$.

Solution. We know $m = 40/3$.

Ans: $(\bar{x}, \bar{y}) = (4/5, 11/5)$
15.4. Applications of Double Integrals

## Probability

**Recall:** The **probability density function** $f$ of a continuous random variable $X$ is a function such that

$$f(x) \geq 0, \ \forall x \in \mathbb{R}, \ \text{and} \ \int_{-\infty}^{\infty} f(x) \, dx = 1.$$  

The **probability** that $X$ lies between $a$ and $b$ is

$$P(a \leq X \leq b) = \int_{a}^{b} f(x) \, dx.$$  

**Definition** 15.36. The **joint density function** of a pair of random variables $X$ and $Y$ is a function $f$ such that

$$f(x, y) \geq 0, \ \forall (x, y) \in \mathbb{R}^2, \ \text{and} \ \iint_{\mathbb{R}^2} f(x, y) \, dA = 1.$$  

The **probability** that $(X, Y)$ lies in a region $D$ is

$$P((X, Y) \in D) = \iint_{D} f(x, y) \, dA.$$  

**Problem** 15.37. If the joint density function for $X$ and $Y$ is given by

$$f(x, y) = \begin{cases} k(3x - x^2)(2y - y^2), & \text{if } (x, y) \in [0, 3] \times [0, 2], \\ 0, & \text{otherwise.} \end{cases}$$

find the constant $k$. Then, find $P(X \leq 2, Y \geq 1)$.

**Solution.**

Ans: $k = 1/6$; $P(X \leq 2, Y \geq 1) = 10/27$
Expected Values of $X$ and $Y$

Recall: If $f$ is a probability density function of a random variable $X$, then its mean is

$$
\mu = \int_{-\infty}^{\infty} x f(x) \, dx.
$$

**Definition 15.38.** Let $f(x, y)$ be a joint density function of random variables $X$ and $Y$. We define the $X$-mean and $Y$-mean, also called the expected values, of $X$ and $Y$, to be

$$
\mu_1 = \iint_{\mathbb{R}^2} x f(x, y) \, dA, \quad \mu_2 = \iint_{\mathbb{R}^2} y f(x, y) \, dA.
$$

**Problem 15.39.** Let $f(x, y) = \begin{cases} 
\frac{4-2x^2-2y^2}{3\pi}, & \text{if } x^2 + y^2 \leq 1, \\
0, & \text{otherwise.}
\end{cases}$

(a) Verify $f$ is a joint density function.

(b) Find $P(X \leq 0, Y \geq 0)$.

(c) Find the expected values of $X$ and $Y$.

**Solution.**

Ans: (b) $1/4$; (c) $\mu_1 = \mu_2 = 0$
15.4. Applications of Double Integrals

Exercises 15.4

1. Find the mass and center of mass of the lamina that occupies the region $D$ and has the given density function $\rho$.

   (a) $D$ is the triangle with vertices $(0,0), (4,0), \text{ and } (2,2)$; $\rho(x,y) = y$

   (b) $D$ is the part of the disk $x^2 + y^2 \leq 4$ in the first quadrant; $\rho$ is proportional to its distance from the origin \textbf{Hint}: Set $\rho(x,y) = k \sqrt{x^2 + y^2}$ and use polar coordinates for the integrals.

   Ans: (a) $m = \frac{8}{3}, (\bar{x}, \bar{y}) = (2, 1)$; (b) $m = \frac{4k\pi}{3}, (\bar{x}, \bar{y}) = (\frac{3}{\pi}, \frac{3}{\pi})$

2. \textbf{CAS} Use a computer algebra system (Maple, Mathematica, etc.) to find the mass and center of mass of the lamina that occupies the region $D$ and has the given density function.

   (a) $D = \{(x, y) \mid 0 \leq x \leq ye^{-y}, \ 0 \leq y \leq 1\}; \ \rho(x, y) = (1 + x^2) \cos y$

   Ans: $m \approx 0.2167$, $(\bar{x}, \bar{y}) \approx (0.1507, 0.5697)$

   (b) $D$ is the region closed by the right loop of the four-leaved rose $r = \cos 2\theta$ (as shown in Figure 15.10 on page 101); $\rho(x,y) = \sqrt{x^2 + y^2}$

3. Suppose $X$ and $Y$ are random variable with joint density function

   \[ f(x,y) = \begin{cases} k(x+1)y, & \text{if } 0 \leq x \leq 2, \ 0 \leq y \leq 1, \\ 0, & \text{otherwise.} \end{cases} \]

   (a) Find the value of the constant $k$.

   (b) Find $P(x \leq 1, y \leq 1)$

   (c) Find $P(x - y \geq 1)$

   (d) Find $X$-mean and $Y$-mean.

   \textit{Ans}: (a) $k = 1/2$; (c) $11/48$
Chapter 15. Multiple Integrals

15.5. Surface Area

We may define the surface area of $S$ to be

$$A(S) = \lim_{m,n \to \infty} \sum_{i=1}^{m} \sum_{j=1}^{n} \Delta T_{ij}, \quad (15.31)$$

where

$$\Delta T_{ij} = |a \times b|.$$

Here,

$$a = \langle \Delta x, 0, f_x(x_{ij})\Delta x \rangle,$$

$$b = \langle 0, \Delta y, f_y(x_{ij})\Delta y \rangle.$$

Since

$$a \times b = \det \begin{bmatrix} i & j & k \\ \Delta x & 0 & f_x\Delta x \\ 0 & \Delta y & f_y\Delta y \end{bmatrix} = (-f_x, -f_y, 1) \Delta x \Delta y, \quad (15.32)$$

we have ($\Delta A = \Delta x \Delta y$)

$$\Delta T_{ij} = |a \times b| = \sqrt{f_x^2 + f_y^2 + 1} \Delta A. \quad (15.33)$$

**Definition 15.40.** The surface area of $S$ with $z = f(x,y)$, $(x,y) \in D$, where $\nabla f$ is continuous, is

$$A(S) = \iint_{D} \sqrt{f_x(x,y)^2 + f_y(x,y)^2 + 1} \, dA. \quad (15.34)$$

**Recall:** For $y = f(x), x \in [a,b]$, the arc length is obtained as

$$L = \int_{a}^{b} \sqrt{1 + [f'(x)]^2} \, dx. \quad (15.35)$$
Note: The surface area will be considered again when we learn Parametric Surfaces and Their Areas; see §16.6.3, p. 207.
Problem 15.41. Find the area of the part of the paraboloid \( z = x^2 + y^2 \) that lies under the plane \( z = 9 \).

Solution. (See Problem 16.88 on p. 210.)

\[
\text{Ans: } \frac{\pi}{6} (37\sqrt{37} - 1)
\]

Problem 15.42. Find the area of the part of the surface \( z = xy \) that lies within the cylinder \( x^2 + y^2 = 1 \).

Solution.

\[
\text{Ans: } \frac{2\pi}{3} (2\sqrt{2} - 1)
\]
15.5. Surface Area

Exercises 15.5

1. Find the area of the surface.
   (a) The part of the plane \(2x + y + 5z = 10\) that lies in the first octant
   (b) The part of the sphere \(x^2 + y^2 + z^2 = 2\) that lies above the plane \(z = 1\)
   \[ Ans: (b) 2\sqrt{2\pi (\sqrt{2} - 1)} \]

2. Find the area of the finite part of the paraboloid \(z = x^2 + y^2\) cut off by the plane \(z = 9\).

3. \textbf{CAS} Use your calculator (or, a computer algebra system) to estimate the area of the surface correct to four decimal places.

   The part of the surface \(z = \sin(x^2 + y^2)\) that lines in the cylinder \(x^2 + y^2 = 4\).

   \textbf{Hint:} If you use Maple for numeric integration for \(\int_a^b f(x) \, dx\), the command looks:
   \[ \text{int}(f(x), x=a..b, \text{numeric}) \]
   \[ Ans: 27.7291 \]
15.6. Triple Integrals

Let’s begin with a function of three variables defined on a rectangular box:

\[ w = f(x, y, z), \quad (x, y, z) \in B, \]

Let \( B \) be the volume defined by

\[ B = [a, b] \times [c, d] \times [r, s]. \]

In defining a triple integral, the first step is to divide \( B \) into sub-boxes.

For some positive integers \( \ell, m, n > 0 \),

\[ \Delta x = \frac{b - a}{\ell}, \quad \Delta y = \frac{d - c}{m}, \quad \Delta z = \frac{s - r}{n}. \]

Let \( B_{ijk} \) be the \((ijk)\)-th sub-box:

\[ B_{ijk} = [x_{i-1}, x_i] \times [y_{j-1}, y_j] \times [z_{k-1}, z_k]; \]

each sub-box has volume \( \Delta V = \Delta x \Delta y \Delta z \).

**Definition 15.43.** The **triple integral** of \( f \) over the box \( B \) is

\[
\iiint_B f(x, y, z) \, dV = \lim_{\ell, m, n \to \infty} \sum_{i=1}^{\ell} \sum_{j=1}^{m} \sum_{k=1}^{n} f(x_{ijk}^*) \Delta V.
\]

where \( x_{ijk}^* = (x_i^*, y_j^*, z_k^*) \in B_{ijk} \).

**Theorem 15.44.** (Fubini’s Theorem for Triple Integrals). If \( f \) is continuous on \( B = [a, b] \times [c, d] \times [r, s] \), then

\[
\iiint_B f(x, y, z) \, dV = \int_a^b \int_c^d \int_r^s f(x, y, z) \, dz \, dy \, dx; \quad (15.36)
\]

the integration order can be changed for five other choices.
Problem 15.45. Evaluate the triple integral \( \iiint_B xyz^2 \, dV \), where \( B = [0, 1] \times [-1, 2] \times [0, 3] \).

Solution.

\[
\text{Ans: } \frac{27}{4}
\]

Triple integral over a general bounded region \( E \):

Strategy 15.46. To evaluate a given triple integral over \( E \):

1. Recognize (visualize in your brain) the domain \( E \).

2. Separate the domain, e.g., \( E = D \times [u_1(x, y), u_2(x, y)] \), \( D \subset \mathbb{R}^2 \).

Then, \( \iiint_E f(x, y, z) \, dV = \iint_D \int_{u_1(x, y)}^{u_2(x, y)} f(x, y, z) \, dz \, dA \).

3. The principle is: you must find a scheme to cover the whole domain \( E \) (without missing, without duplicating).

Let’s go on a journey!!
Problem 15.47. Evaluate \( \iiint_E z \, dV \), where \( E \) is the solid tetrahedron bounded by the four planes \( x = 0, y = 0, z = 0, \) and \( x + y + z = 1 \).

Solution. \( E = D \times [0, 1 - x - y] \), where \( D \) is the unit right triangle in the \( xy \)-plane.

\textit{Ans:} 1/24
15.6. Tri{ple Integrals

15.48. Evaluate \( \iiint_E \sqrt{x^2 + y^2} \, dV \), where \( E \) is the region bounded by the paraboloid \( z = x^2 + y^2 \) and the plane \( z = 4 \).

Solution. \( E = D \times [x^2 + y^2, 4] \), where \( D \) is the disk of center the origin and radius 2.

\[ \text{Ans:} \quad \frac{128\pi}{15} \]
Applications of Triple Integrals

Claim 15.49. Let \( f(x,y,z) = 1 \) for all points in \( E \). Then triple integral of \( f \) over \( E \) represents the volume of \( E \):

\[
V(E) = \iiint_E 1 \, dV. \tag{15.37}
\]

Problem 15.50. Use the triple integral to find the volume of the tetrahedron \( T \) bounded by the four planes \( x = 0, \ y = x, \ z = 0, \) and \( x + y + z = 2 \).

Solution.

Ans: 2/3
Changing the order of integration

Problem 15.51. Write a couple of other iterated integrals that are equivalent to
\[
\int_0^1 \int_y^1 \int_0^y f(x, y, z) \, dx \, dz \, dy
\]

*Hint:* Change the order for adjacent two variables in the integral, keeping the other the same. For example, start with \( x \leftrightarrow z \) or \( z \leftrightarrow y \).

Solution.
Exercises 15.6

1. Evaluate the iterated integral.

(a) \[ \int_0^2 \int_0^1 \int_0^{\ln x} x e^{-y} \, dy \, dx \, dz \]

(b) \[ \int_0^\pi \int_0^2 \int_0^{\sqrt{4-z^2}} z \cos x \, dy \, dz \, dx \]

Ans: (a) \(-1\); (b) 0

2. Evaluate the triple integral.

(a) \[ \iiint_E e^{z/x} \, dV, \quad E = \{(x, y, z) \mid 0 \leq x \leq 1, \, x \leq y \leq 1, \, 0 \leq z \leq x\} \]

(b) \[ \iiint_E y \, dV, \quad E \text{ is determined by the paraboloid } y = x^2 + z^2 \text{ and the plane } y = 4 \]

Ans: (a) \((e - 1)/6\); (b) \(64\pi/3\)

3. Fill the lower and upper bounds appropriately for the triple integral.

\[ \int_0^1 \int_z^1 \int_y^1 f(x, y, z) \, dx \, dy \, dz = \int_{\text{1}}^{\text{2}} \int_{\text{3}}^{\text{4}} \int_{\text{5}}^{\text{6}} f(x, y, z) \, dx \, dz \, dy \]

\[ = \int_{\text{7}}^{\text{8}} \int_{\text{9}}^{\text{10}} \int_{\text{11}}^{\text{12}} f(x, y, z) \, dz \, dx \, dy \]

Ans: (5): \(y\); (6): 1; (7): 0; (8): 1; (11): 0; (12): \(y\)
15.7. Triple Integrals in Cylindrical Coordinates

Recall: (Equation (15.13)). The conversion between the Polar Coordinates and the Rectangular Coordinate system reads

\[
\begin{array}{c|c}
(x, y)_R & (r, \theta)_P \\
\hline
x = r \cos \theta & r^2 = x^2 + y^2 \\
y = r \sin \theta & \tan \theta = \frac{y}{x} \\
\end{array}
\]

Definition 15.52. In the cylindrical coordinate system, a point \( P \) in the 3D space is represented as an ordered triple \((r, \theta, z)\), where \( r \) and \( \theta \) are polar coordinates of the projection of \( P \) onto the \( xy \)-plane and \( z \) is the directed distance from the \( xy \)-plane to \( P \).

Definition 15.53. The conversion between the Cylindrical Coordinates and the Rectangular Coordinate system gives

\[
\begin{array}{c|c}
(x, y, z)_R & (r, \theta, z)_C \\
\hline
x = r \cos \theta & r^2 = x^2 + y^2 \\
y = r \sin \theta & \tan \theta = \frac{y}{x} \\
z = z & z = z \\
\end{array}
\]

Note: The triple integral with a Cylindrical Domain \( E \) can be carried out by first separating the domain like

\[
E = D \times [u_1(x, y), u_2(x, y)], \quad \text{where } D \text{ is a polar region.}
\]
Problem 15.54. (a) Plot the point with the cylindrical coordinates \((2, \frac{2\pi}{3}, 1)_C\) and find its rectangular coordinates.
(b) Find cylindrical coordinates of the point with rectangular coordinates \((3, -3, 7)_R\).

Solution.

Ans: (a) \((-1, \sqrt{3}, 1)_R\); (b) \((3\sqrt{2}, -\pi/4, 7)_C\).

Problem 15.55. Evaluate \(\int_{-2}^{2} \int_{-\sqrt{4-x^2}}^{\sqrt{4-x^2}} \int_{\sqrt{x^2+y^2}}^{2} (x^2 + y^2) \, dz \, dy \, dx\).

Hint. Change the triple integral into cylindrical coordinates.

Solution.

Ans: \(16\pi/5\)
Problem 15.56. Find the volume of the solid that lies within both the cylinder $x^2 + y^2 = 1$ and the sphere $x^2 + y^2 + z^2 = 4$.  

Solution.  

Ans: $\frac{4\pi}{3}(8 - 3\sqrt{3})$
Exercises 15.7

1. Identify the surface whose equation is given.

   (a) \( r^2 + 4z^2 = 4 \)

   (b) \( r = 2 \cos \theta \)

   **Hint:** (b) It can be rewritten as \( r^2 = 2r \cos \theta \), which in turn reads \( x^2 + y^2 = 2x \).

2. Evaluate \( \int_0^2 \int_{\sqrt{4-x^2}}^{\sqrt{x^2+y^2}} \int_{\sqrt{x^2+y^2}}^{2} x \, dz \, dy \, dx \), by changing the triple integral into cylindrical coordinates.

   \[ \text{Ans:} \frac{8}{3} \]

3. Use cylindrical coordinates to find the **volume** of the solid \( E \) that is enclosed by the cone \( z = \sqrt{x^2 + y^2} \) and the sphere \( x^2 + y^2 + z^2 = 2 \).

   \[ \text{Ans:} \frac{4}{3} \pi (\sqrt{2} - 1) \]

4. Use cylindrical coordinates to evaluate \( \iiint_E y \, dV \), where \( E \) is the solid that lies between the cylinders \( x^2 + y^2 = 1 \) and \( x^2 + y^2 = 9 \), above the \( xy \)-plane, and below the plane \( z = y + 3 \).

   \[ \text{Ans:} \ 20\pi \]
15.8. Triple Integrals in Spherical Coordinates

Definition 15.57. The spherical coordinates \((\rho, \theta, \phi)\) of a point \(P\) is shown in Figure 15.15, where \(\rho = |\overrightarrow{OP}| = \sqrt{x^2 + y^2 + z^2}\), \(\theta\) is the angle from the \(x\)-axis to the line segment \(\overline{OP}'\), and \(\phi\) is the angle between the positive \(z\)-axis and the line segment \(\overline{OP}\).

- \(\rho \geq 0\), \(0 \leq \theta \leq 2\pi\), \(0 \leq \phi \leq \pi\).

For a convenient conversion formula, consider first
\[ z = \rho \cos \phi, \quad r = \rho \sin \phi. \]

Definition 15.58. The conversion between the Spherical Coordinates and the Rectangular Coordinate system gives

\[
\begin{align*}
(x, y, z)_R & \leftarrow (\rho, \theta, \phi)_S & (\rho, \theta, \phi)_S & \leftarrow (x, y, z)_R \\
x = r \cos \theta = \rho \sin \phi \cos \theta & \quad \rho^2 = x^2 + y^2 + z^2 \\
y = r \sin \theta = \rho \sin \phi \sin \theta & \quad \cos \phi = \frac{z}{\rho} \\
z = \rho \cos \phi & \quad \cos \theta = \frac{x}{\rho \sin \phi}
\end{align*}
\]
Problem 15.59. (a) Plot the point with the spherical coordinates \((2, \pi/4, \pi/3)\) and find its rectangular coordinates.

(b) Find spherical coordinates of the point with rectangular coordinates \((0, 2\sqrt{3}, -2)\).

Solution.

\[ \text{Ans: (a)} \left( \frac{\sqrt{3}}{2}, \frac{\sqrt{3}}{2}, 1 \right)_R; \text{ (b)} \left( 4, \frac{\pi}{2}, 2\frac{\pi}{3} \right)_S \]

Figure 15.16: A small spherical wedge \(E_{ijk}\), of volume \(\Delta V_{ijk} \approx r \rho \Delta \rho \Delta \theta \Delta \phi\).

Triple Integral with Spherical Coordinates: In the spherical coordinate system, the counterpart of a rectangular box is a spherical wedge

\[ E = \{ (\rho, \theta, \phi) \in \mathbb{R}^3 \mid a \leq \rho \leq b, \alpha \leq \theta \leq \beta, c \leq \phi \leq d \}, \]

where \(a \geq 0\), \(\beta - \alpha \leq 2\pi\), and \(d - c \leq \pi\). We divide smaller spherical wedges \(\{E_{ijk}\}\) by means of equally spaced \(\rho_i, \theta_j, \phi_k\). Figure 15.16 shows that \(E_{ijk}\) is approximately a rectangular box, of which the volume approximates

\[ \Delta V_{ijk} \approx r \rho \Delta \rho \Delta \theta \Delta \phi = \rho^2 \sin \phi \Delta \rho \Delta \theta \Delta \phi. \quad (15.41) \]
Theorem 15.60. (Triple Integral on Spherical Wedges).

\[
\iiint_E f(x, y, z) \, dV = \int_c^d \int_a^b \int_a^b f(\rho \sin \phi \cos \theta, \rho \sin \phi \sin \theta, \rho \cos \phi) \times \rho^2 \sin \phi \, d\rho \, d\theta \, d\phi,
\]

where \( E \) is a spherical wedge given by

\[
E = \{(\rho, \theta, \phi) \in \mathbb{R}^3 \mid a \leq \rho \leq b, \alpha \leq \theta \leq \beta, c \leq \phi \leq d\}.
\]

Note: The scaling factor \( \rho^2 \sin \phi = r \rho \).

Problem 15.61. Evaluate \( \iiint_B e^{(x^2+y^2+z^2)^{3/2}} \, dV \), where \( B \) is the unit ball \( B = \{(x, y, z) \mid x^2 + y^2 + z^2 \leq 1\} \).

Solution.

Ans: \( \frac{4}{3} \pi (e - 1) \)
**Theorem 15.62. (Spherical Fubini’s Theorem).** We can extend Theorem 15.60 to regions defined by

\[ E = \{ (\rho, \theta, \phi) \in \mathbb{R}^3 \mid g_1(\theta, \phi) \leq \rho \leq g_2(\theta, \phi), \alpha \leq \theta \leq \beta, c \leq \phi \leq d \}, \]

in such a way:

\[ \iiint_E f(x, y, z) \, dV = \int_c^d \int_{g_1(\theta, \phi)}^{g_2(\theta, \phi)} \int_{\alpha}^{\beta} f(\rho \sin \phi \cos \theta, \rho \sin \phi \sin \theta, \rho \cos \phi) \rho^2 \sin \phi \, d\rho \, d\theta \, d\phi. \]  

(15.43)

**Problem 15.63.** Use spherical coordinates to find the volume of the solid that lies above the cone \( z = \sqrt{x^2 + y^2} \) and below the sphere \( x^2 + y^2 + z^2 = z \).

**Solution.** Sphere: \( \rho^2 = \rho \cos \phi \Rightarrow \rho = \cos \phi \).

Cone: \( \rho \cos \phi = r = \rho \sin \phi \Rightarrow \cos \phi = \sin \phi \). So, \( \phi = \pi/4 \). Therefore,

\[ V = \int_0^{\pi/4} \int_0^{2\pi} \int_0^{\cos \phi} \rho^2 \sin \phi \, d\rho \, d\theta \, d\phi \]

**Ans:** \( \pi/8 \)
15.8. Triple Integrals in Spherical Coordinates

Exercises 15.8

1. Write the equation in spherical coordinates.

   (a) \( x^2 + y^2 + z^2 = 1 \)
   (c) \( 2x^2 + 2y^2 + z^2 = 4 \)
   (b) \( z = x^2 + y^2 \)
   (d) \( z = x^2 - y^2 \)

   **Hint:** (c) \( 2x^2 + 2y^2 + z^2 = (x^2 + y^2 + z^2) + (x^2 + y^2) \)

2. Sketch the solid whose volume is given by the integral; evaluate the integral.

   (a) \( \int_0^{\pi/4} \int_0^{\pi} \int_0^2 \rho^2 \sin \phi \, d\rho \, d\theta \, d\phi \)
   (b) \( \int_0^{\pi/2} \int_0^{2\pi} \int_0^{\cos \phi} \rho^2 \sin \phi \, d\rho \, d\theta \, d\phi \)

   **Ans:** (b) \( \pi/6 \)

3. Use spherical coordinates to find the volume of the solid that lies above the cone \( z = \sqrt{x^2 + y^2} \) and below the sphere \( x^2 + y^2 + z^2 = 1 \).

4. Use spherical coordinates to evaluate \( \iiint_B x \, e^{(x^2+y^2+z^2)} \, dV \), where \( B \) is the portion of the unit ball \( x^2 + y^2 + z^2 \leq 1 \) that lies in the first octant.

   **Ans:** \( (e - 1)\pi/16 \)
15.9. Change of Variables in Multiple Integrals

We have done changes of variables several times in the past. Dating as far back when we learned integration with the “u-substitution”, we started using changes of variables (we made $u = g(x)$.) Indeed,

$$\int_{c}^{d} f(g(x))g'(x) \, dx = \int_{g(c)}^{g(d)} f(u) \, du. \quad (15.44)$$

Another way of expressing (15.44) is

$$\int_{a}^{b} f(x) \, dx = \int_{c}^{d} f(x(u)) \frac{dx}{du} \, du, \quad (15.45)$$

where $x = x(u) : c \mapsto a, \ d \mapsto b$.

---

**Example 15.64.** Evaluate $\int_{0}^{2} xe^{x^{2}} \, dx$.

**Solution.** $u = x^{2} \Rightarrow du = 2x \, dx \Rightarrow x \, dx = \frac{du}{2}$; $u(0) = 0, u(2) = 4$.

Therefore

$$\int_{0}^{2} xe^{x^{2}} \, dx = \int_{0}^{4} e^{u} \frac{du}{2} = \frac{1}{2} \int_{0}^{4} e^{u} \, du = \frac{1}{2} e^{u}|_{0}^{4} = \frac{1}{2} (e^{4} - 1).$$

Another way: $[x = x(u) = \sqrt{u}] \Rightarrow \frac{dx}{du} = \frac{1}{2\sqrt{u}}$. Therefore

$$\int_{0}^{2} xe^{x^{2}} \, dx = \int_{0}^{4} \sqrt{u} e^{u} \frac{1}{2\sqrt{u}} \, du = \frac{1}{2} \int_{0}^{4} e^{u} \, du = \frac{1}{2} (e^{4} - 1).$$

---

**Example 15.65.** A change of variable is also useful in multiple integrals, as in double integrals in polar coordinates. For a polar region $R$, we have used the conversion:

$$x = r \cos \theta, \quad y = r \sin \theta,$$

which is a transformation from the $r\theta$-plane to the $xy$-plane. Then,

$$\iint_{R} f(x, y) \, dA = \iint_{Q} f(r \cos \theta, r \sin \theta) \, r \, dr \, d\theta, \quad (15.46)$$

where $Q$ is the region in the $r\theta$-plane.
Goal: The goal of this section is to write a general form for a change of variables, which turns the integral easier.

**Definition 15.66.** A change of variables is a **transformation** $T : Q \to R$ (from the $uv$-plane to the $xy$-plane), $T(u, v) = (x, y)$, where $x$ and $y$ are related to $u$ and $v$ by the equations

$$x = g(u, v), \quad y = h(u, v). \quad \text{[or, \; r(u, v) = \langle g(u, v), h(u, v) \rangle]}$$

We usually take these transformations to be $C^1$-**Transformation**, meaning $g$ and $h$ have continuous first-order partial derivatives, and **one-to-one**.

![Transformation diagram](image)

**Problem 15.67.** A transformation is defined by $r(u, v) = \langle 2u - v, u + v \rangle$. Find the image of the unit square $Q = \{(u, v) \mid 0 \leq u \leq 1, \; 0 \leq v \leq 1\}$.

**Solution.**

**Ans:** A rectangle of vertices $(0, 0), (2, 1), (1, 2), (-1, 1)$. 
Now, let’s see how a change of variables affects a double integral.

- See Figure 15.19, where $T: Q \to R$ given by

$$r(u, v) = \langle x(u, v), y(u, v) \rangle.$$  

(15.47)

- The tangent vectors at $r(u_0, v_0)$ w.r.t the $u$- and $v$-directions are

$$r_u(u_0, v_0) = \langle g_u, h_u \rangle (u_0, v_0), \quad r_v(u_0, v_0) = \langle g_v, h_v \rangle (u_0, v_0).$$

- We can approximate the image region $R = T(Q)$ by a parallelogram determined by the scaled tangent vectors. Therefore,

$$\Delta A = A(R) \approx |(r_u \Delta u) \times (r_v \Delta v)| = |r_u \times r_v| \Delta u \Delta v.$$  

(15.48)

- Computing the cross product, we obtain

$$r_u \times r_v = \det \begin{bmatrix} i & j & k \\ x_u & y_u & 0 \\ x_v & y_v & 0 \end{bmatrix} = \det \begin{bmatrix} x_u & y_u \\ x_v & y_v \end{bmatrix} k$$  

(15.49)

**Definition 15.68.** The Jacobian of $T: x = g(u, v), y = h(u, v)$ is

$$\frac{\partial(x, y)}{\partial(u, v)} \overset{\text{def}}{=} \det \begin{bmatrix} x_u & x_v \\ y_u & y_v \end{bmatrix} = x_u y_v - x_v y_u.$$  

(15.50)

**Summary 15.69.** For a differentiable transformation $T: Q \to R$ given by $r(u, v) = \langle x(u, v), y(u, v) \rangle$,

$$\Delta A \approx \left| \frac{\partial(x, y)}{\partial(u, v)} \right| \Delta u \Delta v.$$  

(15.51)
**Theorem 15.70.** Suppose that $T$ is a $C^1$-transformation whose Jacobian is nonzero, and suppose that $T$ maps a region $Q$ in the $uv$-plane onto a region $R$ in the $xy$-plane. Let $f$ be a continuous function on $R$. Suppose also that $T$ is an one-to-one transformation except perhaps along the boundary of the regions. Then

$$
\int\int_{R} f(x, y) \, dA = \int\int_{Q} f(x(u, v), y(u, v)) \left| \frac{\partial(x, y)}{\partial(u, v)} \right| \, du \, dv. \tag{15.52}
$$

**Example 15.71.** (Transformation to polar coordinates). The transformation from $Q = [a, b] \times [\alpha, \beta]$ in the $r\theta$-plane to $R$ in the $xy$-plane is given by

$$
T : x = g(r, \theta) = r \cos \theta, \quad y = h(r, \theta) = r \sin \theta.
$$

The Jacobian of $T$ is

$$
\frac{\partial(x, y)}{\partial(r, \theta)} = \det \begin{bmatrix} \cos \theta & -r \sin \theta \\ \sin \theta & r \cos \theta \end{bmatrix} = r \cos^2 \theta + r \sin^2 \theta = r.
$$

Thus Theorem 15.24 (p. 99) gives

$$
\int\int_{R} f(x, y) \, dA = \int\int_{Q} f(r \cos(\theta), r \sin(\theta)) \left| \frac{\partial(x, y)}{\partial(r, \theta)} \right| \, dr \, d\theta 
= \int_{\alpha}^{\beta} \int_{a}^{b} f(r \cos(\theta), r \sin(\theta)) \, r \, dr \, d\theta. \tag{15.53}
$$
Problem 15.72. Evaluate $\iint_R (x + y) \, dA$, where $R$ is the quadrilateral region with vertices given by $(0, 0), (3, -3), (6, 0),$ and $(3, 3)$, using the transformation $x = u + 3v$ and $y = u - 3v$.

Solution.
Problem 15.73. Evaluate the integral \( \iint_R \frac{e^{x+y}}{x-y} \, dA \), where \( R \) is the trapezoidal region with vertices (1, 0), (2, 0), (0, -2), and (0, -1).

Solution.

\[ \text{Ans: } \frac{3}{4}(e - e^{-1}) \]
Problem 15.74. Evaluate \( \iint_R \sin(x^2 + 4y^2) \, dA \), where \( R \) is the region in the first quadrant bounded by \( x^2 + 4y^2 = 4 \).

Solution. Consider the transformation: \( x = 2u, y = v \).

\( \text{Ans: } \frac{\pi}{8}(1 - \cos 4) \)
15.9. Change of Variables in Multiple Integrals

**Triple Integrals**

**Definition 15.75. (Higher order Jacobian).** The Jacobian of \( T \), given by

\[
x = g(u, v, w), \quad y = h(u, v, w), \quad z = k(u, v, w),
\]

is the following determinant:

\[
\frac{\partial(x, y, z)}{\partial(u, v, w)} = \det \begin{vmatrix}
x_u & x_v & x_w \\
y_u & y_v & y_w \\
z_u & z_v & z_w
\end{vmatrix}.
\]

(15.54)

**Theorem 15.76.** Under hypotheses similar to those in Theorem 15.70, we have the following formula for triple integrals:

\[
\iiint_R f(x, y, z) \, dV = \iiint_Q f(x(u, v, w), y(u, v, w), z(u, v, w)) \left| \frac{\partial(x, y, z)}{\partial(u, v, w)} \right| \, du \, dv \, dw.
\]

(15.55)

**Self-study 15.77.** Show that when dealing with spherical coordinates,

\[
dV = \rho^2 \sin \phi \, d\rho \, d\theta \, d\phi.
\]

(15.56)

*Recall.* \( x = \rho \sin \phi \cos \theta, \) \( y = \rho \sin \phi \sin \theta, \) and \( z = \rho \cos \phi. \)
1. Use the given transformation to evaluate the integral.

(a) \( \iint_R y^2 \, dA \), where \( R \) is the region bounded by \( 4x^2 + 9y^2 = 36; (x, y) = (3u, 2v) \)

(b) \( \iint_R (3x - y) \, dA \), where \( R \) is the triangular region with the three vertices \((0, 0), (2, 1), \) and \((1, 3); (x, y) = (2u + v, u + 3v) \)

\textbf{Hint:} (a) \( \iint_R y^2 \, dA = \iint_Q 4v^2 \cdot 6 \, du \, dv \), where \( Q = \{ (u, v) \mid u^2 + v^2 \leq 1 \} \)

\textbf{Hint:} (b) \( \iint_R (3x - y) \, dA = \iint_Q 5u \cdot 5 \, du \, dv \); figure out \( Q \) by yourself

\textit{Ans:} (a) 6\pi; (b) \( \frac{25}{6} \)

2. Make an appropriate change of variables to evaluate the integral

\[ \iint_R \sin(x^2 + 4y^2) \, dA, \]

where \( R \) is the region in the first quadrant bounded by the ellipse \( x^2 + 4y^2 = 1 \).

3. Make an appropriate change of variables to evaluate \( \iint_R 2(x - y)e^{x^2 - y^2} \, dA \), where \( R \) is the rectangle enclosed by the lines: \( x - y = 0, x - y = 1, x + y = 0, x + y = 2 \).

4. Make an appropriate change of variables to evaluate the integral \( \iint_R e^{x+y} \, dA \), where \( R \) is given by the inequality \( |x| + |y| \leq 1 \).

\textit{Ans:} \( e - e^{-1} \)
15.9. Change of Variables in Multiple Integrals

R.15. Review Problems for Ch. 15

1. Estimate the volume of the solid that lies below the surface \( z = x + y \) and above the rectangle \( R = \{(x, y) \mid 0 \leq x \leq 6, \ 0 \leq y \leq 4\} \). Use a Riemann sum with \( m = 3, \ n = 2 \), and the Midpoint Rule.

\[ \text{Ans: 120} \]

2. Evaluate the double integral following the direction.

\[ \iint_R (4 - x) \, dA, \quad R = [0, 4] \times [0, 5] \]

(a) Identify it as the volume of a solid. (You should visualize the solid.)
(b) Evaluate the double integral, by measuring the volume.

\[ \text{Ans: 40} \]

3. Evaluate the double integral:

\[ \iint_R \frac{y}{1 + xy} \, dA, \quad R = [0, 1] \times [0, 2]. \]

\[ \text{Hint: Use } \int \ln x \, dx = x \ln x - x + C, \text{ if necessary.} \]

\[ \text{Ans: } -2 + 3 \ln(3) \]

4. Evaluate the double integral

\[ \int_0^1 \int_{3y}^3 e^{x^2} \, dx \, dy \]

\[ \text{Ans: } -1/6 + e^9/6 \]

5. Evaluate the iterated integral by converting to polar coordinates.

\[ \int_{-3}^3 \int_0^{\sqrt{9-y^2}} 2 \sin(x^2 + y^2) \, dx \, dy \]

\[ \text{Ans: } \pi(1 - \cos 9) \]

6. A swimming pool is circular with 40–ft diameter. The depth is constant along east-west lines and increases linearly from 2 ft at the south end to 6 ft at the north end. Find the volume of water in the pool, using a double integral in polar coordinates.

\[ \text{Ans: } 1600\pi \]
7. Find the surface area of the part of the plane \( z = 2x + 28y + 2030 \) that lies inside the cylinder \( x^2 + y^2 = 1 \).

\[ \text{Ans: } \sqrt{789} \pi \]

8. Fill the lower and upper bounds appropriately for the triple integral.

\[
\int_0^1 \int_0^x \int_0^y f(x, y, z) \, dz \, dy \, dx = \int_1^2 \int_1^3 \int_1^6 f(x, y, z) \, dz \, dx \, dy
\]

\[
= \int_7^9 \int_9^{11} \int_1^6 f(x, y, z) \, dx \, dz \, dy
\]

\[ \text{Ans: From 1 to 12: } [0, 1, y, 1, 0, y; 0, 1, 0, y, y, 1] \]

9. Use cylindrical coordinates to evaluate \( \iiint_E x^2 \, dV \), where \( E \) is the solid that lies within the cylinder \( x^2 + y^2 = 1 \), above the plane \( z = 0 \), and below the cone \( z^2 = 4x^2 + 4y^2 \).

\[ \text{Ans: } 2\pi/5 \]

10. Use spherical coordinates to evaluate \( \iiint_E e^{(x^2+y^2+z^2)^{3/2}} \, dV \), where \( E \) is the portion of the unit ball \( x^2 + y^2 + z^2 \leq 1 \) that lies in the first octant.

\[ \text{Ans: } (e - 1)\pi/6 \]

11. Use the transformation \( x = 2u, y = v \) to evaluate \( \iint_R (x^2 + 4y^2) \, dA \), where \( R \) is the region bounded by the ellipse \( \frac{x^2}{4} + y^2 = 1 \).

\[ \text{Ans: } 4\pi \]

12. Evaluate \( \iint_R (x + y)e^{x^2-y^2} \, dA \), where \( R \) is rectangle enclosed by the lines \( x - y = 0, x - y = 1, x + y = 0 \), and \( x + y = 1 \). \( \text{Hint: } \) If you set \( u = x+y, v = x-y \), then the transformation becomes \( x = (u + v)/2, y = (u - v)/2 \).

\[ \text{Ans: } e/2 - 1 \]
Project 2. The Volume of the Unit Ball in \( n \)-Dimensions

In this project, we will find formulas for the volume of the unit ball in \( n \)-dimensions (\( n \)-D). From your high school, you learned volumes of unit balls for \( n = 1, 2, 3 \).

\[
\begin{array}{|c|c|c|}
\hline
n & B_n & V_n \\
\hline
1 & \{x \mid x^2 \leq 1\} = [-1, 1] & 2 \\
2 & \{(x, y) \mid x^2 + y^2 \leq 1\} & \pi \\
3 & \{(x, y, z) \mid x^2 + y^2 + z^2 \leq 1\} & 4\pi/3 \\
\hline
\end{array}
\]  
(15.57)

Define the 4D unit ball (hypersphere) as

\[
B_4 = \{(x, y, z, w) \mid x^2 + y^2 + z^2 + w^2 \leq 1\}.
\]  
(15.58)

Before finding its volume, \( V_4 \), let’s try to verify \( V_3 = \frac{4\pi}{3} \) by using a specific integration technique.

Figure 15.20: \( B_3 \) and its projection to \( \mathbb{R}^2 \times \mathbb{R} \): the volume \( V_3 \) approximates the sum of the volume of circular slices having radius \( \cos \theta_i \) and thickness \( \Delta \sin \theta_i := \sin \theta_{i+1} - \sin \theta_i = \frac{\sin \theta_{i+1} - \sin \theta_i}{\Delta \theta} \Delta \theta \approx \cos \theta_i \Delta \theta. \)
The computation of $V_3$: We first partition $B_3$ into horizontal circular slices. Let, for $k > 0$,

$$\Delta \theta = \frac{\pi}{2} \cdot \frac{1}{k} \text{ and } \theta_i = i \Delta \theta, \quad i = 0, 1, \cdots, k. \quad (15.59)$$

One can see from Figure 15.20 that the volume $V_3$ approximates the sum of the volume of circular slices. The $i$-th circular slice $S_i$ has radius $\cos \theta_i$; its area is

$$A(S_i) = V_2 \cdot \cos^2 \theta_i = \pi \cos^2 \theta_i. \quad (15.60)$$

Since $S_i$ has thickness $\Delta \sin \theta_i = \sin \theta_{i+1} - \sin \theta_i$, we have

$$V_3 \approx 2 \sum_{i=0}^{k-1} (\pi \cos^2 \theta_i) \Delta \sin \theta_i. \quad (15.61)$$

Therefore,

$$V_3 = \lim_{k \to \infty} 2 \sum_{i=0}^{k-1} (\pi \cos^2 \theta_i) \Delta \sin \theta_i$$

$$= 2\pi \int_0^{\pi/2} \cos^2 \theta \, d(sin \theta) = 2\pi \int_0^{\pi/2} \cos^3 \theta \, d\theta = 2\pi \cdot \frac{2}{3}. \quad (15.62)$$

Note: Equation (15.62) can be rewritten as

$$V_3 = 2 V_2 \int_0^{\pi/2} \cos^3 \theta \, d\theta. \quad (15.63)$$

The computation of $V_4$: We are now ready for it! First image $B_4$ and its projection to $\mathbb{R}^3 \times \mathbb{R}$. With the same partitioning of the last dimension, the $i$-th horizontal piece $S_i$ now becomes a spherical slice, rather than a circular slice, but having the same radius $\cos \theta_i$ and thickness $\Delta \sin \theta_i$. Thus, the volume of the $i$-th spherical slice reads

$$V(S_i) = V_3 \cos^3 \theta_i \cdot \Delta \sin \theta_i \approx V_3 \cos^4 \theta_i \Delta \theta. \quad (15.64)$$

Recall that $\Delta \sin \theta_i = \sin \theta_{i+1} - \sin \theta_i \approx \cos \theta_i \Delta \theta$. By summing up for $i = 0, 1, \cdots, k - 1$, and multiplying the result by 2 (due to symmetry), we have

$$V_4 \approx 2 V_3 \sum_{i=0}^{k-1} \cos^4 \theta_i \Delta \theta. \quad (15.65)$$
Problem 15.78.

1. Complete a formula for $V_4$, by applying $k \to \infty$ to (15.65).

   **Hint:** Your result must be similar to (15.63).

2. Apply the above arguments recursively to find formulas for $V_n$, $n \geq 2$.

3. Use a computer algebra system (e.g., Maple) to evaluate exact values of $V_n$, for $n = 1, 2, \cdots, 20$.

4. Plot $\{(n, V_n) \mid n = 1, 2, \cdots, 20\}$.

   **Hint:** You may use Maple-code 15.79 and your plot must look like Figure 15.21.

   ![Figure 15.21: A plot for $V_n$, where $\max(V) = V_5 = \frac{8\pi^2}{15} \approx 5.263789$.](image)

Maple-code 15.79. Assume you have a formula for $V_n$ of the form

$$V_n = V_{n-1} g(n). \quad (15.66)$$

Then you may implement a Maple code:

```maple
with(plots): with(plottools):
with(VectorCalculus): with(Student[MultivariateCalculus]):

m := 20:
V := Vector(m):
V[1] := 2:
for n from 2 to m do V[n] := V[n-1]*g(n); end do:
max[index](V); max(V); evalf(%);

X := [seq(n, n = 1..m)]:
pp := pointplot(Vector(X), Vector(V), color = blue, symbol = solidcircle, symbolsize = 12):
pl := plot(Vector(X), Vector(V), color = blue, thickness = 3):
display(pp, pl, scaling = constrained, labels = ["n", V__n], labelfont = ["times", "bold", 13])
```
Figure 15.21 is constructed using the above code, with \( m := 10 \) and \( g(n) \) defined appropriately.

\[
\begin{align*}
\textbf{Report}. & \quad \text{Submit hard copies of your experiences.} \\
& \quad \text{• Derive a formula for } V_n \text{ of the form in (15.66).} \\
& \quad \text{• Implement a code to evaluate } V_n, \ n = 1, 2, \ldots, 20, \text{ exactly.} \\
& \quad \text{• Plot the results.} \\
& \quad \text{• Collect all your work, in order.} \\
& \quad \text{• Attach a “summary” or “conclusion” page at the beginning of report.}
\end{align*}
\]

You may work in a small group; however, you must report individually.
CHAPTER 16

Vector Calculus

In this chapter, we study the calculus of vector fields. In particular, you will learn

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line integral</td>
<td>Work done by a force vector field in moving an object along a curve</td>
</tr>
<tr>
<td>Surface integral</td>
<td>The rate of fluid flow across a surface</td>
</tr>
<tr>
<td>Fundamental theorem of calculus, in 2/3-D</td>
<td>Green’s theorem, Stokes’s theorem, and Divergence theorem</td>
</tr>
</tbody>
</table>

Contents of Chapter 16

16.1. Vector Fields .......................................................... 148
16.2. Line Integrals ........................................................... 156
16.3. The Fundamental Theorem for Line Integrals ...................... 170
16.4. Green’s Theorem ....................................................... 182
16.5. Curl and Divergence ................................................... 192
16.6. Parametric Surfaces and Their Areas ................................ 199
16.7. Surface Integrals ....................................................... 213
16.8. Stokes’s Theorem ....................................................... 222
16.9. The Divergence Theorem ............................................... 226
Project 3. The Area of Heart ................................................ 230
R.16. Review Problems for Ch. 16 ............................................ 233
F.1. Formulas for Chapter 16 .................................................. 236

This chapter corresponds to Chapter 16 in Stewart, Calculus (8th Ed.), 2015.
16.1. Vector Fields

16.1.1. Definitions

**Definition** 16.1. If $D$ is a region in $\mathbb{R}^2$, a (2D) **vector field** on $D$ is a function $F$ that assigns to each point $(x, y) \in D$ a two-dimensional vector $F(x, y)$. If $D$ is a solid region in $\mathbb{R}^3$, a (3D) **vector field** on $D$ is a function $F$ that assigns to each point $(x, y, z) \in D$ a three-dimensional vector $F(x, y, z)$.

**Expressions for vector fields:**

$$F(x, y) = \langle P(x, y), Q(x, y) \rangle = P(x, y)i + Q(x, y)j,$$

$$F(x, y, z) = \langle P(x, y, z), Q(x, y, z), R(x, y, z) \rangle = P(x, y, z)i + Q(x, y, z)j + R(x, y, z)k.$$

**Example** 16.2. $F(x, y) = \langle x, x - y \rangle$ is a vector field in $\mathbb{R}^2$. $G(x, y, z) = x^2i + y^2j + z^2k$ is a vector field in $\mathbb{R}^3$. Let’s sketch $F$.

<table>
<thead>
<tr>
<th>$(x, y)$</th>
<th>$F(x, y) = \langle x, x - y \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0, 0)</td>
<td></td>
</tr>
<tr>
<td>(1, 0)</td>
<td></td>
</tr>
<tr>
<td>(1, 1)</td>
<td></td>
</tr>
<tr>
<td>(0, 1)</td>
<td></td>
</tr>
</tbody>
</table>
**Problem 16.3.** Let $F(x, y) = \langle -y, x \rangle$. Describe $F$ by sketching some of the vectors $F(x, y)$.

**Solution.**

<table>
<thead>
<tr>
<th>$(x, y)$</th>
<th>$F(x, y) = \langle -y, x \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1, 0)</td>
<td>$(1, 0)$</td>
</tr>
<tr>
<td>(0, 1)</td>
<td>$(0, 1)$</td>
</tr>
<tr>
<td>(-1, 0)</td>
<td>$(-1, 0)$</td>
</tr>
<tr>
<td>(0, -1)</td>
<td>$(0, -1)$</td>
</tr>
</tbody>
</table>

**Note:**

- $x \cdot F(x) = \langle x, y \rangle \cdot \langle -y, x \rangle = -xy + xy = 0$.
  
  Thus, $F(x) = \langle -y, x \rangle$ is perpendicular to the position vector $x$.

- $|F(x)| = \sqrt{y^2 + x^2} = |x|$. 
  
  Therefore, $F(x)$ has the same magnitude as $x$.

![Figure 16.1: The vector field $F = \langle -y, x \rangle$, showing directions only.](image-url)
Vector fields in $\mathbb{R}^3$

**Problem 16.4.** Sketch the vector field on $\mathbb{R}^3$ given by $F(x, y, z) = z \mathbf{k} = \langle 0, 0, z \rangle$.

**Example 16.5.**

![Airfoil simulation, showing the velocity field.](image)

Figure 16.2: Airfoil simulation, showing the velocity field.
16.1.2. Gradient fields and potential functions

- Suppose that $f(x, y)$ is a differentiable function on $D$. Earlier we defined the gradient $\nabla f$ of $f$:

$$\nabla f(x, y) = (f_x(x, y), f_y(x, y)) = f_x i + f_y j.$$  

We now see that $\nabla f$ is a two-dimensional vector field on $D$.

- Similarly, if $f(x, y, z)$ is a differentiable function on a solid $D \subset \mathbb{R}^3$, then $\nabla f(x, y, z)$ is a three-dimensional vector field on $D$.

From now on, we will refer to the gradient of a function $f$ as the gradient vector field of $f$.

**Problem 16.6.** Find the gradient vector field of 

$$f(x, y) = x^2 y - y^3.$$ 

**Solution.**

Ans: $(2xy, x^2 - 3y^2)$

**Definition 16.7.** A vector field $F$ is **conservative** if there is a differentiable function $f$ such that

$$\nabla f = F.$$ 

The function $f$ is called a **potential function** of $F$, or simply **potential**.

**Claim 16.8.** Gradient fields are, always, conservative.
**Problem 16.9.** (Continuation of Problem 16.6). Let \(F(x, y) = \langle 2xy, x^2 - 3y^2 \rangle\). Then \(F\) is conservative.

**Solution.** Let’s try to find \(f\) such that \(\nabla f = F\).

\[
\text{Ans: } f(x, y) = x^2y - y^3 + K
\]

**Note:** Not every vector field is conservative, and it is not difficult to give an example of a vector field that is nonconservative.

**Example 16.10.** Show that the vector field \(F(x, y) = (x^2 + y) \mathbf{i} + y^3 \mathbf{j}\) is not conservative.

**Proof. Assume that \(F\) is conservative.** Then, there exists \(f\) such that \(\nabla f = \langle f_x, f_y \rangle = F\):

\[
\begin{align*}
f_x &= x^2 + y, \\
f_y &= y^3.
\end{align*}
\]

Then

\[
f_{xy} = 1 \quad \text{and} \quad f_{yx} = 0. \tag{16.1}
\]

Since both mixed partials are constants, they are continuous everywhere. Thus, by the Clairaut’s theorem, we must have

\[
f_{xy} = f_{yx}.
\]

However, in (16.1), they are not equal. Contradiction! 

We will study properties of **conservative vector fields** in Section 16.3 below, in detail.
Problem 16.11. At time $t = 1$, a particle is located at $(1, 3)$. When it moves in a velocity field $v(x, y) = \langle xy - 2, y^2 - 10 \rangle$, find its approximate location at $t = 1.05$.

Solution. Clue: $\mathbf{r}(t) \approx \mathbf{r}(t_0) + \mathbf{r}'(t_0) \cdot (t - t_0)$, where $\mathbf{r}'$ is the velocity vector.

Ans: $(1.05, 2.95)$
Exercises 16.1

1. Match the vector fields $F$ with the plots labeled (I)–(IV). Give reasons for your choices.

   (a) $F = \langle e^x, 5y \rangle$
   (b) $F = \langle \sin(x + y), x \rangle$
   (c) $F = \langle x + y, y \rangle$
   (d) $F = \langle x, -y \rangle$

   ![Figure 16.3: Maple fieldplot.](image)

   **Hint:** Let's see Figure (III), for example; arrows are directing up for $x > 0$ and down for $x < 0$, which implies that the second component of $F$ is closely related to $x$. Now, what can you say about Figure (IV)? Arrows never look the west direction, which implies that the first component of $F$ is nonnegative.

2. **CAS** Use a CAS (fieldplot in Maple and PlotVectorField in Mathematica) to plot

   
   \[ F(x, y) = (y^3 - xy^2) \mathbf{i} + (2xy - 2x^2) \mathbf{j}. \]

   Explain the appearance by finding the set of points $(x, y)$ such that $F(x, y) = 0$. (Attach the figure.)
3. Find the gradient vector field $\nabla f$ and sketch it.

(a) $f(x, y) = \frac{(x - y)^2}{2}$

(b) $f(x, y) = \frac{x^3 - y^3}{3}$

4. Match the functions $f$ with their gradient vector fields plotted with labels (I)–(IV). Give reasons for your choices.

(a) $f(x, y) = xe^y$

(b) $f(x, y) = x^2 + y^2$

(c) $f(x, y) = x(x - 2y)$

(d) $f(x, y) = \cos(x^2 + y^2)$

Figure 16.4: Maple fieldplot for $\nabla f$. 
16.2. Line Integrals

**Recall:** In single-variable calculus, if a force \( f(x) \) is applied to an object to move it along a straight line from \( x = a \) to \( x = b \), then the amount of work done is given by the integral

\[
W = \int_a^b f(x) \, dx \quad (= \lim_{n \to \infty} \sum_{i=1}^n f(x_i^*) \Delta x).
\] (16.2)

Up to this point, our intervals of integration were always either bijective function or a closed interval \([a, b]\). In this section, we will be integrating over a *parametrized curve* instead of a nice interval as before.

**Goal:** To integrate functions along a curve, as opposed to along an interval.

**Definition 16.12.** A *plane curve* \( C \) is given by the vector equation

\[
r(t) = \langle x(t), y(t) \rangle, \quad a \leq t \leq b,
\] (16.3)

or equivalently, by the *parametric equations*

\[
x = g(t), \quad y = h(t), \quad a \leq t \leq b.
\] (16.4)

**Recall:** You have learned

\[
\Delta s_i = \sqrt{\Delta x_i^2 + \Delta y_i^2} = \sqrt{\left(\frac{\Delta x_i}{\Delta t}\right)^2 + \left(\frac{\Delta y_i}{\Delta t}\right)^2} \Delta t
\]

and therefore

\[
ds = \lim_{n \to \infty} \Delta s_i = \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} \, dt
\]

\[= \sqrt{(x'(t))^2 + (y'(t))^2} \, dt = |r'(t)| \, dt.
\]

Thus the **arc length** of \( C \) can be computed as

\[
L = \int_C ds = \int_a^b \sqrt{(x'(t))^2 + (y'(t))^2} \, dt.
\]
16.2.1. Line integrals for scalar functions in the plane

Now, suppose that a force is applied to move an object along a path traced by a curve \( C \). If the amount of force is given by \( f(x, y) \), then the amount of work done must be given by the integral

\[
W = \int_C f(x, y) \, ds,
\]

where \( s \) is the arc length element, i.e., \( ds = \sqrt{dx^2 + dy^2} \).

Assumption. The curve \( C \) is smooth, i.e., \( r'(t) \) is continuous and \( r'(t) \neq 0 \).

**Definition** 16.13. If \( f \) is defined on a smooth curve \( C \) given by (16.3), then the *line integral of \( f \) along \( C \) is*

\[
\int_C f(x, y) \, ds = \lim_{n \to \infty} \sum_{i=1}^{n} f(x_i^*, y_i^*) \, \Delta s_i,
\]

if this limit exists. Here \( \Delta s_i = \sqrt{\Delta x_i^2 + \Delta y_i^2} \).
Chapter 16. Vector Calculus

The line integral defined in (16.6) can be rewritten as

\[
\int_C f(x, y) \, ds = \int_a^b f(x(t), y(t)) \sqrt{(x'(t))^2 + (y'(t))^2} \, dt
\]

\[
= \int_a^b f(x(t), y(t)) |r'(t)| \, dt.
\]

(16.7)

**Problem 16.14.** Evaluate \( \int_C (2 + x^2 y) \, ds \), where \( C \) is upper half of the unit circle \( x^2 + y^2 = 1 \).

**Solution. Clue:** Find the parametric equation for \( C \) and then follow the formula (16.7).

**Ans:** \( 2\pi + \frac{2}{3} \)
**Definition 16.15.** $C$ is a **piecewise smooth curve** if it is a union of a finite number of smooth curves $C_1$, $C_2$, $\cdots$, $C_n$. That is,

$$C = C_1 \cup C_2 \cup \cdots \cup C_n.$$  

In the case, we define the integral of $f$ along $C$ as the sum of the integrals of $f$ along each of the smooth pieces of $C$:

$$\int_C f(x, y) \, ds = \int_{C_1} f(x, y) \, ds + \int_{C_2} f(x, y) \, ds + \cdots + \int_{C_n} f(x, y) \, ds. \quad (16.8)$$

**Problem 16.16.** Evaluate $\int_C 2x \, ds$, where $C$ consists of the arc $C_1$ of the parabola $y = x^2$ from $(0,0)$ to $(1,1)$ followed by the vertical line segment $C_2$ from $(1,1)$ to $(1,2)$.

**Solution.** **Clue:** Begin with parametric representation of $C_1$ and $C_2$. For example, $C_1 : x = t, y = t^2$, $0 \leq t \leq 1$ and $C_2 : x = 1, y = t$, $1 \leq t \leq 2$.

\[\text{Ans: } \frac{1}{6}(5\sqrt{5} - 1) + 2\]
Application to Physics: To compute the mass of a wire that is shaped like a plane curve \( C \), where the density of the wire is given by a function \( \rho(x, y) \) defined at each point \((x, y)\) on \( C \), we can evaluate the line integral

\[
m = \int_C \rho(x, y) \, ds. \tag{16.9}
\]

Thus the center of mass of the wire is the point \((\overline{x}, \overline{y})\), where

\[
\overline{x} = \frac{1}{m} \int_C x \rho(x, y) \, ds, \quad \overline{y} = \frac{1}{m} \int_C y \rho(x, y) \, ds. \tag{16.10}
\]

Problem 16.17. A wire takes the shape of the semicircle, \( x^2 + y^2 = 1, \ y \geq 0 \), and its density is proportional to the distance from the line \( y = 1 \). Find the center of mass of the wire.

Solution. Clue: First parametrize the wire and use \( \rho(x, y) = k(1 - y) \).

\[
\text{Ans: } (\overline{x}, \overline{y}) = \left(0, \frac{4 - \pi}{2(\pi - 2)} \approx 0.38\right), \text{ where } m = k(\pi - 2)
\]
16.2. Line Integrals

**Definition 16.18.** Line integrals of $f$ along $C$ with respect to $x$ and $y$ are defined as

\[ \int_C f(x, y) \, dx = \lim_{n \to \infty} \sum_{i=1}^{n} f(x_i^*, y_i^*) \Delta x_i, \]
\[ \int_C f(x, y) \, dy = \lim_{n \to \infty} \sum_{i=1}^{n} f(x_i^*, y_i^*) \Delta y_i. \]  

(16.11)

The line integrals can be evaluated by expressing everything in terms of $t$:

\[ x = x(t), \ y = y(t), \ dx = x'(t) \, dt, \ dy = y'(t) \, dt. \]

\[ \int_C f(x, y) \, dx = \int_{a}^{b} f(x(t), y(t)) x'(t) \, dt, \]
\[ \int_C f(x, y) \, dy = \int_{a}^{b} f(x(t), y(t)) y'(t) \, dt. \]  

(16.12)

**Note:** It frequently happens that line integral with respect $x$ and $y$ occur together. When this happens, it is customary to abbreviate by writing

\[ \int_C P(x, y) \, dx + \int_C Q(x, y) \, dy = \int_C P(x, y) \, dx + Q(x, y) \, dy. \]

Let $\mathbf{F}(x, y) = \langle P(x, y), Q(x, y) \rangle$ and $\mathbf{r} = \langle x, y \rangle = \langle x(t), y(t) \rangle$ represent the curve $C$. Then, since $d\mathbf{r} = \langle dx, dy \rangle$, we can rewrite the above as

\[ \int_C P(x, y) \, dx + Q(x, y) \, dy = \int_C \mathbf{F} \cdot d\mathbf{r}, \]  

(16.13)

which is a line integral of vector fields. We will consider it in detail in §16.2.3 below (p. 166).
Problem 16.19. Evaluate $\int_C y^2 \, dx + x \, dy$, where

\[
\begin{cases}
  \text{(a) } C = C_1 & \text{: the line segment from } (-5, -3) \text{ to } (0, 2) \\
  \text{(b) } C = C_2 & \text{: the arc of } x = 4 - y^2 \text{ from } (-5, -3) \text{ to } (0, 2)
\end{cases}
\]

Solution. Clue: $C_1: r(t) = (1 - t)r_0 + tr_1, \ 0 \leq t \leq 1$ and $C_2: x = 4 - t^2, \ y = t, \ -3 \leq t \leq 2$.

Ans: (a) $-\frac{5}{6}$ (b) $40\frac{5}{6}$
16.2. Line Integrals

**Orientation of curves:** It is important to note that the value of line integrals with respect to $x$ or $y$ (or $z$, in 3-D) depends on the **orientation of $C$**, unlike line integrals with respect to the arc length $s$. If the curve is traced in reverse (that is, from the terminal point to the initial point), then the sign of the line integral is reversed as well. We denote by $-C$ the **curve with its orientation reversed**. We then have

$$\int_{-C} P \, dx = - \int_{C} P \, dx, \quad \int_{-C} Q \, dy = - \int_{C} Q \, dy.$$  \hspace{1cm} (16.14)

![Figure 16.6: Curve $C$ and its reversed curve $-C$.](image)

**Note:** For line integrals with respect to the arc length $s$,

$$\int_{-C} f \, ds = \int_{C} f \, ds. \hspace{1cm} (16.15)$$

**Problem 16.20. (Variant of Problem 16.19(a)):** The reversed curve $-C_1$ is the line segment from $(0, 2)$ to $(-5, -3)$:

$$r(t) = (1 - t)(0, 2) + t(-5, -3) = (-5t, -5t + 2), \quad 0 \leq t \leq 1.$$  

Thus we must have

$$\int_{-C_1} y^2 \, dx + x \, dy = \frac{5}{6}.$$  

**Solution.**
16.2.2. Line integrals in space

First, the definition for the line integral (with respect to arc length) can be generalized as follows.

**Definition 16.21.** Suppose that \( C \) is a smooth space curve given by

\[
r(t) = \langle x(t), y(t), z(t) \rangle, \quad a \leq t \leq b.
\]

Then the line integral of \( f \) along \( C \) is defined in a similar manner as in Definition 16.13:

\[
\int_C f(x, y, z) \, ds = \lim_{n \to \infty} \sum_{i=1}^{n} f(x_i^*, y_i^*, z_i^*) \Delta s_i.
\] (16.16)

It can be evaluated using a formula similar to (16.7):

\[
\int_C f(x, y, z) \, ds = \int_a^b f(r(t)) |r'(t)| \, dt
\] (16.17)

\[
= \int_a^b f(x(t), y(t), z(t)) \sqrt{(x')^2 + (y')^2 + (z')^2} \, dt.
\]

**Note:**

- When \( f(x, y, z) \equiv 1 \),

\[
\int_C ds = \int_a^b |r'(t)| \, dt = L : \text{arc length}
\]

- When \( F = \langle P, Q, R \rangle \),

\[
\int_C F \cdot \, dr = \int_C P \, dx + Q \, dy + R \, dz.
\]
Problem 16.22. Evaluate $\int_C y \sin z \, ds$, where $C$ is the circular helix given by $r(t) = \langle \cos t, \sin t, t \rangle$, $0 \leq t \leq 2\pi$.

**Solution.** *Hint:* You may use one of formulas: $\sin^2 t = (1 - \cos 2t)/2$, $\cos^2 t = (1 + \cos 2t)/2$.

Problem 16.23. Evaluate $\int_C z \, dx + x \, dy + y \, dz$, where $C$ is given by $x = t^2$, $y = t^3$, $z = t^2$, $0 \leq t \leq 1$.

**Solution.**

Ans: $\sqrt{2}\pi$

Ans: $3/2$
16.2.3. Line integrals of vector fields

**Recall**: In Calculus III, we have found that the *work* done by a constant force \( F \) in moving an object from a point to another point \( Q \) in the space is

\[
W = F \cdot D, \quad (16.18)
\]

where \( D = \overrightarrow{PQ} \), the displacement vector. □

**In general**: Let \( C \) be a smooth space curve given by

\[
r(t) = \langle x(t), y(t), z(t) \rangle, \quad a \leq t \leq b.
\]

Then the *work* done by a force \( F \) in moving an object along the curve \( C \) is

\[
W = \lim_{n \to \infty} \sum_{i=1}^{n} F(x_i^*, y_i^*, z_i^*) \cdot [T(x_i^*, y_i^*, z_i^*) \Delta s_i] = \int_{C} F \cdot T \, ds, \quad (16.19)
\]

where \( r(t_i) = (x_i, y_i, z_i), \Delta s_i = |r(t_i) - r(t_{i-1})| \), and \( T \) is the unit tangential vector

\[
T(t) = \frac{r'(t)}{|r'(t)|}. \quad (16.20)
\]

Since \( ds = |r'(t)| \, dt \), we have

\[
W = \int_{C} F \cdot T \, ds = \int_{a}^{b} F \cdot \frac{r'(t)}{|r'(t)|} |r'(t)| \, dt = \int_{a}^{b} F \cdot r'(t) \, dt = \int_{C} F \cdot dr. \quad (16.21)
\]

![Figure 16.7](image-url)
Definition 16.24. Let $F$ be a continuous vector field defined on a smooth curve $C$ given by $r(t), a \leq t \leq b$. Then the **line integral of $F$ along $C$** is

$$\int_C F \cdot dr \overset{\text{def}}{=} \int_C F \cdot T \, ds = \int_a^b F(r(t)) \cdot r'(t) \, dt.$$  
(16.22)

We say that work is the line integral with respect to arc length of the **tangential component** of force.

**Note:** Although $\int_C F \cdot dr = \int_C F \cdot T \, ds$ and integrals with respect to arc length are unchanged when orientation is reversed, it is still true that

$$\int_{-C} F \cdot dr = - \int_C F \cdot dr.$$

Why?

**Problem** 16.25. Evaluate $\int_C F \cdot dr$, where $F(x, y, z) = xy \mathbf{i} + yz \mathbf{j} + zx \mathbf{k}$ and $C$ is given by $r(t) = \langle t, t^2, t^3 \rangle$, $0 \leq t \leq 1$.

**Solution.**
\textbf{Theorem 16.26. (Equivalent to Definition 16.24, p. 167).}

Let $F = \langle P, Q, R \rangle$. Then

$$\int_C F \cdot dr = \int_C P \, dx + Q \, dy + R \, dz. \quad (16.23)$$

\textbf{Problem 16.27.} Let $F(x, y) = \left\langle \frac{x}{\sqrt{x^2 + y^2}}, \frac{y}{\sqrt{x^2 + y^2}} \right\rangle$ and $C$ the parabola $y = 1 + x^2$ from $(-1, 2)$ to $(1, 2)$.

(a) Use a graph of $F$ and $C$ to guess whether $\int_C F \cdot dr$ is positive, negative, or zero.

(b) Evaluate the integral.

\textbf{Solution.} \textit{Hint: (b)}: $C: r(t) = \langle t, 1 + t^2 \rangle, \ -1 \leq t \leq 1$; use Eqn. (16.22).

\textit{Ans: 0}
Exercises 16.2

1. Evaluate the line integral, using the formula $\int_C f(x, y) ds = \int_a^b f(r(t)) |r'(t)| dt$.

   (a) $\int_C x^2 y ds$, where $C$ is given by $r(t) = \langle \cos 2t, \sin 2t \rangle, \ 0 \leq t \leq \pi/4$

   (b) $\int_C 2xye^{xyz} ds$, where $C$ is the line segment from $(0, 0, 0)$ to $(2, 1, 2)$

   Ans: (a) $1/3$; (b) $e^4 - 1$

2. Let $F$ be the vector field shown in the Figure 16.8.

   (a) If $C_1$ is the horizontal line segment from $P(3, 2)$ to $Q(-3, 2)$, determine whether $\int_{C_1} F \cdot dr$ is positive, negative, or zero.

   (b) Let $C_2$ be the clockwise-oriented circle of radius 3 centered at the origin. Determine whether $\int_{C_2} F \cdot dr$ is positive, negative, or zero.

3. Use (16.22) to evaluate the line integral $\int_C F \cdot dr$, where $C$ is parameterized by $r(t)$.

   (a) $F(x, y) = x^2y^3 \mathbf{i} + x^3y^2 \mathbf{j}$, $r(t) = (t^3 - 2t) \mathbf{i} + (t^3 + 2t) \mathbf{j}, \ 0 \leq t \leq 1$

   (b) $F(x, y, z) = \langle -y, x, xy \rangle$, $r(t) = \langle \cos t, \sin t, t \rangle, \ 0 \leq t \leq \pi$

   Ans: (a) $-9$; (b) $\pi$

4. A thin wire is bent into the shape of a semicircle $x^2 + y^2 = 4, \ y \geq 0$. If the linear density of the wire is $\rho(x, y) = ky$, find the mass and center of mass of the wire. Hint: $C : r(t) = \langle 2\cos t, 2\sin t \rangle, \ 0 \leq t \leq \pi$

   Ans: $8k, (0, \pi/2)$
Chapter 16. Vector Calculus

16.3. The Fundamental Theorem for Line Integrals

Recall: The Part 2 of Fundamental Theorem of Calculus (FTC2) is
\[ \int_a^b f'(x) \, dx = f(b) - f(a). \]  
(16.24)

Goal: It would be nice to get a generalization of the FTC2 (16.24) to line integrals.

16.3.1. Conservative vector fields

Theorem 16.28. Suppose that \( F \) is continuous, and is a conservative vector field; that is, \( F = \nabla f \) for some \( f \). Then
\[ \int_C F \cdot dr = \int_C \nabla f \cdot dr = f(r(b)) - f(r(a)). \]  
(16.25)

Proof. By the Chain rule and the FTC2,
\[
\int_C F \cdot dr = \int_a^b \nabla f(r(t)) \cdot r'(t) \, dt = \int_a^b \frac{d}{dt}[(f \circ r)(t)] \, dt \\
= (f \circ r)(t)|_a^b = f(r(b)) - f(r(a)).
\]

Theorem 16.28 is the Fundamental Theorem for Line Integrals, which is a generalization of the FTC2. The function \( f \) is called a potential function of \( F \), or simply potential.
16.3. The Fundamental Theorem for Line Integrals

Problem 16.29. Let \( F(x, y) = \langle 3 + 2xy^2, 2x^2y - 4 \rangle \).

(a) Find a function \( f \) such that \( \nabla f = F \).

(b) Evaluate \( \int_C F \cdot dr \), where \( C : r(t) = \langle \cos t, 2 \sin t \rangle \), \( 0 \leq t \leq \pi \).

Solution.

\[ \text{Ans:} \quad (a) \quad f(x, y) = 3x + xy^2 - 4y + K \quad (b) \quad -6 \]

Problem 16.30. (Revisit of Problem 16.27). Let \( F(x, y) = \frac{x}{\sqrt{x^2 + y^2}} \mathbf{i} + \frac{y}{\sqrt{x^2 + y^2}} \mathbf{j} \) and \( C \) the parabola \( y = 1 + x^2 \) from \((-1, 2)\) to \((1, 2)\). Find a potential of \( F \) and evaluate \( \int_C F \cdot dr \).

Solution.

\[ \text{Ans:} \quad f(x, y) = \sqrt{x^2 + y^2} \quad \text{and} \quad \int_C F \cdot dr = 0. \]
16.3.2. Independence of path

**Definition 16.31.** We say the line integral \( \int_C F \cdot dr \) is independent of path if
\[
\int_{C_1} F \cdot dr = \int_{C_2} F \cdot dr,
\]
for any two paths \( C_1 \) and \( C_2 \) that have the same initial and terminal points.

**Observation 16.32.** In general, \( \int_{C_1} F \cdot dr \neq \int_{C_2} F \cdot dr \). (See Problem 16.19, p. 162.) However, Theorem 16.28 says that when \( F = \nabla f \),
\[
\int_{C_1} F \cdot dr = \int_{C_1} \nabla f \cdot dr = f(r(b)) - f(r(a)) = \int_{C_2} \nabla f \cdot dr = \int_{C_2} F \cdot dr.
\]
Thus line integrals of conservative fields are independent of path.

**Definition 16.33.** A curve \( C \) is closed if its terminal point coincides with its initial point, that is, \( r(b) = r(a) \). A simple curve is a curve that does not intersect itself.

![Figure 16.9](image)

<table>
<thead>
<tr>
<th>closed</th>
<th>not closed</th>
<th>closed</th>
<th>not closed</th>
<th>closed</th>
<th>not closed</th>
</tr>
</thead>
<tbody>
<tr>
<td>simple</td>
<td>simple</td>
<td>not simple</td>
<td>not simple</td>
<td>not simple</td>
<td>not simple</td>
</tr>
</tbody>
</table>

Figure 16.9
16.3. The Fundamental Theorem for Line Integrals

**Theorem 16.34.** \( \int_C F \cdot dr \) is independent of path in \( D \) if and only if \( \int_C F \cdot dr = 0 \) for every closed path \( C \) in \( D \).

**Proof.** (\( \Rightarrow \)) For a closed curve \( C \), choose two points \( A \) and \( B \) to decompose \( C \) into two parts: \( C = C_1 \cup C_2 \). Then

\[
\int_C F \cdot dr = \int_{C_1} F \cdot dr + \int_{C_2} F \cdot dr = \int_{C_1} F \cdot dr - \int_{-C_2} F \cdot dr = 0,
\]

because \( C_1 \) and \( -C_2 \) have the same initial and terminal points.

(\( \Leftarrow \)) Let \( C_1 \) and \( C_2 \) have the same initial and terminal points. Then

\[
0 = \int_{C_1 \cup (-C_2)} F \cdot dr = \int_{C_1} F \cdot dr + \int_{-C_2} F \cdot dr = \int_{C_1} F \cdot dr - \int_{C_2} F \cdot dr,
\]

where the first equality comes from the assumption. \( \square \)

**Pictorial definitions**

![Pictorial definitions for D](image)

Figure 16.10: Pictorial definitions for \( D \).
**Definition 16.35.** A set $D$ is said to be **open** if every point $P$ in $D$ has a disk with center $P$ that is contained wholly and solely in $D$. **Note.** $D$ cannot contain any boundary points.

**Definition 16.36.** A set $D$ is said to be **connected** if for every two points $P$ and $Q$ in $D$, there exists a path which connects $P$ to $Q$.

**Theorem 16.37.** Suppose that the line integral of a vector field $F$ is **independent of path** within an **open connected region** $D$, then $F$ is a **conservative** vector field on $D$.

**Proof.** (sketch). Choose an arbitrary point $(a, b) \in D$ and define

$$f(x, y) = \int_{(a,b)}^{(x,y)} F \cdot dr.$$ 

Since this line integral is independent of path, we can define $f(x, y)$ using any path between $(a, b)$ and $(x, y)$. By choosing a path that ends with a horizontal line segment from $(x_1, y)$ to $(x, y)$ contained entirely in $D$, $x_1 < x$, we can show that

$$\frac{\partial f}{\partial x}(x, y) = \frac{\partial}{\partial x}\left[\int_{(a,b)}^{(x_1,y)} F \cdot dr + \int_{(x_1,y)}^{(x,y)} F \cdot dr\right] = 0 + \frac{\partial}{\partial x} \int_{x_1}^{x} F \cdot (dx, 0) = P.$$ 

Similarly, we can prove that $\frac{\partial f}{\partial y}(x, y) = Q$. □

It follows from Observation 16.32 and Theorem 16.37:

**Corollary 16.38.** In an open connected region, $F$ is **conservative** if and only if its line integral is **independent of path**.
Theorem 16.39. (Clairaut’s Theorem for conservative vector fields). If $F(x, y) = \langle P(x, y), Q(x, y) \rangle$ is a conservative vector field, where $P$ and $Q$ have continuous first-order partial derivatives on $D$, then

$$\frac{\partial P}{\partial y} = \frac{\partial Q}{\partial x}, \quad (16.26)$$

throughout the domain $D$.

Question. Does (16.26) imply conservativeness of $F$?

Ans: No, in general. But, almost!

![Simply-connected and not simply-connected regions](image)

Figure 16.11: Simply-connectedness of $D$.

Definition 16.40. $D$ is a simply-connected region if it is connected and every simple closed curve contains only points in $D$.

Theorem 16.41. Let $F = \langle P, Q \rangle$ be a vector field on an open simply-connected region $D$. If $P$ and $Q$ have continuous first-order partial derivatives throughout $D$,

$$\frac{\partial P}{\partial y} = \frac{\partial Q}{\partial x}, \quad (16.27)$$

then $F$ is conservative.

Note: Theorem 16.41 is a special case of Green’s Theorem which we will see in Section 16.4.
**Self-study 16.42.** Determine whether or not the vector field \( \mathbf{F}(x, y) = \langle 3 + 2xy, x^2 + x - 3y^2 \rangle \) is conservative.

**Solution.** *Hint:* Check if \( P_y = Q_x \) is satisfied.  

\[ \text{Ans: no} \]

**Problem 16.43.** Determine whether or not the vector field \( \mathbf{F}(x, y) = \langle e^y + y \cos x, xe^y + \sin x \rangle \) is conservative.

**Solution.**  

\[ \text{Ans: yes} \]
16.3.3. Potential functions

Recall: When $F$ is conservative, we know from (16.25) on p.170 that

$$\int_C F \cdot dr = \int_C \nabla f \cdot dr = f(r(b)) - f(r(a)), \quad (16.28)$$

which is easy to evaluate when the potential $f$ is known.

Problem 16.44. Given $F(x, y) = \langle e^y + y \cos x, xe^y + \sin x \rangle$,

(a) Find a potential.

(b) Evaluate $\int_C F \cdot dr$, where $C$ is parameterized as

$$r(t) = \langle e^t \cos t, e^t \sin t \rangle, \quad 0 \leq t \leq \pi.$$

Solution.

Ans: (a) $f(x, y) = xe^y + y \sin x + K$ (b) $-e^\pi - 1$
Problem 16.45. Let $F(x, y, z) = \langle y^2, 2xy + e^{3z}, 3ye^{3z} \rangle$. Find $f$ such that $\nabla f = F$.

Solution.

\[ Ans: f = xy^2 + ye^{3z} + K \]
Problem 16.46. Let $F = \langle P, Q, R \rangle$ be a conservative vector field, where $P, Q, R$ have continuous first-order partial derivatives. Then,

$$P_y = Q_x, \quad P_z = R_x, \quad Q_z = R_y. \quad (16.29)$$

Solution. Hint: Use Clairout’s theorem.

Problem 16.47. Show that $\int_C y \, dx + x \, dy + yz \, dz$ is not independent of path.

Solution. Hint: Use (16.29) to check if it is conservative.
Exercises 16.3

1. The figure shows a curve $C$ and a contour map of a function $f$ whose gradient is continuous. Find $\int_C \nabla f \cdot dr$.

![Figure 16.12](image)

2. Determine whether the vector field $F$ is conservative or not. If it is, find its potential.

   (a) $F(x, y) = \langle x + y, x - y \rangle$
   (b) $F(x, y) = \langle 2xy, x^2 + 2xy \rangle$
   (c) $F(x, y) = \langle 2xy^4, x^2y^3 \rangle$
   (d) $F(x, y) = \langle ye^x, e^x - 2y \rangle$

3. (i) Find the potential of $F$ and (ii) use part (i) to evaluate $\int_C F \cdot dr$ along the given curve $C$.

   (a) $F(x, y) = \langle e^y, xe^y + \sin y \rangle$, $C: r(t) = \langle -\cos t, e^t \sin t \rangle$, $0 \leq t \leq \pi$
   (b) $F(x, y, z) = \langle 2y + z, 2x + z, x + y \rangle$, $C$ is the line segment from $(1, 0, 0)$ to $(2, 2, 2)$
   (c) $F(x, y, z) = \langle \sin z, -\sin y, x \cos z \rangle$, $C: r(t) = \langle \cos t, \sin t, t \rangle$, $0 \leq t \leq \pi/2$

   Ans: (a) 2; (b) 16; (c) $\cos(1) - 1$

4. Show that the line integral is independent of path and evaluate the integral.

   (a) $\int_C x \, dx - y \, dy$, $C$ is any path from $(0, 1)$ to $(3, 0)$
   (b) $\int_C (\sin y - ye^{-x}) \, dx + (e^{-x} + x \cos y) \, dy$, $C$ is any path from $(1, 0)$ to $(0, \pi)$

   Ans: (a) 5; (b) $\pi$
5. The figure below depicts two vector fields, one of which is conservative. Which one is it? Why is the other one not conservative?

Figure 16.13: Two vector fields, one of which is conservative.
16.4. Green’s Theorem

Green’s Theorem gives the relationship between a line integral around a simple closed curve $C$ and a double integral over the plane region $D$ bounded by $C$.

**Definition 16.48.** The **positive orientation** of a simple closed curve $C$ refers to a single counterclockwise traversal of $C$ (with keeping the domain on the left). The other directional orientation is called the negative orientation.

![Figure 16.14: ⊕-orientation and ⊖-orientation of a simple closed curve $C$.](image)

**Theorem 16.49.** (Green’s Theorem). Let $C$ be positively oriented, piecewise-smooth, simple closed curve in the plane and $D$ be the region bounded by $C$. If $F = \langle P, Q \rangle$ has **continuous partial derivatives** on an open region including $D$, then

$$\oint_C Pdx + Qdy = \iint_D \left( \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) dA. \quad (16.30)$$
Note: The proof of Green’s Theorem on simple regions is based on the following identities

\[ \oint_C P \, dx = -\iint_D \frac{\partial P}{\partial y} \, dA, \quad \oint_C Q \, dy = \iint_D \frac{\partial Q}{\partial x} \, dA. \]  
(16.31)

Notation 16.50. We denote the line integral calculated by using the positive orientation of the closed curve \( C \) by

\[ \oint_C P \, dx + Q \, dy, \quad \oint_C P \, dx + Q \, dy, \text{ or } \oint_C P \, dx + Q \, dy. \]

We denote line integrals calculated by using the negative orientation of the closed curve \( C \) by

\[ \oint_C P \, dx + Q \, dy. \]

Problem 16.51. Evaluate \( \oint_C x^4 \, dx + xy \, dy \), where \( C \) is the triangular curve consisting of the line segments from \((0,0)\) to \((1,0)\), from \((1,0)\) to \((0,1)\), and from \((0,1)\) to \((0,0)\).

Solution. Although the given line integral could be evaluated by the methods of Section 6.2, we would use Green’s Theorem.

\[ \text{Ans: } \frac{1}{6} \]
Problem 16.52. Evaluate $\oint_C \mathbf{F} \cdot d\mathbf{r}$, where $\mathbf{F} = \langle y - \cos y, x \sin y \rangle$ and $C$ is the circle $(x - 3)^2 + (y + 4)^2 = 4$ oriented clockwise.

Solution. Hint: Check the orientation of the curve.

Ans: $4\pi$

16.4.1. Application to area computation

Recall

$$A(D) = \iint_D 1 \, dA.$$  

If we choose $P$ and $Q$ such that

$$\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} = 1,$$  \hfill (16.32)

then the area of $D$ can be computed as

$$A(D) = \iint_D 1 \, dA = \oint_C P \, dx + Q \, dy.$$  \hfill (16.33)

The following choices are common:

\[
\begin{align*}
\{ \quad & P(x, y) = 0 & \{ \quad & P(x, y) = -y & \{ \quad & P(x, y) = -\frac{y}{2} \\
Q(x, y) = x & Q(x, y) = 0 & Q(x, y) = \frac{x}{2}
\end{align*}
\]  \hfill (16.34)

Then, Green’s Theorem give the following formulas for the area of $D$:

$$A(D) = \oint_C x \, dy = -\oint_C y \, dx = \frac{1}{2} \oint_C \left( x \, dy - y \, dx \right)$$  \hfill (16.35)
**Problem 16.53.** Find the area enclosed by \( \frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \), an ellipse.

**Solution.** **Clue:** The ellipse has parametric equations \( x = a \cos t \) and \( y = b \sin t \), \( 0 \leq t \leq 2\pi \). **Hint:** You may use \( \sin^2 x = \frac{1 - \cos 2x}{2} \) or \( \cos^2 x = \frac{1 + \cos 2x}{2} \).

**Ans:** \( ab\pi \)

**Problem 16.54.** Use a formula in (16.35) to find the area of the shaded region in Figure 16.15.

**Solution.** **Hint:** For the slanted edge \( (C_3) : x = t, y = 3 - t, 1 \leq t \leq 3 \).

**Ans:** 14
Problem 16.55. Using the identity (an application of Green’s Theorem)

\[ A(D) = \iint_D dA = \oint_{\partial D} x \, dy, \]

we will try to show that the area of \( D \) (the shaded region) is 6.

- First, observe that the line integrals on vertical and horizontal line segments of the figure are all zero.

- Thus the area must be the same as the line integral on the slant side, the line segment from \( P(4,0) \) to \( Q(2,2) \), which we denote by \( C_2 \).

(a) Evaluate \( \int_{C_2} x \, dy \), where \( C_2 \) is parametrized by

\[ r(t) = (1-t)P + tQ, \quad 0 \leq t \leq 1. \]

(b) Evaluate \( \int_{C_2} x \, dy \), where \( C_2 \) is parametrized by

\[ r(t) = \langle t, 4-t \rangle, \text{ with } t \text{ moving } 4 \searrow 2. \]

(c) Find “the mid value of \( x \)” and “the change in \( y \)”, on \( C_2 \). Multiply the results to see if it is the same as the output in (a) and (b).\(^1\)

Solution.

\(^1\)The method introduces an effective algorithm for the computation of area. See Project 3, p.230.
16.4.2. Generalization of Green’s Theorem

Although Green’s Theorem is proved only for the case where $D$ is simple, we can now extend it to the case where $D$ is either a finite union of simple regions or of holes.

For example: For the right figure above,

$$\iint_D \left( \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) \, dA = \iint_{D_1} \left( \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) \, dA + \iint_{D_2} \left( \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) \, dA$$

$$= \oint_{\partial D_1} P \, dx + Q \, dy + \oint_{\partial D_2} P \, dx + Q \, dy. \quad (16.36)$$

Along the common boundary, the opposite directional line integral will be canceled. Thus

$$\iint_D \left( \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) \, dA = \oint_{\partial D} P \, dx + Q \, dy. \quad (16.37)$$
Theorem 16.56. (Generalized Green’s Theorem). Let $D$ be either a finite union of simply-connected regions or of holes, of which the boundary is finite and oriented. If $F = \langle P, Q \rangle$ has continuous partial derivatives on an open region including $D$, then

$$\oint_{\partial D} P\,dx + Q\,dy = \iint_D \left( \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right)\,dA,$$

(16.38)

where $\partial D$ is the boundary of $D$ positively oriented.

Problem 16.57. Evaluate $\int_C (1 - y^3)\,dx + (x^3 + e^{y^2})\,dy$, where $C$ is the boundary of the region between the circles $x^2 + y^2 = 4$ and $x^2 + y^2 = 9$, having the positive orientation.

Solution.

Ans: $\frac{195\pi}{2}$
**Example 16.58.** Let \( F(x, y) = \langle \frac{-y}{x^2 + y^2}, \frac{x}{x^2 + y^2} \rangle. \) Show that \( \int_C F \cdot dr = 2\pi \) for any positively oriented simple closed curve \( C \) that encloses the origin.

**Warning:** You CANNOT use Green’s Theorem for this problem. Why?

**Solution.** **Clue:** Choose \( C' : x^2 + y^2 = a^2, \) for small \( a. \) Then,

\[
\oint_{\partial D} F \cdot dr = \oint_C F \cdot dr + \oint_{-C'} F \cdot dr = \iint_D \left( \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) dA,
\]

where \( D \) is the region bounded by \( C \) and \(-C'.\) However,

\[
\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} = \frac{y^2 - x^2}{(x^2 + y^2)^2} - \frac{y^2 - x^2}{(x^2 + y^2)^2} = 0.
\]

(16.39)

Thus we have

\[
\oint_C F \cdot dr = \oint_{C'} F \cdot dr
\]

(16.40)

By introducing parametric representation of \( C' : \mathbf{r}(t) = (a \cos t, a \sin t), \ 0 \leq t \leq 2\pi, \) we can conclude

\[
\oint_{C'} F \cdot dr = \int_0^{2\pi} F(\mathbf{r}(t)) \cdot \mathbf{r}'(t) \, dt = \int_0^{2\pi} a^2 \sin^2 t + a^2 \cos^2 t \, dt = 2\pi.
\]

**Problem 16.59.** Let \( F(x, y) = \langle \frac{-y}{x^2 + y^2}, \frac{x}{x^2 + y^2} \rangle, \) the same as in the above example. Show that \( \oint_C F \cdot dr = 0 \) for any simple closed path \( C \) that does not pass through or enclose the origin.

**Now, you CAN use Green’s Theorem. Why?**

**Solution.** **Clue:** See if \( F \) is conservative, i.e., \( Q_x = P_y, \) checking conditions of Theorem 16.41 (p. 175) or Green’s Theorem.
Let’s try to solve another problem before closing the section.

**Problem 16.60.** Evaluate $\int_C y^2 \, dx + 3xy \, dy$, where $C$ is the boundary of the semiannual region $D$ in the upper half-plane between the circles $x^2 + y^2 = 1$ and $x^2 + y^2 = 4$.

**Solution.**

**Summary 16.61.** Green’s Theorem can be summarized as follows.

$$\oint_{\partial D} P \, dx + Q \, dy = \iint_D \left( \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) \, dA \tag{16.41}$$

is applicable when

1. The boundary of $D$ is **finite and oriented**.
2. The vector field $F = \langle P, Q \rangle$ has **continuous partial derivatives** over the whole region $D$. (It is about quality of the vector field.)
16.4. Green’s Theorem

Exercises 16.4

1. Evaluate the line integral \( \int_C y^2 \, dx + 3xy \, dy \), where \( C \) is the triangle with vertices \((0, 0)\), \((2, 0)\), and \((2, 2)\):

   (a) directly
   (b) using Green’s theorem

**Hint:** For (a), you should parametrize each of three line segments. For example: \( C_3 : r(t) = \langle t, t \rangle \), \( t = 2 \searrow 0 \).

**Ans:** 4/3

2. Use Green’s Theorem to evaluate the line integral along the given positively oriented curve.

   (a) \( \int_C (2y + \ln(1 + x^2)) \, dx + (6x + y^2) \, dy \), where \( C \) is the triangle with vertices \((0, 0)\), \((3, 0)\), and \((1, 1)\)

   (b) \( \int_C (x^2 - y^3 + y) \, dx + (x^3 + x - y^2) \, dy \), where \( C \) is the circle \( x^2 + y^2 = 4 \)

**Ans:** (b) \( 24\pi \)

3. Use Green’s Theorem to evaluate \( \int_C F \cdot dr \). (Check the orientation of the curve before applying the theorem.)

   (a) \( F(x, y) = \langle y^3 \cos x, x + 3y^2 \sin x \rangle \), \( C \) is the triangle from \((0, 0)\) to \((8, 0)\) to \((4, 4)\) to \((0, 0)\)

   (b) \( F(x, y) = \langle 5y - 2030x^2 + \sin y, y^2 + x \cos y \rangle \), \( C \) consists of the three line segments: from the origin to \((0, 2)\), then to \((2, 0)\), and then back down to the origin

   (c) \( F(x, y) = \langle y + y^2 - \cos y, x \sin y \rangle \), \( C \) is the circle \( x^2 + y^2 = 4 \) oriented clockwise

**Ans:** (a) 16; (c) \( 4\pi \)

4. Use the identity (an application of Green’s Theorem)

   \[ A(D) = \iint_D \, dA = \int_{\partial D} x \, dy \]

   to show that the area of \( D \) (the shaded region) is 6. You should compute the line integral for each line segment of the boundary, first introducing an appropriate parametrization.
16.5. Curl and Divergence

16.5.1. Curl

We now define the curl of a vector field, which helps us represent rotations of different sorts in physics and such fields. It can be used, for instance, to represent the velocity field in fluid flow.

**Definition 16.62.** Let \( F = \langle P, Q, R \rangle \) be a vector field on \( \mathbb{R}^3 \) and the partial derivatives of \( P, Q, \) and \( R \) all exist. Then the **curl** of \( F \) is the vector field on \( \mathbb{R}^3 \) defined by

\[
\text{curl } F = \begin{pmatrix}
\frac{\partial R}{\partial y} - \frac{\partial Q}{\partial z} \\
\frac{\partial P}{\partial z} - \frac{\partial R}{\partial x} \\
\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y}
\end{pmatrix}.
\]  

(16.42)

**Definition 16.63.** Define the **vector differential operator** \( \nabla \) ("del") as

\[
\nabla = \langle \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \rangle = (\partial_x, \partial_y, \partial_z).
\]

Then

\[
\nabla \times F = \det \begin{bmatrix}
i & j & k \\
\partial_x & \partial_y & \partial_z \\
P & Q & R
\end{bmatrix} = \langle R_y - Q_z, P_z - R_x, Q_x - P_y \rangle = \text{curl } F
\]

(16.43)

So, the easiest way to remember Definition 16.62 is

\[
\text{curl } F = \nabla \times F.
\]  

(16.44)

**Note:** If \( F \) represents the velocity field in fluid flow, then the particles in the fluid tend to rotate about the axis that points in the direction of \( \nabla \times F \); the magnitude \( |\nabla \times F| \) measures how quickly the fluid rotates.

**Question.** Why do **tornado** evolve? What is the **change in the air** after a tornado?

**Answer:** Energy consumption
16.5. Curl and Divergence

**Remark 16.64.** If $F$ is **conservative** and has **continuous partial derivatives**, then

\[ \text{curl } F = 0. \quad (16.45) \]

(See also Problem 16.46 on p.179.)

**Theorem 16.65.** If $f$ is a function of three variables that has continuous second-order partial derivatives, then

\[ \text{curl} (\nabla f) = \nabla \times (\nabla f) = 0. \quad (16.46) \]

**Proof.** Use Clairout’s Theorem.

---

**Problem 16.66.** Show that the vector field $F = \langle xz, xyz, -y^2 \rangle$ is not conservative.

**Solution.** **Clue:** Check if $\text{curl } F \neq 0$. 
Chapter 16. Vector Calculus

**Theorem 16.67.** If $F$ is a vector field whose component functions have continuous partial derivatives on a simply-connected domain and $\text{curl} \ F = 0$, then $F$ is conservative.

**Note:** The above theorem is a 3D version of Theorem 16.41, p. 175.

**Problem 16.68.** Let $F = \langle y^2 z^3, 2xyz^3, 3xy^2 z^2 \rangle$.

(a) Show that $F$ is conservative.

(b) Find $f$ such that $F = \nabla f$.

**Solution.**

$\text{Ans:}$ (a) $\text{curl} \ F = 0$, (b) $f(x, y) = xy^2 z^3 + K$
16.5.2. Divergence

**Definition** 16.69. Let \( F = \langle P, Q, R \rangle \) be a vector field on \( \mathbb{R}^3 \) and its partial derivatives exist. Then the **divergence** of \( F \) is defined as

\[
\text{div} \, F \equiv \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} + \frac{\partial R}{\partial z} = \nabla \cdot F.
\]

**Theorem** 16.70. Let \( F = \langle P, Q, R \rangle \) whose components have continuous second-order partial derivatives. Then

\[
\nabla \cdot (\nabla \times F) = 0. \tag{16.47}
\]

**Note:** The above theorem is analogous to \( a \cdot (a \times b) = 0 \) for all \( a, b \in \mathbb{R}^3 \).

**Problem** 16.71. Show that \( F = \langle xz, xyz, -y^2 \rangle \) cannot be the curl of another vector field.

**Solution.** Clue: Check if \( \nabla \cdot F = 0 \)
Remark 16.72. The reason for the name divergence can be understood in the context of fluid flow. If $F$ is the velocity of a fluid, the div $F$ represents the net change rate of the mass per unit volume. Thus, if $\text{div} F = 0$, then $F$ is said to be incompressible. Another differential operator occurs when we compute the divergence of a gradient vector field $\nabla f$:

$$\text{div}(\nabla f) = \nabla \cdot (\nabla f) = \nabla^2 f = \Delta f.$$ 

The operator $\nabla^2 = \nabla \cdot \nabla = \Delta$ is called the Laplace operator, which is also applicable to vector fields like

$$\Delta F = \Delta\langle P, Q, R \rangle = \langle \Delta P, \Delta Q, \Delta R \rangle.$$ 

16.5.3. Vector forms of Green’s Theorem

**Recall:** Green’s Theorem (p. 182): Let $F = \langle P, Q \rangle$. Then

$$\oint_C F \cdot dr \equiv \oint_C P \, dx + Q \, dy = \iint_D \left( \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) \, dA. \quad (16.48)$$

Now, regard $F$ as a vector field in $\mathbb{R}^3$ with the 3rd component 0. Then

$$\nabla \times F = \text{det} \begin{pmatrix} i & j & k \\ \partial/\partial x & \partial/\partial y & \partial/\partial z \\ P & Q & 0 \end{pmatrix} = \langle 0, 0, Q_x - P_y \rangle.$$ 

So we can rewrite the equation in Green’s Theorem as

$$\oint_C F \cdot dr \equiv \oint_C F \cdot T \, ds = \iint_D (\nabla \times F) \cdot k \, dA, \quad (16.49)$$

which expresses the line integral of the tangential component of $F$ along $C$ as the double integral of the vertical component of $\text{curl} F$ over the region $D$ enclosed by $C$. 
16.5. Curl and Divergence

Line integral of the normal component of $F$

**Example 16.73.** Let $F = \langle P, Q \rangle$. What is $\oint_C F \cdot n \, ds$?

**Solution.** Let $r = \langle x(t), y(t) \rangle$ define the curve $C$. Then

$$T = \frac{r'}{|r'|} = \frac{\langle x', y' \rangle}{|r'|} \quad \text{and} \quad n = \frac{\langle y', -x' \rangle}{|r'|},$$

where $n$ is the **outward unit normal vector**, $90^\circ$ clockwise rotation of $T$. Thus we have

$$F \cdot n \, ds = \langle P, Q \rangle \cdot \frac{\langle y', -x' \rangle}{|r'|} |r'| \, dt$$

$$= (P y' - Q x') \, dt$$

$$= -Q \, dx + P \, dy.$$

![Figure 16.18](image)

It follows from Green’s Theorem that

$$\oint_C F \cdot n \, ds = \iint_D -Q \, dx + P \, dy = \iint_D (P_x - (-Q)_y) \, dA$$

$$= \iint_D (P_x + Q_y) \, dA = \iint_D \nabla \cdot F \, dA.$$  \hspace{1cm} (16.51)

when $P$ and $Q$ have continuous partial derivatives over $D$. □
Exercises 16.5

1. Find (i) the curl and (ii) the divergence of the vector field.

   (a) \( \mathbf{F}(x, y, z) = x^2yz \mathbf{j} + y^2z^2 \mathbf{k} \)
   \[ \nabla \times \mathbf{F} = -y \cos z, \quad \nabla \cdot \mathbf{F} = x \sin y + y \sin z + z \sin x \]

   (b) \( \mathbf{F}(x, y, z) = \langle x \sin y, y \sin z, z \sin x \rangle \)

2. The vector field \( \mathbf{F} \) is shown in the \( xy \)-plane and looks the same in all other horizontal planes. (That is, \( \mathbf{F} \) is independent of \( z \) and its third component is 0.)

   (a) Is \( \text{div} \mathbf{F} \) positive, negative, or zero? Explain.
   (b) Determine whether \( \text{curl} \mathbf{F} = 0 \). If not, in which direction does it point?
   (c) Use Theorem 16.67 to conclude if \( \mathbf{F} \) is conservative.

   **Hint:** The vector field in (I): You may express it as \( \mathbf{F} = \langle P(x), 0, 0 \rangle \), where \( P \) is a decreasing function of \( x \) only. Thus \( \text{div} \mathbf{F} < 0 \). The vector field in (II): Let \( \mathbf{F} = \langle P(x, y), Q(x, y), 0 \rangle \). Then \( \text{div} \mathbf{F} = P_x + Q_y \) and \( \text{curl} \mathbf{F} = \langle 0, 0, Q_x - P_y \rangle \). For example, \( P_y < 0 \) in (II), because the horizontal components of the arrows (\( P \)) become smaller as \( y \) increases. What can you say about \( P_x, Q_y, \) and \( Q_x \)?

   (I) \( \quad \) (II)

   ![Figure 16.19](image)

3. Determine whether or not \( \mathbf{F} \) is conservative. If it is conservative, find its potential.

   (a) \( \mathbf{F} = \langle yz^4, xz^4 + 2y, 4xyz^3 \rangle \)
   \[ \text{Ans: (b)} \quad f = y + x \sin z + K \]

   (b) \( \mathbf{F} = \langle \sin z, 1, x \cos z \rangle \)
16.6. Parametric Surfaces and Their Areas

16.6.1. Parametric surfaces

**Goal:** This section will aim to describe surfaces by a function \( r(u, v) = \langle x(u, v), y(u, v), z(u, v) \rangle \), in a similar fashion that we described vector functions by \( r(t) \) earlier.

**Definition 16.74.** A **parametric surface** is the set of points \( \{(x, y, z)\} \) in \( \mathbb{R}^3 \) such that the components are expressed by a vector function of the form

\[
r(u, v) = \langle x(u, v), y(u, v), z(u, v) \rangle, \quad (u, v) \in D \subset \mathbb{R}^2.
\]

---

Figure 16.20: Examples of parametric surfaces.

---

Maple Script

```maple
with(plots): with(plottools):
plot3d([(4+2*cos(p))*cos(t), (4+2*cos(p))*sin(t), 2*sin(p)], p = 0..2*Pi, t = 0..2*Pi,
axes = none, lightmodel = light1, scaling = constrained, orientation = [30,55]);

r := z/2+sin(z):
plot3d([r, t, z], t = 0..2*Pi, z =0..10, coords = cylindrical,
axes = none, lightmodel = light1, scaling = constrained, orientation = [30,55]);
```
Problem 16.75. Identify and sketch \( \mathbf{r}(u, v) = \langle 2 \cos u, v, 2 \sin u \rangle \), when \((u, v) \in D \equiv [0, 2\pi] \times [0, 5]\).

Solution. Clue: \(x^2 + z^2 = 4\).

Self-study 16.76. Sketch \( \mathbf{r}(s, t) = \langle s \cos 3t, s \sin 3t, s^2 \rangle \), when \((s, t) \in [0, 2] \times [0, 2\pi]\). Discuss what the effect of the “3” is.
Question. Given a surface, what is a parametric representation of it?

Problem 16.77. Find a parametric representation of the plane which passes $P_0(1, 1, 1)$ and contains $a = \langle 1, 2, 0 \rangle$ and $b = \langle 2, 0, -3 \rangle$.

Solution. Clue: $r(u, v) = P_0 + u a + v b$.

Problem 16.78. Find a parametric representation of $x^2 + y^2 + z^2 = a^2$.

Solution. Clue: Use the spherical coordinates; the parameters are $(\theta, \phi)$.

Ans: $r(\theta, \phi) = \langle a \sin \phi \cos \theta, a \sin \phi \sin \theta, a \cos \phi \rangle$, $D$?
**Problem 16.79.** Find a parametric representation of the cylinder $x^2 + y^2 = 4$, $0 \leq z \leq 1$.

**Solution.** *Hint:* Use cylindrical coordinates $(r, \theta, z)$.

**Problem 16.80.** Find a vector representation of the elliptic paraboloid $z = x^2 + 2y^2$.

**Solution.** *Hint:* Let $x, y$ be parameters.

*Ans:* $\mathbf{r}(x, y) = \langle x, y, x^2 + 2y^2 \rangle$
16.6. Parametric Surfaces and Their Areas

In general, for \( z = f(x, y) \),

\[
\mathbf{r}(x, y) = \langle x, y, f(x, y) \rangle
\]  

(16.52)

is considered as a parametric representation of the surface.

**Note:** Parametric representations are not unique.

**Problem 16.81.** Find a parametric representation of \( z = 2\sqrt{x^2 + y^2} \).

**Clue:** A representation is as in (16.52), while another one can be formulated using \((r, \theta)\) as with polar coordinates. Also, recall that when polar coordinates are considered, \( x = r \cos \theta, y = r \sin \theta \).

**Solution.** ①

![Figure 16.22](image)

Figure 16.22

②
Surfaces of Revolution

Let $S$ be the surface obtained by rotating

$$y = f(x), \quad a \leq x \leq b,$$

about the $x$-axis (where $f(x) \geq 0$). Then, $S$ can be represented as

$$\mathbf{r}(x, \theta) = \langle x, f(x) \cos \theta, f(x) \sin \theta \rangle,$$

$$(x, \theta) \in [a, b] \times [0, 2\pi]. \quad (16.53)$$

**Problem 16.82.** Find parametric equations for the surface generated by rotating the curve $y = \sin(x)$, $0 \leq x \leq 2\pi$, about the $x$-axis.

**Solution.**
16.6.2. Tangent planes

Recall: The plane passing \( x_0 = (x_0, y_0, z_0) \) and having a normal vector \( \mathbf{v} = \langle a, b, c \rangle \) can be formulated as

\[
\mathbf{v} \cdot (\mathbf{x} - \mathbf{x}_0) = 0,
\]
or equivalently

\[
a(x-x_0) + b(y-y_0) + c(z-z_0) = 0. \tag{16.54}
\]

Now, we will find the tangent plane to a parametric surface \( S \) traced out by

\[
\mathbf{r}(u,v) = \langle x(u,v), y(u,v), z(u,v) \rangle
\]
at a point \( P_0 \) with position vector \( \mathbf{r}(u_0, v_0) \).

What we need: a normal vector, which can be determined by

\[
\mathbf{r}_u \times \mathbf{r}_v.
\]

Definition 16.83.

1. A surface \( S \) represented by \( \mathbf{r} \) is smooth if \( \mathbf{r}_u \times \mathbf{r}_v \neq 0 \) over the whole domain.

2. A tangent plane is the plane containing \( \mathbf{r}_u \) and \( \mathbf{r}_v \) and having a normal vector \( \mathbf{r}_u \times \mathbf{r}_v \).
Problem 16.84. Find the tangent plane to

\[ S : x = u^2, \ y = v^2, \ z = u + 2v; \quad \text{at} \ (1, 1, 3) \]

Solution.

\[ \text{Ans: } -2(x - 1) - 4(y - 1) + 4(z - 3) = 0 \]
16.6.3. Surface area

Let \( \mathbf{r} : D \subset \mathbb{R}^2 \rightarrow S \subset \mathbb{R}^3 \). Then the surface area of \( S \) is

\[
A(S) = \iint_S dS. \tag{16.55}
\]

Figure 16.25: \( \mathbf{r} : R_{ij} \mapsto S_{ij} \).

Figure 16.26: Approximating a patch by a parallelogram.

The area of the patch \( S_{ij} \) can be approximated by

\[
\Delta S_{ij} \approx A(\text{parallelogram}) = |(\Delta u \mathbf{r}_u) \times (\Delta v \mathbf{r}_v)| = |\mathbf{r}_u \times \mathbf{r}_v| \Delta u \Delta v \tag{16.56}
\]
**Definition** 16.85. If a smooth surface $S$ is represented by

$$\mathbf{r}(u,v) = \langle x(u,v), y(u,v), z(u,v) \rangle, \quad (u,v) \in D,$$

and $S$ is covered just once as $(u,v)$ ranges throughout the parameter domain $D$, then the **surface area** of $S$ is

$$A(S) = \iint_S dS = \iint_D |\mathbf{r}_u \times \mathbf{r}_v| \, dA. \quad (16.57)$$

That is, $dS = |\mathbf{r}_u \times \mathbf{r}_v| \, dA$.

**Problem** 16.86. Find the area of the surface given by parametric equations $x = u^2$, $y = uv$, $z = \frac{1}{2}v^2$, $0 \leq u \leq 1$, $0 \leq v \leq 1$.

**Solution.**

\[ \text{Ans: 1} \]
### 16.6. Parametric Surfaces and Their Areas

**Change of Variables vs.** \[ \Delta S \approx |r_u \times r_v| \Delta u \Delta v \]

**Recall:** (Summary 15.69 in § 15.9, p. 134). For a differentiable transformation \( T : Q \subset \mathbb{R}^2 \to R \subset \mathbb{R}^2 \) given by \( r(u, v) = (x(u, v), y(u, v)) \),

\[
\Delta A \approx \left| \frac{\partial(x, y)}{\partial(u, v)} \right| \Delta u \Delta v, \quad (16.58)
\]

where \( \frac{\partial(x, y)}{\partial(u, v)} \) is the **Jacobian** of \( T \) defined as

\[
\frac{\partial(x, y)}{\partial(u, v)} = \det \begin{bmatrix} x_u & x_v \\ y_u & y_v \end{bmatrix} = x_u y_v - x_v y_u. \quad (16.59)
\]

Now, consider \( R \) as a flat region embedded in \( \mathbb{R}^3 \). Define

\[
\tilde{R} = R \times \{0\} \subset \mathbb{R}^3.
\]

Then, \( \tilde{T} : Q \to \tilde{R} \) is represented by \( \tilde{r}(u, v) = (x(u, v), y(u, v), 0) \);

\[
\tilde{r}_u \times \tilde{r}_v = \det \begin{pmatrix} i & j & k \\ x_u & y_u & 0 \\ x_v & y_v & 0 \end{pmatrix} = (0, 0, x_u y_v - x_v y_u). \quad (16.60)
\]

Therefore

\[
|\tilde{r}_u \times \tilde{r}_v| = \left| \frac{\partial(x, y)}{\partial(u, v)} \right|. \quad (16.61)
\]

Eqn. (16.58) is a special case of

\[
\Delta S \approx |r_u \times r_v| \Delta u \Delta v.
\]

**Summary 16.87.** Let \( r : D \subset \mathbb{R}^2 \to S \subset \mathbb{R}^3 \) be a **parametric representation** of the surface \( S \). Then

1. The map \( r \) can be viewed as a **change of variables**.
2. The quantity \( |r_u \times r_v| \) is simply the **scaling factor** for \( r \).
Surface Area of the Graph of a Function

As a special case, consider the surface \( S \) made by the graph of

\[
z = g(x, y), \ (x, y) \in D.
\]

Then the surface \( S \) can be represented by

\[
r(x, y) = \langle x, y, g(x, y) \rangle.
\]

Since

\[
r_x = \langle 1, 0, g_x \rangle \quad \text{and} \quad r_y = \langle 0, 1, g_y \rangle,
\]

we obtain

\[
r_x \times r_y = \det \begin{pmatrix} i & j & k \\ 1 & 0 & g_x \\ 0 & 1 & g_y \end{pmatrix} = \langle -g_x, -g_y, 1 \rangle \tag{16.62}
\]

Thus we conclude the following.

Let \( S \) be made by the graph of \( z = g(x, y), \ (x, y) \in D \). Then the surface area of \( S \) is

\[
A(S) = \iint_D \sqrt{g_x^2 + g_y^2 + 1} \, dA. \tag{16.63}
\]

**Problem 16.88.** Find the area of the part of paraboloid \( z = x^2 + y^2 \) that lies under the plane \( z = 9 \).

**Solution.** (See Problem 15.41 on p. 114.)

\[
\text{Ans: } \frac{\pi}{6} (37\sqrt{37} - 1)
\]
Exercises 16.6

1. Identify the surface with the vector equation.

(a) \( \mathbf{r}(u,v) = \langle u - 3, u + v, 4u + 3v - 2 \rangle \)

(b) \( \mathbf{r}(s,t) = \langle 2 \cos t, s, 2 \sin t \rangle, \ 0 \leq t \leq \pi \)

2. Match the parametric equations with the graphs labeled (I)–(III) and give reasons for your choices. Determine which families of grid curves on the surface have \( u \) constant and which have \( v \) constant.

(a) \( \mathbf{r}(u) = \langle u \cos v, u \sin v, v \rangle \)

(b) \( \mathbf{r}(u,v) = \langle v, 2 \cos u, 2 \sin u \rangle \)

(c) \( \mathbf{r}(u,v) = \langle v \sin u, v \cos u, \cos v \sin v \rangle \)

![Figure 16.27](image)

3. Find the parametric representation for the surface.

(a) The part of the sphere \( x^2 + y^2 + z^2 = 4 \) that lies above the plane \( z = 1 \).

(b) The part of the plane \( y + z = 1 \) that lies inside the cylinder \( x^2 + z^2 = 1 \). (See Figure 16.28.)

**Hint**: For (a), use the spherical coordinates (with \( \rho = 2 \)) to specify the values of \( \phi \) appropriately. Of course, \( 0 \leq \theta \leq 2\pi \). For (b), use the polar coordinates for the region in the \( xz \)-plane; that is, \( x = r \cos \theta, \ z = r \sin \theta \). Then, you may set \( y = 1 - z \). You have to specify the domain, values of \( r \) and \( \theta \), appropriately.

![Figure 16.28](image)
4. Find an equation of the tangent plane to the given surface at the specific point.

(a) \( \mathbf{r}(x, y) = \langle x, y, x^2 - y^2 \rangle, \quad (2, 1, 3) \)

(b) \( \mathbf{r}(u, v) = \langle u \cos v, u \sin v, v \rangle, \quad (u, v) = (1, \pi/2) \)

\( \text{Ans: (b)} \mathbf{r}_u \times \mathbf{r}_v(1, \pi/2) = \langle 1, 0, 1 \rangle \Rightarrow 1 \cdot (x - 0) + 0 \cdot (y - 1) + 1 \cdot (z - \pi/2) = x + z - \pi/2 = 0 \)

5. Find the area of the surface.

(a) The part of the paraboloid \( y = x^2 + z^2 \) cut off by the plane \( y = 6 \)

(b) The surface parametrized by \( \mathbf{r}(u, v) = \langle u^2, uv, \frac{v^2}{2} \rangle \), defined on \( \{(u, v) \mid u^2 + v^2 \leq 1\} \)

\( \text{Ans: (a)} \frac{62\pi}{3}; \text{(b)} 3\pi/4 \)
16.7. Surface Integrals

This section deals with surface integrals of the form
\[ \int_S f(x, y, z) \, dS \quad \text{or} \quad \int_S F \cdot dS \]

16.7.1. Surface integrals of scalar functions

Suppose that the surface \( S \) has a parametric representation
\[ \mathbf{r}(u, v) = \langle x(u, v), y(u, v), z(u, v) \rangle, \quad (u, v) \in D. \]

Then, from the previous section, we have
\[ dS = |\mathbf{r}_u \times \mathbf{r}_v| \, dA \]

Thus we can reach at the formula
\[ \int_S f(x, y, z) \, dS = \iint_D f(\mathbf{r}(u, v))|\mathbf{r}_u \times \mathbf{r}_v| \, dA. \quad (16.64) \]

**Remark 16.89.**
- **When** \( z = g(x, y) \), \( r_x \times r_y = \langle -g_x, -g_y, 1 \rangle \). **Thus the formula (16.64) reads**
\[ \int_S f(x, y, z) \, dS = \iint_D f(x, y, g(x, y))\sqrt{g_x^2 + g_y^2 + 1} \, dA. \quad (16.65) \]
- **Similarity:** For line integrals, \( \int_C f(x, y, z) \, ds = \int_a^b f(\mathbf{r}(t)) |\mathbf{r}'(t)| \, dt. \)
**Problem 16.90.** Compute the surface integral \( \iint_S xy \, dS \), where \( S \) is the triangular region with vertices \((1, 0, 0)\), \((0, 2, 0)\), and \((0, 0, 2)\).

**Solution.** Clue: The surface \( S \) (triangular region) can be expressed by \( \frac{x}{1} + \frac{y}{2} + \frac{z}{2} = 1 \). Thus \( z = 2 - 2x - y \). Now, what is \( D \)?

\( \text{Ans: } \frac{1}{\sqrt{6}} \)
Problem 16.91. Evaluate $\int \int_S z \, dS$, where $S$ is the surface whose side $S_1$ is given by the cylinder $x^2 + y^2 = 1$, whose bottom $S_2$ is the disk $x^2 + y^2 \leq 1$ in the plane $z = 0$, and whose top $S_3$ is the disk $x^2 + y^2 \leq 1$ in the plane $z = 1$.

Solution. Clue: $S_1: x = \cos \theta, y = \sin \theta, z = z; (\theta, z) \in D \equiv [0, 2\pi] \times [0, 1]$. Then $|r_\theta \times r_z| = 1$.

Ans: $\pi + 0 + \pi = 2\pi$
16.7.2. Surface integrals of vector fields

Oriented Surfaces

![Figure 16.29: Oriented surface and Möbius strip.](image)

**Definition 16.92.** Let the surface $S$ have a vector representation $\mathbf{r}$.

- A unit normal vector $\mathbf{n}$ is defined as
  $$\mathbf{n} = \frac{\mathbf{r}_u \times \mathbf{r}_v}{|\mathbf{r}_u \times \mathbf{r}_v|}. \quad (16.66)$$

- The surface $S$ is called an **oriented surface** if the (chosen) unit normal vector $\mathbf{n}$ **varies continuously** over $S$.
  (A counter example: Möbius strip.)

- For closed surfaces, the **positive orientation** is the one outward.

Is it confusing? Then, consider this:

**Definition 16.93.** A surface $S$ is called **orientable** if it has **two separate sides**.
A Historic View, for Surface Integrals of Vector Fields

Suppose that $S$ is an oriented surface. Imagine we have a fluid flowing through $S$, such that $v(x)$ determines the velocity of the fluid at $x$. The flux is defined as the quantity of fluid flowing through $S$ per unit time.

The illustration implies that if the vector field is tangent to $S$ at each point, then the flux is zero because the fluid just flows in parallel to $S$, and neither in nor out. Thus, if $v$ has both a tangential and a normal component, then only the normal component contributes to the flux. Based on this reasoning, to find the flux, we need to take the dot product of $v$ with the unit surface normal $n$ to $S$, which will give us a scalar field to be integrated over $S$ appropriately.

**Definition 16.94.** Let $F$ be a continuous vector field defined on an oriented surface $S$ with unit normal vector $n$. The **surface integral of $F$ over $S$** is

$$\iint_S F \cdot dS \overset{\text{def}}{=} \iint_S F \cdot n \, dS.$$  

(16.67)

This integral is also called the **flux of $F$ across $S$**.

For the computation of the flux, the right side of (16.67), you may utilize

$$n = \frac{r_u \times r_v}{|r_u \times r_v|} \quad \text{and} \quad dS = |r_u \times r_v| \, dA,$$

(16.68)

when $S$ is parametrized by $r : D \rightarrow S$. 

Surface Integrals of Vector Fields. Let \( \mathbf{r} \) be a parametric representation of \( S \), from \( D \subset \mathbb{R}^2 \). The flux across the surface \( S \) can be measured by

\[
\iint_S \mathbf{F} \cdot d\mathbf{S} \overset{\text{def}}{=} \iint_S \mathbf{F} \cdot \mathbf{n} \, dS \\
= \iint_D \mathbf{F}(\mathbf{r}) \cdot \left( \frac{\mathbf{r}_u \times \mathbf{r}_v}{|\mathbf{r}_u \times \mathbf{r}_v|} \right) |\mathbf{r}_u \times \mathbf{r}_v| \, dA \\
= \iint_D \mathbf{F}(\mathbf{r}) \cdot (\mathbf{r}_u \times \mathbf{r}_v) \, dA. \tag{16.69}
\]

Note that \( \mathbf{F} \cdot \mathbf{n} \) and \( \mathbf{F}(\mathbf{r}) \cdot (\mathbf{r}_u \times \mathbf{r}_v) \) are scalar functions.

Remark 16.95. Line integrals of vector fields is defined to measure quantities along the curve. That is,

\[
\int_C \mathbf{F} \cdot d\mathbf{r} \overset{\text{def}}{=} \int_C \mathbf{F} \cdot \mathbf{T} \, ds \\
= \int_a^b \mathbf{F}(\mathbf{r}(t)) \cdot \frac{\mathbf{r}'(t)}{|\mathbf{r}'(t)|} |\mathbf{r}'(t)| \, dt = \int_a^b \mathbf{F}(\mathbf{r}(t)) \cdot \mathbf{r}'(t) \, dt, \tag{16.70}
\]

where \( C \) is parametrized by \( \mathbf{r} : [a, b] \rightarrow C \).

Problem 16.96. Find the flux of \( \mathbf{F} = \langle x, y, 1 \rangle \) across a upward helicoid: \( \mathbf{r}(u, v) = \langle u \cos v, u \sin v, v \rangle \), \( 0 \leq u \leq 2 \), \( 0 \leq v \leq \pi \).

Solution. Hint: \( \mathbf{r}_u \times \mathbf{r}_v = \langle \sin v, -\cos v, u \rangle \).

\[\text{Ans: } 2\pi\]
Example 16.97. Find the flux of \( F = \langle z, y, x \rangle \) across the unit sphere \( x^2 + y^2 + z^2 = 1 \).

Solution. First, consider a vector representation of the surface:

\[
r(\phi, \theta) = \langle \sin \phi \cos \theta, \sin \phi \sin \theta, \cos \phi \rangle, \quad 0 \leq \phi \leq \pi, \quad 0 \leq \theta \leq 2\pi.
\]

Then,

\[
F(r) = \langle \cos \phi, \sin \phi \sin \theta, \sin \phi \cos \theta \rangle,
\]

\[
r_\phi \times r_\theta = \langle \sin^2 \phi \cos \theta, \sin^2 \phi \sin \theta, \sin \phi \cos \theta \rangle,
\]

from which we have

\[
F(r) \cdot (r_\phi \times r_\theta) = 2 \sin^2 \phi \cos \phi \cos \theta + \sin^3 \phi \sin^2 \theta.
\]

Thus

\[
\text{Flux} = \iint_S F \cdot dS = \iiint_D F(r) \cdot (r_\phi \times r_\theta) \, dA
\]

\[
= \int_0^{2\pi} \int_0^\pi (2 \sin^2 \phi \cos \phi \cos \theta + \sin^3 \phi \sin^2 \theta) \, d\phi \, d\theta
\]

\[
= \int_0^{2\pi} \int_0^\pi (\sin^3 \phi \sin^2 \theta) \, d\phi \, d\theta
\]

\[
= \int_0^{2\pi} \sin^2 \theta \, d\theta \int_0^\pi \sin^3 \phi \, d\phi = \pi \cdot \frac{4}{3}.
\]

Note: The answer of the previous example is actually the volume of the unit sphere. In Section 16.9, we will study the so-called Divergence Theorem (formulated for closed surfaces)

\[
\iint_{\partial E} F \cdot dS = \iiint_E \nabla \cdot F \, dV
\]

The above example can be solved easily using the Divergence Theorem; see Problem 16.105, p. 227.
Surfaces defined by $z = g(x, y)$:

- A vector representation: $\mathbf{r}(x, y) = \langle x, y, g(x, y) \rangle$.
- Normal vector: $\mathbf{r}_x \times \mathbf{r}_y = \langle -g_x, -g_y, 1 \rangle$.
- Thus, when $\mathbf{F} = \langle P, Q, R \rangle$,

\[
\iint_S \mathbf{F} \cdot d\mathbf{S} = \iint_D \mathbf{F} \cdot (\mathbf{r}_x \times \mathbf{r}_y) \, dA = \iint_D (-P \, g_x - Q \, g_y + R) \, dA. \tag{16.71}
\]

**Problem 16.98.** Evaluate $\iint_S \mathbf{F} \cdot d\mathbf{S}$, where $\mathbf{F} = \langle y, x, z \rangle$ and $S$ is the boundary of the solid region $E$ enclosed by the paraboloid $z = 1 - x^2 - y^2$ and the plane $z = 0$.

**Solution.** Hint: For $S_1$ (the upper part), use the formula in (16.71). For $S_2$ (the bottom: $z = 0$), you may try to get $\mathbf{F} \cdot \mathbf{n}$, where $\mathbf{n} = -\mathbf{k}$.

\[\text{Ans: } \frac{\pi}{2} + 0 = \frac{\pi}{2}\]
16.7. Surface Integrals

**Formula 16.99.** Let \( \mathbf{F} = \langle P, Q, R \rangle \).

- \( \iiint_S f(x, y, z) \, dS = \iint_D f(r(u, v))|r_u \times r_v| \, dA \)
- \( \iiint_S f(x, y, z) \, dS = \iint_D f(x, y, g(x, y))\sqrt{g_x^2 + g_y^2 + 1} \, dA \), when \( S \) is given by \( z = g(x, y) \)
- \( \iiint_S \mathbf{F} \cdot dS = \iint_S \mathbf{F} \cdot \mathbf{n} \, dS = \iint_D \mathbf{F} \cdot (r_u \times r_v) \, dA \)
- \( \iiint_S \mathbf{F} \cdot dS = \iint_D (-Pg_x - Qg_y + R) \, dA \), when \( S \) is given by \( z = g(x, y) \)

**Note:** When \( S \) is given by \( z = g(x, y) \), \( r_x \times r_y = \langle -g_x, -g_y, 1 \rangle \)

**Exercises 16.7**

1. Evaluate the surface integral \( \iiint_S f(x, y, z) \, dS \).
   - (a) \( f(x, y, z) = x \), \( S \) is the helicoid given by the vector equation \( \mathbf{r}(u, v) = \langle u \cos v, u \sin v, v \rangle \), \( 0 \leq u \leq 1, \ 0 \leq v \leq \pi/2 \) \( \text{(Hint: } \mathbf{r}_u \times \mathbf{r}_v = \langle \sin v, -\cos v, u \rangle) \) \( \text{Ans: (a) } (2\sqrt{2} - 1)/3; \text{ (b) } \pi/2 \)
   - (b) \( f(x, y, z) = (x^2 + y^2)z \), \( S \) is the hemisphere \( x^2 + y^2 + z^2 = 1, z \geq 0 \)

2. Evaluate the surface integral \( \iiint_S \mathbf{F} \cdot dS \).
   - (a) \( \mathbf{F}(x, y, z) = xi + yj + 2zk \), \( S \) is the part of the paraboloid \( z = x^2 + y^2 \), \( z \leq 1 \)
   - (b) \( \mathbf{F}(x, y, z) = \langle z, x - z, y \rangle \), \( S \) is the triangle with vertices \((1, 0, 0), (0, 1, 0), \text{ and } (0, 0, 1)\), oriented downward
   - (c) \( \mathbf{F} = \langle y, -x, z \rangle \), \( S \) is the upward helicoid parametrized by \( \mathbf{r}(u, v) = \langle u \cos v, u \sin v, v \rangle \), \( 0 \leq u \leq 2, \ 0 \leq v \leq \pi \) \( \text{(Hint: } \mathbf{r}_u \times \mathbf{r}_v = \langle \sin v, -\cos v, u \rangle) \) \( \text{Ans: (a) } 0; \text{ (b) } -1/3; \text{ (c) } 2\pi + \pi^2 \)

3. **CAS** Use a CAS to find the integral, either \( \iint_S f(x, y, z) \, dS \) or \( \iint_S \mathbf{F} \cdot dS \). First try to find the exact value; if the CAS does not work properly for the exact value, then try to estimate the integral correct four decimal places.
   - (a) \( f(x, y, z) = 2x^2 + 2y^2 + z^2 \), \( S \) is the surface \( z = x \cos y \), \( 0 \leq x \leq 1, \ 0 \leq y \leq 1 \)
   - (b) \( \mathbf{F}(x, y, z) = \langle x^2 + y^2, y^2 + z^2, x^2 \rangle \), \( S \) is the part of the cylinder \( x^2 + z^2 = 1 \) that lies above the \( xy \)-plane and between the planes \( y = 0 \) and \( y = 1 \), with upward orientation \( \text{Hint: } \text{You may use } \mathbf{r}(\theta, y) = \langle \cos \theta, y, \sin \theta \rangle, \text{ for a representation of } S \).
   \( \text{Ans: (b) } 2/3 \)
16.8. Stokes’s Theorem

Stokes’ Theorem is a high-dimensional version of Green’s Theorem studied in § 16.4.

**Recall** (Green’s Theorem, p. 182). Let $C$ be positively oriented, piecewise-smooth, simple closed curve in the plane and $D$ be the region bounded by $C$. If $F = \langle P, Q \rangle$ have continuous partial derivatives on an open region including $D$, then

$$\int_C F \cdot dr \overset{\text{def}}{=} \int_C P \, dx + Q \, dy = \iiint_D \left( \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) \, dA = \iint_D (\text{curl} \, F) \cdot k \, dA.$$  

(16.72)

(For the last equality, see (16.49) on p. 196.)

**Theorem** 16.100. (Stokes’s Theorem) Let $S$ be an oriented piecewise-smooth surface that is bounded by a simple, closed, piecewise-smooth curve $C$ with positive orientation. Let $F = \langle P, Q, R \rangle$ be a vector field whose components have continuous partial derivatives on an open region in $\mathbb{R}^3$ that contains $S$. Then

$$\int_C F \cdot dr = \iint_S (\text{curl} \, F) \cdot dS.$$  

(16.73)

**Remark** 16.101.

- See Figure 16.29(left) on p. 216, for an oriented surface of which the boundary has positive orientation.

- **Computation** of the surface integral: for $r : D \rightarrow S$,

$$\iint_S (\text{curl} \, F) \cdot dS \overset{\text{def}}{=} \iint_S (\text{curl} \, F) \cdot n \, dS = \iint_D (\text{curl} \, F) \cdot (r_u \times r_v) \, dA.$$  

(16.74)

- Green’s Theorem is a special case in which $S$ is flat and lies on the $xy$-plane ($n = k$). Compare the last terms in (16.72) and (16.74).
Problem 16.102. Evaluate $\int_C \mathbf{F} \cdot d\mathbf{r}$, where $\mathbf{F} = \langle -y^2, x, z^2 \rangle$ and $C$ is the curve of intersection of the plane $y + z = 2$ and the cylinder $x^2 + y^2 = 1$.

Solution. Clue: You may start with the computation of $\nabla \times \mathbf{F}$ and consider a vector representation for $S$: $z = g(x, y) = 2 - y$. Then use the formula (16.74).

Ans: $\pi$
**Problem 16.103.** Use Stokes’s Theorem to compute the surface integral \( \iint_S (\nabla \times \mathbf{F}) \cdot dS \), where \( \mathbf{F} = \langle xz, yz, xy \rangle \) and \( S \) is the part of sphere \( x^2 + y^2 + z^2 = 4 \) that lies inside the cylinder \( x^2 + y^2 = 1 \) and above the \( xy \)-plane.

**Solution.** Hint: \( \iint_S (\nabla \times \mathbf{F}) \cdot dS = \oint_C \mathbf{F} \cdot d\mathbf{r} = \int_a^b \mathbf{F} \cdot \mathbf{r}'(t) \, dt. \) A vector representation of \( C \) is \( \mathbf{r}(t) = \langle \cos t, \sin t, \sqrt{3} \rangle, \ 0 \leq t \leq 2\pi. \)

Ans: 0
Exercises 16.8

1. A hemisphere \( H \) and a part \( P \) of a paraboloid are shown in the figure below. Let \( F \) be a vector field on \( \mathbb{R}^3 \) whose components have continuous partial derivatives. Which of the following is true? Give reasons for your choice.

   A. \( \int_H (\text{curl } F) \cdot dS < \int_P (\text{curl } F) \cdot dS \)
   
   B. \( \int_H (\text{curl } F) \cdot dS = \int_P (\text{curl } F) \cdot dS \)
   
   C. \( \int_H (\text{curl } F) \cdot dS > \int_P (\text{curl } F) \cdot dS \)
   
   D. cannot compare

2. Use Stokes’s Theorem to evaluate \( \iint_S \text{curl } F \cdot dS \), where \( F(x,y) = < -y, x, x^2 + y^2 > \) and \( S \) is the part of the sphere \( x^2 + y^2 + z^2 = 8 \) that lies inside the cone \( z = \sqrt{x^2 + y^2} \), oriented upward. (Clue: The boundary of \( S \) can be parametrized as \( r(t) = (2 \cos t, 2 \sin t, 2), 0 \leq t \leq 2\pi. \))

   \( \text{Hint:} \) Use the formula given in the hint of Problem 16.103.

   \( \text{Ans:} \) 16\( \pi \)

3. Use Stokes’s Theorem to evaluate \( \int_C F \cdot dr \). For each case, let \( C \) be oriented counterclockwise when viewed from above.

   (a) \( F(x,y,z) = < z^2 + x, x^2 + y, y^2 + z > \), \( C \) is the triangle with vertices \( (1,0,0), (0,1,0), \) and \( (0,0,1) \)

   (b) \( F(x,y,z) = < x, y, z - x > \), \( C \) is the curve of intersection of the plane \( 2y + z = 2 \) and the cylinder \( x^2 + y^2 = 1 \)

   \( \text{Hint:} \) \( \int_C F \cdot dr = \iint_S \text{curl } F \cdot dS = \oint_D \text{curl } F \cdot (r_x \times r_y) dS \).

   (a) \text{curl } F = \langle 2y, 2z, 2x \rangle \) and \( r_x \times r_y = \langle 1, 1, 1 \rangle \). Figure out yourself what \( S, D, \) and \( r \) are.

   \( \text{Ans:} \) (a) 1; (b) 2\( \pi \)
16.9. The Divergence Theorem

Recall: Let $F = \langle P, Q \rangle$. In §16.5.3, we considered vector forms of Green’s Theorem including

\[ \oint_C F \cdot n \, ds = \iint_D \nabla \cdot F \, dA. \]  \tag{16.75}

(See (16.51), p. 197.)

The Divergence Theorem is a generalization of the above.

**Theorem 16.104. (Divergence Theorem)** Let $E$ be a simple solid region and $S$ be the boundary surface of $E$, given with positive (outward) orientation. Let $F = \langle P, Q, R \rangle$ have continuous partial derivatives on an open region that contains $E$. Then

\[ \iiint_S F \cdot dS = \iiint_E \nabla \cdot F \, dV. \]  \tag{16.76}

**Note:** Let a surface $S$ is parametrized by $r$. Then, from §16.7.2 (p. 216), we know

\[ \iiint_S F \cdot dS \overset{\text{def}}{=} \iint_S F \cdot n \, dS = \iint_D F \cdot (r_u \times r_v) \, dA, \]  \tag{16.77}

whether or not $S$ is closed. □

**Note:** The Divergence Theorem is developed mainly for closed surfaces; however, it can be applied for **unclosed surfaces** as in Review Problem R.16.10, p. 235.
Problem 16.105. (Revisit of Example 16.97, p. 219) Find the flux of 
\( F = (z, y, x) \) over the unit sphere \( x^2 + y^2 + z^2 = 1 \).

Solution.

\[ \text{Ans: } \frac{4}{3} \pi, \text{ the volume of the unit sphere} \]

Problem 16.106. Find the flux of \( F \) across \( S \), where

\[ F(x, y, z) = (\cos z + xy^2) \mathbf{i} + xe^{-z} \mathbf{j} + (\sin y + x^2z) \mathbf{k} \]

and \( S \) is the surface of the solid bounded by the paraboloid \( z = x^2 + y^2 \) and the plane \( z = 4 \).

Solution.

\[ \text{Ans: } \frac{32}{3} \pi \]
Problem 16.107. Use the Divergence Theorem to evaluate
\[ \iiint_S (x^2 + 2y^2 + z^2) \, dS, \] where \( S \) is the unit sphere \( x^2 + y^2 + z^2 = 1 \).

Solution. Hint: Find \( n \) and express the integrand as \( F \cdot n \); then try to use the Divergence Theorem.

Problem 16.108. Assume that \( S \) and \( E \) satisfy the conditions of the Divergence Theorem and functions have all required continuous partial derivatives, first or second-order. Prove the following.

1. \( \iiint_S a \cdot n \, dS = 0 \), where \( a \) is a constant vector.

2. \( V(\mathcal{E}) = \frac{1}{3} \iiint_S F \cdot dS \), where \( F(x, y, z) = \langle x, y, z \rangle \).

3. \( \iiint_S \text{curl} \, F \cdot dS = 0 \).
Exercises 16.9

1. Verify the Divergence Theorem is true for the vector field $F$ defined on the region $E$.

   \[ F(x, y, z) = \langle 2x, yz, xy \rangle, \quad E = [0, 1] \times [0, 1] \times [0, 1], \text{ the unit cube} \]

   **Clue**: For the computation of $\iint_S F \cdot dS$, you should evaluate it on each of the six sides.

2. Use the Divergence Theorem to evaluate the total flux $\iint_S F \cdot dS$.

   (a) $F(x, y, z) = y \mathbf{i} + x \mathbf{j} + 2z \mathbf{k}$, \( S \) is the boundary of the solid region $E$ enclosed by the paraboloid $z = 1 - x^2 - y^2$ and the plane $z = 0$

   (b) $F(x, y, z) = (x + y^2 + \cos z) \mathbf{i} + [\sin(\pi z) + xe^{-z}] \mathbf{j} + z \mathbf{k}$, \( S \) is a part of the cylinder $x^2 + y^2 = 1$ that lies between $z = 0$ and $z = 1$

   (c) $F(x, y, z) = \langle x^2 y^2, yxe^z, xy^2z - xe^z \rangle$, \( S \) is the boundary of the box bounded by the coordinate planes and the planes $x = 1$, $y = 3$, and $z = 4$

   **Ans**: (b) $2\pi$; (c) $54$

3. As a variant of Problem 16.107, let’s consider the following problem:

   Evaluate $\iint_S (x^2 + 2y^2 + 3z^2 + ze^x) \, dS$, where $S$ is the unit sphere $x^2 + y^2 + z^2 = 4$.

   **Ans**: $128\pi$
Chapter 16. Vector Calculus

Project 3. The Area of Heart

In this project, we will use the identity (an application of Green’s Theorem)

\[ A(D) = \int_D dA = \oint_{\partial D} x \, dy \]  

(16.78)

to compute the area of a closed curve saved in a data file. Also we will explore a mid-point formula for line integrals.

A dataset

- Download a heart data and save it in heart-data.txt:
  
  [link](https://skim.math.msstate.edu/LectureNotes/heart-data.txt).
  
  It includes data points of the form \( \{(x_i, y_i)\} \), representing a closed curve starting and ending at \((0, 0)\), positively oriented.

- When you draw a figure for it, using e.g. heart.m below, you will see a heart as in Figure 16.33.

```matlab
1  DATA = readmatrix('heart-data.txt');
2  X = DATA(:,1); Y = DATA(:,2);
3  figure, plot(X,Y,'r-','linewidth',2);
```

Figure 16.33: A plot of the closed curve in heart-data.txt.
16.9. The Divergence Theorem

We will explore a **mid-point approximation** for line integrals.

**What to do**

- *First, download a heart data and save it in* heart-data.txt: [https://skim.math.msstate.edu/LectureNotes/heart-data.txt](https://skim.math.msstate.edu/LectureNotes/heart-data.txt).

- In the following, let \((\hat{x}_i, \hat{y}_i)\) be the mid-point of \((x_i, y_i)\) and \((x_{i+1}, y_{i+1})\):

  \[
  \hat{x}_i = \frac{x_i + x_{i+1}}{2} \quad \text{and} \quad \hat{y}_i = \frac{y_i + y_{i+1}}{2}.
  \]

1. Draw a figure for the dataset.

2. Implement a computer program for the computation of the area:

   \[
   A(\mathcal{C}) = \oint_{\mathcal{C}} x \, dy = \sum_{i=1}^{m-1} \int_{C_i} x \, dy \approx \sum_{i=1}^{m-1} \hat{x}_i \cdot (y_{i+1} - y_i), \quad (16.79)
   \]

   where \(m\) denotes the number of points in the data file and \(C_i\) is the line segment connecting \((x_i, y_i)\) and \((x_{i+1}, y_{i+1})\).

   **Note:** The approximation in (16.79) results in the exact value. Why?

3. Implement a program for an **approximation** of the line integral:

   \[
   \oint_{\partial \mathcal{C}} (x + y) \, dx + (x - y) \, dy \approx \sum_{i=1}^{m-1} (\hat{x}_i + \hat{y}_i)(x_{i+1} - x_i) + (\hat{x}_i - \hat{y}_i)(y_{i+1} - y_i). \quad (16.80)
   \]

   (a) In general, the mid-point formula for line integrals may not result in the exact value. However, the approximation in (16.80) can produce the exact value for the vector field \(F = \langle x + y, x - y \rangle\). Why?

   (b) Can you predict how large the integral must be? Why?
Let’s consider a very basic for coding.

**Computer implementation, in a nutshell**

- In computer implementation, one of the major issues is how to deal with ‘loop’, which is a recursive execution of operations.
- A loop can start with an initialization.
- For example, let’s try to add the square of integers from 1 to 10. Then, you may implement a code as in `square_sum.m` below.

```matlab
n = 10;
sum = 0;
for i = 1:n
    sum = sum + i^2;
end
```

**Report.** Upload a file including your experiences:

- Plot the given data.
- Implement a code for each of (16.79) and (16.80).
- Collect all your work, in order, including the plot, the code, the results (the area and the estimation of line integral).
- Attach a “summary” or “conclusion” page at the beginning of report.
R.16. Review Problems for Ch. 16

1. Evaluate the line integral \( \int_C x^2 y \, ds \), where \( C \) is given by \( r(t) = \langle \cos t, \sin t \rangle \), \( 0 \leq t \leq \pi/2 \). Formula: \( \int_C f(x,y) \, ds = \int_a^b f(r(t)) |r'(t)| \, dt \)
   \[ \text{Ans: } \frac{1}{3} \]

2. Let \( F(x,y) = x^2 y^3 \mathbf{i} + x^3 y^2 \mathbf{j} \).
   (a) Is \( F \) conservative? Why?
   (b) Find a function \( f \) such that \( \nabla f = F \).
   (c) Evaluate the line integral \( \int_C F \cdot dr \), where \( C \) is parameterized as \( r(t) = \langle t^3 - 2t, t^3 + 2t \rangle \), \( 0 \leq t \leq 1 \).
   Formula: \( \int_C F \cdot dr = \int_a^b F(r(t)) \cdot r'(t) \, dt \). When \( F \) is conservative, \( \int_C F \cdot dr = f(r(b)) - f(r(a)) \).
   \[ \text{Ans: } \text{(a) Yes. (b) } f = x^3 y^3 / 3 + K \text{. (c) } -9 \]
6. Use the identity (an application of Green’s Theorem)

\[ A(D) = \iint_D dA = \int_{\partial D} x \, dy \]

to show that the area of \( D \) (the shaded region) is \( 16 - \frac{4^2}{2} = 12 \). You have to compute the line integral for each of four line segments of the boundary. For the slant line segment, in particular, you should introduce an appropriate parameterization for the line integral.

**Answer:** For the slant line segment \((C_1)\) : \( x = t, y = t/2, 0 \leq t \leq 4 \). So, \( \int_{C_1} x \, dy = \int_0^4 t \frac{1}{2} \, dt = 4 \). For the right vertical line segment \((C_2)\): \( \int_{C_2} x \, dy = \int_{C_2} 4 \, dy = 8 \). For the others, the line integral is zero.

7. Evaluate the **surface integral** \( \iint_{S} F \cdot dS \), where \( F(x, y, z) = x \, \mathbf{i} + y \, \mathbf{j} + 2z \, \mathbf{k} \) and \( S \) is a part of the paraboloid \( z = x^2 + y^2, z \leq 1 \).

**Formula:** \( \iint_{S} F \cdot dS = \iint_{S} F \cdot \mathbf{n} \, dS = \iint_{D} F \cdot (\mathbf{r}_u \times \mathbf{r}_v) \, dA. \) When \( F = <P, Q, R> \) and the surface is given by \( z = g(x, y) \), \( \iint_{S} F \cdot dS = \iint_{D} (-Pg_x - Qg_y + R) \, dA. \)

**Ans:** \( \iint_{S} F \cdot dS = \iint_{D} (-Pg_x - Qg_y + R) \, dA = \iint_{D} (-2x^2 - 2y^2 + 2z) \, dA = \iint_{D} 0 \, dA = 0. \)

8. Use **Stokes’s Theorem** to evaluate \( \int_{C} F \cdot dr \), where

\[ F(x, y, z) = <x + y^2, y + z^2, z + x^2> \]
and \( C \) is the triangle with vertices \((1, 0, 0), (0, 1, 0), \) and \((0, 0, 1)\). (Orient \( C \) to be counterclockwise when viewed from above.)

**Hint:** Let \( S \) be the part of plane \( x + y + z = 1 \) defined over the triangle of vertices \((0, 0), (1, 0), \) and \((0, 1)\). Then the curve \( C \) is the boundary of \( S \). **Formula:** \( \int_C \mathbf{F} \cdot d\mathbf{r} = \iint_S (\nabla \times \mathbf{F}) \cdot dS \). For the surface integral, you may use the last equality in **Formula** of Problem 7.

**Answer:** \( \nabla \times \mathbf{F} = \langle -2z, -2x, -2y \rangle \) and \( \mathbf{r}_x \times \mathbf{r}_y = \langle 1, 1, 1 \rangle \). \( G = \iint_D (-2x - 2y - 2z) \, dA = \iint_D (-2) \, dA = -1. \)

9. Use the **Divergence Theorem** to evaluate the flux of \( \mathbf{F} \) across \( S \), where

\[
\mathbf{F}(x, y, z) = 12z \, \mathbf{i} + 4y \, \mathbf{j} - 5x \, \mathbf{k}
\]

and \( S \) is the boundary of of the solid region \( E \) enclosed by the paraboloid \( z = 1 - x^2 - y^2 \) and the plane \( z = 0 \). **Formula:** **Divergence Theorem:** \( \iint_S \mathbf{F} \cdot dS = \iiint_E \nabla \cdot \mathbf{F} \, dV \)

**Ans:** \( 2\pi \)

10. (Unclosed Surface). Use the **Divergence Theorem** to evaluate the flux of \( \mathbf{F} \) across \( S \), where

\[
\mathbf{F}(x, y, z) = 3018y \, \mathbf{i} + (5x + 3y) \, \mathbf{j} + (z - 1) \, \mathbf{k}
\]

and \( S \) is a part of the paraboloid \( z = 1 - x^2 - y^2, \, z \geq 0 \).

**Hint:** Note that \( S \) is not a closed surface. First compute integrals over \( S_1 \) and \( S_2 = S \cup S_1 \), where \( S_1 \) is the disk \( x^2 + y^2 \leq 1, \, z = 0 \), oriented downward. **Formula:** \( \iint_S \mathbf{F} \cdot dS = \iiint_E \nabla \cdot \mathbf{F} \, dV \). **Divergence Theorem:** \( \iint_S \mathbf{F} \cdot dS = \iiint_E \nabla \cdot \mathbf{F} \, dV \).

**Answer:** \( \iint_{S_2} \mathbf{F} \cdot dS = \iiint_E \nabla \cdot \mathbf{F} \, dV = \iiint_E 4 \, dV = 4 \oint_{S_1} \int_0^{1-x^2-y^2} dz \, dA = 2\pi. \) And \( \iint_{S_1} \mathbf{F} \cdot dS = \iint_{S_1} \mathbf{F} \cdot \mathbf{n} \, dS = \iint_{S_1} (1 - z) \, dS = \pi, \) because \( \mathbf{n} = \langle 0, 0, -1 \rangle \) and \( z = 0 \) on \( S_1 \). Thus \( 2\pi - \pi = \pi. \)
F.1. Formulas for Chapter 16

**Line Integrals**

**Formula 16.109.** (16.17) If \( f \) is defined on a smooth curve \( C \) given by a vector equation \( r(t) = (x(t), y(t), z(t)), \ a \leq t \leq b \), then **line integral of \( f \) along \( C \)** is

\[
\int_C f(x, y, z) \, ds = \int_a^b f(r(t)) |r'(t)| \, dt = \int_a^b f(x(t), y(t), z(t)) \sqrt{(x')^2 + (y')^2 + (z')^2} \, dt. \tag{16.81}
\]

**Formula 16.110.** (16.22) Let \( F \) is a continuous vector field defined on a smooth curve \( C \) given by \( r(t), \ a \leq t \leq b \). Then the line integral of \( F \) along \( C \) is

\[
\int_C F \cdot dr \overset{\text{def}}{=} \int_C F \cdot T \, ds = \int_a^b F(r(t)) \cdot r'(t) \, dt. \tag{16.82}
\]

**The Fundamental Theorem for Line Integrals**

**Formula 16.111.** (16.25) Suppose that \( F \) is continuous, and is a **conservative** vector field; that is, \( F = \nabla f \) for some scalar-valued function \( f \). Then

\[
\int_C F \cdot dr = \int_C \nabla f \cdot dr = f(r(b)) - f(r(a)). \tag{16.83}
\]

**Note:** If \( F = \langle P, Q \rangle \) satisfies \( P_y = Q_x \) over an open simply-connected domain, then \( F \) is conservative.

**Green’s Theorem**

**Formula 16.112.** (16.30) Let \( C \) be positively oriented, piecewise-smooth, simple closed curve in the plane and \( D \) be the region bounded by \( C \). If \( F = \langle P, Q \rangle \) have **continuous partial derivatives** on an open region including \( D \), then

\[
\oint_C F \cdot dr \overset{\text{def}}{=} \oint_C P \, dx + Q \, dy = \iint_D \left( \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) \, dA. \tag{16.84}
\]

**Surface Integrals**

**Formula 16.113.** (16.64) Suppose the surface \( S \) is defined by a vector function \( r(u, v) = \langle x(u, v), y(u, v), z(u, v) \rangle, \ (u, v) \in D \). Then

\[
\iint_S f(x, y, z) \, dS = \iint_D f(r(u, v)) |r_u \times r_v| \, dA. \tag{16.85}
\]

**Formula 16.114.** (16.65) When \( z = g(x, y) \), \( r_x \times r_y = \langle -g_x, -g_y, 1 \rangle \). Thus the formula \((16.85)\) reads

\[
\iint_S f(x, y, z) \, dS = \iint_D f(x, y, g(x, y)) \sqrt{g_x^2 + g_y^2 + 1} \, dA. \tag{16.86}
\]
16.9. The Divergence Theorem

**Surface Integrals of Vector Fields**

**Formula 16.115.** (16.70) Let $F$ be a continuous vector field defined on an oriented surface $S$ with unit normal vector $n$. The surface integral of $F = \langle P, Q, R \rangle$ over $S$ is

\[
\int_C F \cdot dr \overset{\text{def}}{=} \int_C F \cdot T \, ds = \left. \int_a^b F(r(t)) \cdot \frac{r'(t)}{|r'(t)|} \, |r'(t)| \right| \, dt = \int_a^b F(r(t)) \cdot r'(t) \, dt, \quad (16.87)
\]

**Formula 16.116.** (16.71) When the surface $S$ is defined by $z = g(x, y)$, $r_x \times r_y = \langle -g_x, -g_y, 1 \rangle$ and

\[
\iint_S F \cdot dS = \iint_D F \cdot (r_x \times r_y) \, dA = \iint_D (-P g_x - Q g_y + R) \, dA. \quad (16.88)
\]

**Stokes’ Theorem**

**Formula 16.117.** (16.74) Let $S$ be an oriented piecewise-smooth surface that is bounded by a simple, closed, piecewise-smooth curve $C$ with positive orientation. Let $F = \langle P, Q, R \rangle$ be a vector field whose components have continuous partial derivatives. Then

\[
\oint_C F \cdot dr = \int_S (\text{curl } F) \cdot dS \overset{\text{def}}{=} \int_S (\text{curl } F) \cdot n \, dS = \iint_D (\text{curl } F) \cdot (r_u \times r_v) \, dA. \quad (16.89)
\]

**The Divergence Theorem**

**Formula 16.118.** (16.76) Let $E$ be a simple solid region and $S$ be the boundary surface of $E$, given with positive (outward) orientation. Let $F = \langle P, Q, R \rangle$ have continuous partial derivatives on an open region that contains $E$. Then

\[
\iiint_E F \cdot dV = \iiint_S \nabla \cdot F \, dV. \quad (16.90)
\]
CHAPTER 17

Optimization Methods

Optimization is the branch of research-and-development that aims to solve the problem of finding the elements which maximize or minimize a given real-valued function, while respecting constraints. Many problems in engineering and machine learning can be cast as optimization problems, which explains the growing importance of the field. An optimization problem is the problem of finding the best solution from all feasible solutions.

In this chapter, we will discuss details about two of common optimization methods:

- Method of Euler-Lagrange equations (variational calculus), and
- Gradient descent method.

Contents of Chapter 17

17.1. Variational Calculus: Euler-Lagrange Equations .............................................. 240
   17.1.1. Total variation ............................................................................................... 241
   17.1.2. Calculus of variation .................................................................................... 242
17.2. Gradient Descent Method ................................................................................... 247
   17.2.1. The gradient descent method in 1D .............................................................. 249
   17.2.2. Examples ...................................................................................................... 251
   17.2.3. The choice of step length and line search ...................................................... 252
   17.2.4. Optimizing optimization .............................................................................. 254
17.1. Variational Calculus: Euler-Lagrange Equations

Consider the following minimization problem

$$\min_u \int_\Omega |\nabla u| \, dx \quad \text{subj. to} \quad \|v_0 - u\| = \sigma, \quad (17.1)$$

where $\|v_0 - u\| = \left( \int_\Omega (v_0 - u)^2 \, dx \right)^{1/2}$ and $v_0$ : given observed data (image)

$u$ : a desired image to be restored

$\sigma$ : the standard deviation of noise $\eta = v_0 - u$

Introducing a Lagrange multiplier $\lambda$, the problem (17.1) can be written equivalently as

$$\min_u J(u), \quad J(u) \overset{\text{def}}{=} \int_\Omega |\nabla u| \, dx + \frac{\lambda}{2} \|v_0 - u\|^2 = \int_\Omega \left[ |\nabla u| + \frac{\lambda}{2} (v_0 - u)^2 \right] \, dx. \quad (17.2)$$

Method of Lagrange multipliers

Recall: Earlier in §14.8, we considered a problem of the form

$$\min_x f(x) \quad \text{subj. to} \quad g(x) = c. \quad (17.3)$$

The problem could be solved by finding $x, \lambda$ such that

$$\nabla f(x) = \lambda \nabla g(x) \quad \text{and} \quad g(x) = c. \quad (17.4)$$

(See Strategy 14.85, p. 65.) The first equation of (17.4) can be written as

$$\nabla [f(x) + \lambda g(x)] = 0, \quad (17.5)$$

which (assuming $\lambda$ found) is a necessary condition for

$$\min_x [f(x) + \lambda g(x)]. \quad (17.6)$$
17.1.1. Total variation

**Definition 17.1.** Let $f$ be a differentiable function defined on $\Omega \subset \mathbb{R}^d$. Then the total variation (TV) of $f$ over $\Omega$ is defined as

$$TV(f) = \int_{\Omega} |\nabla f| \, dx.$$  \hfill (17.7)

**Remark 17.2.** Thus the problem in (17.1),

$$\min_{u} \int_{\Omega} |\nabla u| \, dx \quad \text{subj. to} \quad \|v_0 - u\| = \sigma,$$  \hfill (17.8)

is the problem of finding a solution that minimizes the TV, given the constraint $\|v_0 - u\| = \sigma$. It has been widely used in the field of image processing, particularly in mathematical denoising.

**Example 17.3.** Let $f$ be defined on an interval $[a, b]$. Then it follows from (17.7) that

$$TV(f) = \int_{a}^{b} |f'(x)| \, dx.$$  \hfill (17.9)

**Problem 17.4.** Find the TV of $f(x) = 2x^3 - 3x^2 + 4$ over $[-1, 2]$.

**Solution.**

Ans: 11
17.1.2. Calculus of variation

For simplicity, we will derive the **Euler-Lagrange equation** for problems in one variable. Consider

\[
\min_u J(u), \quad J(u) = \int_{x_1}^{x_2} f(x, u, u') \, dx. \tag{17.10}
\]

**The Question:**

What is the function \( u \) that satisfies

\[
u(x_1) = u_1 \quad \text{and} \quad u(x_2) = u_2\]

and renders \( J \) in (17.10) a minimum?

---

**Figure 17.1:** The minimizer \( u \) and its variation \( U \) as a comparison function.

---

**An Answer:**

1. Let \( u \) be the minimizing function of \( J \) in (17.10).
2. Consider the one-parameter family of **comparison functions**

\[
U(x) = u(x) + \varepsilon \eta(x). \tag{17.12}
\]

where \( \eta \) is an arbitrary differentiable function such that
\[
\eta(x_1) = \eta(x_2) = 0.
\]

3. See Figure 17.1. Note

\[
U'(x) = u'(x) + \varepsilon \eta'(x). \tag{17.13}
\]

4. Consider

\[
J(\varepsilon) = \int_{x_1}^{x_2} f(x, U, U') \, dx = \int_{x_1}^{x_2} f(x, u + \varepsilon \eta, u' + \varepsilon \eta') \, dx.
\]

Then, since \( U = u \) (the minimizer) when \( \varepsilon = 0 \), we have

\[
J'(0) = 0. \tag{17.14}
\]
17.1. Variational Calculus: Euler-Lagrange Equations

Implication of $J'(0) = 0$

Differentiating $J$ with respect to $\varepsilon$ reads

$$
\frac{dJ}{d\varepsilon} = J'(\varepsilon) = \int_{x_1}^{x_2} \left( \frac{\partial f}{\partial U} \frac{\partial U}{\partial \varepsilon} + \frac{\partial f}{\partial U'} \frac{\partial U'}{\partial \varepsilon} \right) dx = \int_{x_1}^{x_2} \left( \frac{\partial f}{\partial U} \eta + \frac{\partial f}{\partial U'} \eta' \right) dx.
$$

(17.15)

Thus,

$$
J'(0) = \int_{x_1}^{x_2} \left( \frac{\partial f}{\partial u} \eta + \frac{\partial f}{\partial u'} \eta' \right) dx = 0.
$$

(17.16)

Now, apply integration by parts (for the second part) to get

$$
J'(0) = \int_{x_1}^{x_2} \frac{\partial f}{\partial u} \eta dx + \frac{\partial f}{\partial u'} \eta \bigg|_{x_1}^{x_2} - \int_{x_1}^{x_2} \frac{d}{dx} \left( \frac{\partial f}{\partial u'} \right) \eta dx
$$

(17.17)

$$
= \int_{x_1}^{x_2} \left[ \frac{\partial f}{\partial u} - \frac{d}{dx} \left( \frac{\partial f}{\partial u'} \right) \right] \eta dx = 0.
$$

Since the above holds for arbitrary $\eta$, we must have

$$
\frac{\partial f}{\partial u} - \frac{d}{dx} \left( \frac{\partial f}{\partial u'} \right) = 0,
$$

(17.18)

which is called the Euler-Lagrange equation of $J$.

Problem 17.5. Let $f(x) = |x|^{\alpha}$. Find $\frac{df}{dx}$. What is $\frac{df}{dx}$ when $\alpha = 1$?

Solution. Hint: Begin with $\ln f = \alpha \ln |x|$. Or, define $f_\varepsilon(x) = \left( \sqrt{x^2 + \varepsilon^2} \right)^\alpha$ and find $\lim_{\varepsilon \to 0} f'_\varepsilon(x)$.

Ans: $\frac{d|x|^\alpha}{dx} = \frac{\alpha}{x} |x|^\alpha$, $\frac{d|x|}{dx} = \frac{x}{|x|}$. 

\[ \int_{x_1}^{x_2} \]
**Problem 17.6.** In 1D, the objective function $\mathcal{J}$ in (17.2) reads

$$
\mathcal{J}(u) = \int_a^b \left[ |u_x| + \frac{\lambda}{2} (v_0 - u)^2 \right] dx,
$$

(17.19)

where $u_x = du/dx$. Find its Euler-Lagrange equation.

**Solution.**

**Ans:** $-\lambda(v_0 - u) - \left( \frac{u_x}{|u_x|} \right)_x = 0$, or $-\left( \frac{u_x}{|u_x|} \right)_x = \lambda(v_0 - u)$.

**Self-study 17.7.** Find the Euler-Lagrange equation for

$$
\mathcal{J}(u) = \int_a^b \left[ (u_x)^2 + \lambda(v_0 - u)^2 \right] dx.
$$

(17.20)

**Solution.**

**Ans:** $-u_{xx} = \lambda(v_0 - u)$. 
17.1. Variational Calculus: Euler-Lagrange Equations

**Remark 17.8.** In 2D, the objective function (17.2) becomes

\[
\mathcal{J}(u) = \int_{\Omega} \left[ |\nabla u| + \frac{\lambda}{2} (v_0 - u)^2 \right] dx = \int_{\Omega} \left[ \sqrt{u_x^2 + u_y^2} + \frac{\lambda}{2} (v_0 - u)^2 \right] dx; \tag{17.21}
\]

its Euler-Lagrange equation reads

\[
-\nabla \cdot \left( \frac{\nabla u}{|\nabla u|} \right) = \lambda (v_0 - u), \tag{17.22}
\]

where the left-hand side is called the **curvature**. For a convenient simulation of (17.22), we can parametrize the **energy descent direction** by an artificial time \( t \):

\[
\frac{\partial u}{\partial t} - \nabla \cdot \left( \frac{\nabla u}{|\nabla u|} \right) = \lambda (v_0 - u), \quad u(x, t = 0) = v_0(x). \tag{17.23}
\]

which is called the **total variation (TV) model** [6] in the literature of **image processing**. The stationary solution of (17.23) would show a smaller TV value than \( v_0 \).

**Example 17.9.** The TV model has a tendency to converge to a piecewise constant image, which is called a **staircasing**.

![Figure 17.2: Staircasing of the TV model: (a) The original Elaine and (b) its TV result.](image)
Example 17.10. To overcome the staircasing effect, the TV model can be modified as
\[
\frac{\partial u}{\partial t} - |\nabla u| \nabla \cdot \left( \frac{\nabla u}{|\nabla u|} \right) = \lambda |\nabla u| (v_0 - u),
\] (17.24)
where the Euler-Lagrange equation is scaled by $|\nabla u|$ before applying time parametrization. The above is call the improved TV (ITV) model [4].

\begin{figure}[h]
\centering
\begin{subfigure}{0.4\textwidth}
\includegraphics[width=\textwidth]{image1}
\end{subfigure}
\begin{subfigure}{0.4\textwidth}
\includegraphics[width=\textwidth]{image2}
\end{subfigure}
\begin{subfigure}{0.4\textwidth}
\includegraphics[width=\textwidth]{image3}
\end{subfigure}
\begin{subfigure}{0.4\textwidth}
\includegraphics[width=\textwidth]{image4}
\end{subfigure}
\caption{Lena: (a) The original image, (b) a noisy image, (c) a restored image by ITV, and (d) a restored image by ITV-END. The PSNR (peak signal-to-noise ratio) measures 22.8, 27.0, and 30.3 respectively for (b), (c), and (d).}
\end{figure}

Note: END stands for equalized net diffusion, which is invented by Kim [2] as another scaling operation incorporated with ITV, in order to preserve fine features of the image more effectively.
17.2. Gradient Descent Method

The first method is one of the oldest methods in optimization: gradient descent method, a.k.a steepest descent method. The method was suggested by Augustin-Louis Cauchy in 1847 [3]. He was a French mathematician and physicist who made pioneering contributions to mathematical analysis. Today, it is used to solve problems with thousands of variables comfortably.

Figure 17.4: Augustin-Louis Cauchy

Optimization Problem

Let \( \Omega \subset \mathbb{R}^d, d \geq 1 \). Given a real-valued function \( f : \Omega \to \mathbb{R} \), the general problem of finding the value that minimizes \( f \) is formulated as follows.

\[
\min_{x \in \Omega} f(x).
\]

(17.25)

In this context, \( f \) is the objective function. \( \Omega \subset \mathbb{R}^d \) is the domain of the function (also known as the constraint set).

Problem 17.11. (Revisit of Problem 14.79). Find all local extrema of \( f(x, y) = x^4 + y^4 - 4xy + 1 \). What is the global minimum, \( \min_{(x,y) \in \mathbb{R}^2} f(x, y) \)?

Solution.

Ans: local min at: \((\pm 1, \pm 1)\), saddle point: \((0, 0)\); global min = \(-1\)
Example 17.12. (Rosenbrock function). For example, the Rosenbrock function in the two-dimensional (2D) space is defined as\(^1\)

\[
f(x, y) = (1 - x)^2 + 100 (y - x^2)^2.
\]

(17.26)

Figure 17.6: Plots of the Rosenbrock function \(f(x, y) = (1 - x)^2 + 100 (y - x^2)^2\).

Rosenbrock function

Note: The Rosenbrock function is commonly used when evaluating the performance of optimization algorithms, due to the following reasons.

- Its minimizer \(x = \text{np.array([1., 1.])}\) is found in curved valley, and so minimizing the function is non-trivial, and
- Python: The Rosenbrock function is included in the `scipy.optimize` package (as `rosen`), as well as its gradient (`rosen_der`) and its Hessian (`rosen_hess`).

\(^1\)The Rosenbrock function in 3D is given as \(f(x, y, z) = [(1 - x)^2 + 100 (y - x^2)^2] + [(1 - y)^2 + 100 (z - y^2)^2]\), which has exactly one minimum at \((1, 1, 1)\). Similarly, one can define the Rosenbrock function in general \(N\)-dimensional spaces, for \(N \geq 4\), by adding one more component for each enlarged dimension. That is, \(f(x) = \sum_{i=1}^{N-1} [(1 - x_i)^2 + 100(x_{i+1} - x_i^2)^2]\), where \(x = [x_1, x_2, \cdots, x_N] \in \mathbb{R}^N\). See Wikipedia (https://en.wikipedia.org/wiki/Rosenbrock_function) for details.
Recall: The gradient $\nabla f$ is a vector (a direction to move), which is

• pointing in the **direction of greatest increase** of the function, and
• **zero** ($\nabla f = 0$) at local maxima or local minima.

The goal of the **gradient descent** (GD) method is to address directly the process of minimizing the function $f$, using the fact that $-\nabla f(x)$ is the direction of **steepest descent** of $f$ at $x$. Given an initial point $x_0$, we move it to the direction of $-\nabla f(x_0)$ so as to get a smaller function value. That is,

$$x_1 = x_0 - \gamma \nabla f(x_0) \Rightarrow f(x_1) < f(x_0).$$

We repeat this process till reaching at a desirable minimum. Thus the method is formulated as follows.

**Gradient descent method**

**Algorithm** 17.13. Given an initial point $x_0$, find iterates $x_{n+1}$ recursively using

$$x_{n+1} = x_n - \gamma \nabla f(x_n),$$

for some $\gamma > 0$. The parameter $\gamma$ is called the **step length** or **learning rate**.

To understand the basics of GD method thoroughly, we consider the method for solving unconstrained minimization problems defined in 1D.

**17.2.1. The gradient descent method in 1D**

Consider the minimization problem in 1D:

$$\min_x f(x), \quad x \in S, \quad (17.28)$$

where $S$ is a closed interval in $\mathbb{R}$. Then its gradient descent method reads

$$x_{n+1} = x_n - \gamma f'(x_n). \quad (17.29)$$
Picking the step length $\gamma$: Assume that the step length was chosen to be independent of $n$, although one can play with other choices as well. **The question is how to select $\gamma$ in order to make the best gain of the method.** To turn the right-hand side of \((17.29)\) into a more manageable form, we invoke Taylor's Theorem:

$$f(x + t) = f(x) + tf'(x) + \int_x^{x+t} (x + t - s) f''(s) \, ds. \tag{17.30}$$

Assuming that $|f''(s)| \leq L$, we have

$$f(x + t) \leq f(x) + tf'(x) + \frac{t^2}{2} L.$$  

Now, letting $x = x_n$ and $t = -\gamma f'(x_n)$ reads

$$f(x_{n+1}) = f(x_n - \gamma f'(x_n))$$
$$\leq f(x_n) - \gamma f'(x_n) f'(x_n) + \frac{1}{2} L [\gamma f'(x_n)]^2$$
$$= f(x_n) - [f'(x_n)]^2 \left( \gamma - \frac{L}{2} \gamma^2 \right). \tag{17.31}$$

The gain (learning) from the method occurs when

$$\gamma - \frac{L}{2} \gamma^2 > 0 \quad \Rightarrow \quad 0 < \gamma < \frac{2}{L}, \tag{17.32}$$

and it will be best when $\gamma - \frac{L}{2} \gamma^2$ is maximal. This happens at the point

$$\gamma = \frac{1}{L}. \tag{17.33}$$

It follows from (17.31) and (17.33) that

$$f(x_{n+1}) \leq f(x_n) - \frac{1}{2L} [f'(x_n)]^2. \tag{17.34}$$

**Theorem 17.14. (Convergence of GD method).** If $f$ is bounded from below and the level sets of $f$ are bounded, there is a point $\hat{x}$ such that

$$\lim_{n \to \infty} x_n = \hat{x}, \quad f'(\hat{x}) = 0. \tag{17.35}$$

---

2 Taylor's Theorem, with integral remainder: Suppose $f \in C^{n+1}[a, b]$ and $x_0 \in [a, b]$. Then, for every $x \in [a, b]$, $f(x) = \sum_{k=0}^{n} \frac{f^{(k)}(x_0)}{k!} (x - x_0)^k + R_n(x)$, $R_n(x) = \frac{1}{n!} \int_{x_0}^{x} (x - s)^n f^{(n+1)}(s) \, ds$. 

17.2.2. Examples

Here we examine the convergence of gradient descent on three examples: a well-conditioned quadratic, an badly-conditioned quadratic, and a non-convex function, as shown by Dr. Fabian Pedregosa, UC Berkeley.

Figure 17.7: On a well-conditioned quadratic function, the gradient descent converges in a few iterations to the optimum

\[ \gamma = 0.2 \]

Figure 17.8: On a badly-conditioned quadratic function, the gradient descent converges and takes many more iterations to converge than on the above well-conditioned problem. This is partially because gradient descent requires a much smaller step length on this problem to converge.

\[ \gamma = 0.02 \]

Figure 17.9: Gradient descent also converges on a badly-conditioned non-convex problem. Convergence is slow in this case.
17.2.3. The choice of step length and line search

The convergence of the gradient descent method can be extremely sensitive to the choice of step length. It often requires to choose the step length adaptively: the step length would better be chosen small in regions of large variability of the gradient, while in regions with small variability we would like to take it large.

Backtracking line search procedures allow to select a step length depending on the current iterate and the gradient. In this procedure, we select an initial (optimistic) step length $\gamma_n$ and evaluate the following inequality (known as sufficient decrease condition):

$$f(x_n - \gamma_n \nabla f(x_n)) \leq f(x_n) - \frac{\gamma_n}{2} \|\nabla f(x_n)\|^2.$$  (17.36)

If this inequality is verified, the current step length is kept. If not, the step length is divided by 2 (or any number larger than 1) repeatedly until (17.36) is verified. To get a better understanding, refer to (17.34) on p. 250, with (17.33).

GD, with Backtracking Line Search

The GD algorithm with backtracking line search becomes

**input**: initial guess $x_0$, step length $\gamma > 0$;

for $n = 0, 1, 2, \ldots$ do

- initial step length estimate $\gamma_n$;

while (TRUE) do

  if $f(x_n - \gamma_n \nabla f(x_n)) \leq f(x_n) - \frac{\gamma_n}{2} \|\nabla f(x_n)\|^2$

    break;

  else $\gamma_n = \gamma_n / 2$;

end while

$x_{n+1} = x_n - \gamma \nabla f(x_n)$;

end for

return $x_{n+1}$;
17.2. Gradient Descent Method

The following examples show the convergence of gradient descent with the aforementioned backtracking line search strategy for the step length.

Figure 17.10: On a well-conditioned quadratic function, the gradient descent converges in a few iterations to the optimum. Adding the backtracking line search strategy for the step length does not change much in this case.

Figure 17.11: In this example we can clearly see the effect of the backtracking line search strategy: once the algorithm is in a region of low curvature, it can take larger step lengths. The final result is a much improved convergence compared with the fixed step-length equivalent.

Figure 17.12: The backtracking line search also improves convergence on non-convex problems.
17.2.4. Optimizing optimization

Multiple Local Minima Problem

**Remark 17.15.** Although you can choose the step length *smartly*, there is no guarantee for your algorithm to converge to the desired solution (the global minimum), particularly when the objective involves multiple local minima.

![Figure 17.13: Smooth sailing, through a Gaussian smoothing.](image)

- Here, we consider the so-called **Gaussian homotopy continuation** method [5], which may overcome the local minima problem for certain classes of optimization problems.
- The method begins by trying to find a convex approximation of an optimization problem, using a technique called **Gaussian smoothing**.
- Gaussian smoothing converts the cost function into a related function that gives not the value that the cost function would, but a weighted average of all the surrounding values.
- This has the effect of smoothing out any abrupt dips or ascents in the cost function’s graph, as shown in Figure 17.13.
- The weights assigned the surrounding values are determined by a Gaussian function, or normal distribution.
Problem 17.16. Let \( f(x) = x^4 - \frac{4}{3}x^3 - 4x^2 + 11 \). Perform two GD iterations to estimate \( \min_x f(x) \), starting from \( x_0 = 1 \) and setting \( \gamma_n = 0.1/(n + 1) \).

Solution. Clue: \( f'(x) = 4x^3 - 4x^2 - 8x = 4x(x^2 - x - 2) \) and \( \min_x f(x) = f(2) = 1/3 \).

Algorithm 17.17. The above problem is implemented as follows.

```
%% An Example for Gradient Descent Method
f = @(x) x.^4 -4/3*x.^3 -4*x.^2 +11;
df = @(x) 4*x.^3 -4*x.^2 -8*x;
x0 = 1.0;
xn = gd1D(df,x0,tol=1.0e-5,itmax=1000);
   fprintf("min f = %.7f @ xn= %.10f\n",feval(f,xn),xn);
```

```
function xn = gd1D(df,x0,tol, itmax)
    % function xn = gd1D(df,x0,tol)
    % Input: df: derivative of f; x0: initial value
    % Default: gamma = 0.1/n
    if nargin==2, tol=1.0e-5; itmax=1000; end
    xn = x0;
    for n=1:itmax
        gamma = 0.1/n;
        h = gamma*feval(df,xn); xn = xn - h;
        if (abs(h)<tol)
            fprintf('gd1D.m: converged @ n = %d (tol=%g)\n',n,tol); break;
        end
    end
end
```

The Result

```
[Sat Oct.26] octave GD.m
gd1D.m: converged @ n = 8 (tol=1e-05)
min f = 0.3333333 @ xn= 2.0000182623
```
Exercises 17.2

By solving problems below, you will learn numerical characteristics of GD, particularly the importance of initial values \((x_0)\) and step lengths \((\gamma_n)\).

1. **CAS** Implement GD as in Algorithm 17.17 in **MATLAB**\(^3\) and test it as follows.
   
   (a) Run GD.m with \{\(x_0=3.0; \) itmax=10;\}.
   
   (b) Plot \(y = f(x)\) with the iterates \(x_n, n = 1, \cdots, 10\), being located on the \(x\)-axis.
   
   (c) First edit gd1D.m to replace gamma=0.1/n with gamma=0.1/(n+3) and then run GD.m again with \{\(x_0=3.0; \) itmax=10;\}.
   
   (d) Plot \(y = f(x)\) again with the iterates \(x_n, n = 1, \cdots, 10\), being located on the \(x\)-axis.
   
   (e) Discuss your experiments, focusing on the importance of initial values \((x_0)\) and step lengths \((\gamma_n)\).

2. **CAS** Now, consider the last four digits of your student ID (say, \(abcd\)). Let

   \[
g(x) = \hat{a} x^4 - b x^3 - c x^2 + d,
   \]

   where \(\hat{a} = \max(a, 1)\).

   (a) Plot \(y = g(x)\).
   
   (b) Examine the figure to find an accurate initial value \(x_0\) for solving \(\min_x g(x)\).
   
   (c) Edit gd1D.m to set gamma for GD to converge as fast as possible.
   
   (d) Report your experiments.

---

\(^3\)**MATLAB** (matrix laboratory) is a multi-paradigm numerical computing environment and proprietary programming language developed by MathWorks.
APPENDIX A

Review for 12 Selected Sections

In this appendix, we will review the following 12 sections by considering major concepts and representing problems.

Contents of Appendix A

A.1. (§14.4) Tangent Planes and Linear Approximations .......................... 258
A.2. (§14.6) Directional Derivatives and Gradient Vector .......................... 260
A.3. (§14.8) Lagrange Multipliers .................................................. 262
A.4. (§15.2) Double Integrals over General Regions .............................. 264
A.5. (§15.7) Triple Integrals in Cylindrical Coordinates ...................... 266
A.6. (§15.9) Change of Variables in Multiple Integrals ..................... 268
A.7. (§16.2) Line Integrals .............................................................. 270
A.8. (§16.3) The Fundamental Theorem for Line Integrals ............... 272
A.9. (§16.4) Green’s Theorem ......................................................... 274
A.10. (§16.7) Surface Integrals ......................................................... 276
A.11. (§16.8) Stokes’s Theorem ....................................................... 280
A.12. (§16.9) The Divergence Theorem ........................................... 281
A.1. (§14.4) Tangent Planes and Linear Approximations

**Definition A.1.** Given \( z = f(x, y) \), the linear (tangent plane) approximation of \( f \) near \((a,b)\) is

\[
L(x,y) \equiv z_0 + f_x(a,b) (x-a) + f_y(a,b) (y-b),
\]

where \( z_0 = f(a,b) \).

**Note:** The equation of the tangent plane is

\[
z - z_0 = f_x(a,b) (x-a) + f_y(a,b) (y-b),
\]

or equivalently

\[
-f_x(a,b) (x-a) - f_y(a,b) (y-b) + (z-z_0) = 0.
\]

A level surface form of \( z = f(x, y) \) can be rewritten as

\[
F(x, y, z) = z - f(x, y) = 0;
\]

its gradient becomes

\[
\nabla F = (-f_x, -f_y, 1).
\]

**Theorem A.3.** If \( f_x \) and \( f_y \) exist near \((a,b)\) and continuous at \((a,b)\), then \( f \) is differentiable at \((a,b)\).

**Definition A.4.** For a differentiable function \( z = f(x, y) \), the (total) differential is

\[
dz = f_x(x,y) \, dx + f_y(x,y) \, dy,
\]

where \( dx \) and \( dy \) represent the change in the \( x \) and \( y \) directions, respectively.
Problem A.5. Find an equation for the tangent plane to the elliptic paraboloid 
\( z = x^2 + 4y^2 \) at the point \((1, 1, 5)\).

Solution.

\[
\text{Ans: } z - 5 = 2 \cdot (x - 1) + 8 \cdot (y - 1) \iff z = 2x + 8y - 5.
\]

Problem A.6. Let \( f(x, y) = \ln(x + 1) + \cos(x/y) \). Explain why the function is differentiable at \((0, 2)\).

Problem A.7. Use a linear approximation to estimate \( f(2.2, 4.9) \), provided that \( f(2, 5) = 6, f_x(2, 5) = 1, \) and \( f_y(2, 5) = -1 \).

Solution.

\[
\text{Ans: } 6.3
\]
A.2. (§14.6) Directional Derivatives and Gradient Vector

**Claim** A.8. For a unit vector $u$, the **directional derivative** for a differential function $f$ is

$$D_u f(x, y) = \nabla f(x, y) \cdot u.$$ 

**Theorem** A.9. Let $f$ be differentiable. Then,

$$\max_u D_u f = |\nabla f|$$  \hspace{1cm} (A.6)

**Note:** The gradient vector $\nabla f$ is directing the fastest increasing direction.

Tangent Plane and Normal Line to a Level Surface

Suppose $S$ is a surface given as $F(x, y, z) = k$ and $x_0 = (x_0, y_0, z_0)$ is on $S$. Then the **tangent plane** to $S$ at $x_0$ is

$$\nabla F(x_0) \cdot (x - x_0) = F_x(x_0)(x - x_0) + F_y(x_0)(y - y_0) + F_z(x_0)(z - z_0) = 0.$$  \hspace{1cm} (A.7)

The **normal line** to $S$ at $x_0$ is

$$\frac{x - x_0}{F_x(x_0)} = \frac{y - y_0}{F_y(x_0)} = \frac{z - z_0}{F_z(x_0)}.$$  \hspace{1cm} (A.8)
Problem A.10. Let $f(x,y) = x + \sin(xy)$.

1. Find the directional derivative of $f$ at the point $(1,0)$ in the direction given by the angle $\theta = \pi/3$.

2. In what direction does $f$ have the maximum rate of change? What is the maximum rate of change?

Solution.

Solution.

Ans: (a) $(1 + \sqrt{3})/2$ (b) $\sqrt{2}$

Problem A.11. Find the equations of the tangent plane and the normal line at $P(0,0,1)$ to $x + y + z = e^{xyz}$.

Solution.

Solution.

Ans: (a) $x + y + z = 1$ (b) $x = y = z - 1$
A.3. (§14.8) Lagrange Multipliers

Consider the optimization problem

\[
\begin{align*}
\max & \quad f(x) \\
\text{subject to} & \quad g(x) = c
\end{align*}
\]

**Strategy A.12. (Method of Lagrange multipliers).** For the max/min values of the optimization problem,

(a) Find all values of \(x, y, z,\) and \(\lambda\) such that

\[
\nabla f(x, y, z) = \lambda \nabla g(x, y, z) \quad \text{and} \quad g(x, y, z) = c.
\]

(b) Evaluate \(f\) at all these points, to find the maximum and minimum.

**Example A.13.** Use Lagrange Multipliers to prove that the rectangle with maximum area that has a give perimeter \(p\) is a square.
Problem A.14. Find the maximum and minimum values of \( f(x, y) = 2x^2 + (y - 1)^2 \) on the **circle** \( x^2 + y^2 = 4 \).

Solution. \( \nabla f = \lambda \nabla g \iff \begin{bmatrix} 4x \\ 2(y - 1) \end{bmatrix} = \lambda \begin{bmatrix} 2x \\ 2y \end{bmatrix} \). Therefore, \( \begin{cases} 2x = \lambda x \\ y - 1 = \lambda y \\ x^2 + y^2 = 4 \end{cases} \)

From (1), \( x = 0 \) or \( \lambda = 2 \).

Ans: min: \( f(0, 2) = 1 \); max: \( f(\pm \sqrt{3}, -1) = 10 \)

Problem A.15. Find the maximum and minimum values of \( f(x, y) = 2x^2 + (y - 1)^2 \) on the **disk** \( x^2 + y^2 \leq 4 \).

Solution. **Hint**: You should check values at **critical points** as well.

Ans: min: \( f(0, 1) = 0 \); max: \( f(\pm \sqrt{3}, -1) = 10 \)
A.4. (§15.2) Double Integrals over General Regions

Multiple integrals can be computed with iterated integral where the given domain must be covered once-and-only-once, without missing and without overlap. Furthermore, you should be able to change the order of integration properly.

[Problem A.16. (Problem 15.16).] Find the volume of the solid that lies under the plane \( z = 1 + 2y \) and above the region \( D \) in the \( xy \)-plane bounded by the line \( y = 2x \) and the parabola \( y = x^2 \).

Solution. Try for both orders.

Ans: \( \frac{28}{5} \)
A.4. (§15.2) Double Integrals over General Regions

Problem A.17. Evaluate the integral by reversing the order of integration:

\[ \int_0^4 \int_{\sqrt{y}}^2 e^{x^3} \, dx \, dy \]

Solution.

Self-study A.18. Sketch the region of integration and change the order of integration.

\[ \int_{-2}^2 \int_0^{\sqrt{4-y^2}} f(x, y) \, dx \, dy \quad \quad \int_0^{\ln 2} \int_{e^y}^2 f(x, y) \, dx \, dy \]

Solution. 

\textbf{Ans:} \frac{1}{3} (e^8 - 1)
A.5. (§15.7) Triple Integrals in Cylindrical Coordinates

Definition A.19. (Definition 15.53). The conversion between the Cylindrical Coordinates and the Rectangular Coordinate system gives

\[
\begin{align*}
(x, y, z)_R & \leftarrow (r, \theta, z)_C \\
x &= r \cos \theta \\
y &= r \sin \theta \\
z &= z \\
(r, \theta, z)_C & \leftarrow (x, y, z)_R \\
r^2 &= x^2 + y^2 \\
tan \theta &= \frac{y}{x} \\
z &= z
\end{align*}
\]

(A.9)

Note: The triple integral with a Cylindrical Domain \( E \) can be carried out by first separating the domain like

\[ E = D \times [u_1(x, y), u_2(x, y)], \text{ where } D \text{ is a polar region.} \]

Problem A.20. Evaluate \( \iiint_E y \, dV \), where \( E \) is the solid that lies between the cylinders \( x^2 + y^2 = 1 \) and \( x^2 + y^2 = 9 \), above the \( xy \)-plane, and below the plane \( z = y + 3 \).

Solution.

Ans: \( 20\pi \)
[Self-study] A.21. Use the cylindrical coordinates to find the volume of the solid $E$ that is enclosed by the cone $z = \sqrt{x^2 + y^2}$ and the sphere $x^2 + y^2 + z^2 = 8$.

Solution.

\textit{Ans:} $\frac{32}{3} \pi (\sqrt{2} - 1)$
A.6. (§15.9) Change of Variables in Multiple Integrals

**Definition A.22.** A change of variables is a **transformation** $T : Q \rightarrow R$ (from the $uv$-plane to the $xy$-plane), $T(u,v) = (x,y)$, where $x$ and $y$ are related to $u$ and $v$ by the equations

$$x = g(u,v), \quad y = h(u,v). \quad \text{[or, \;} r(u,v) = \langle g(u,v), h(u,v) \rangle \text{]}$$

We usually take these transformations to be $C^1$-**Transformation**, meaning $g$ and $h$ have continuous first-order partial derivatives, and **one-to-one**.

![Transformation](image)

**Figure A.1:** Transformation: $R = T(Q)$, the image of $T$.

**Definition A.23.** The **Jacobian** of $T : x = g(u,v), y = h(u,v)$ is

$$\frac{\partial (x,y)}{\partial (u,v)} \overset{\text{def}}{=} \det \begin{bmatrix} x_u & x_v \\ y_u & y_v \end{bmatrix} = x_u y_v - x_v y_u. \quad (A.10)$$

**Claim A.24.** Suppose $T : Q \rightarrow R$ is an one-to-one $C^1$ transformation whose Jacobian is nonzero. Then

$$\iint_R f(x,y) \, dA = \iint_Q f(x(u,v), y(u,v)) \left| \frac{\partial (x,y)}{\partial (u,v)} \right| \, du \, dv \quad (A.11)$$

**Note:** In **linear algebra**, an $n \times n$ matrix $A$ is considered as a transformation from $\mathbb{R}^n$ to $\mathbb{R}^n$. Furthermore its **determinant** can be viewed as a **volume scaling factor**. For details, see Section 3.1 of *Introduction to Linear Algebra*:

https://skim.math.msstate.edu/LectureNotes/Linear_Algebra_LectureNote.pdf.
Problem A.25. Make an appropriate change of variables to evaluate the integral

\[ \int \int_{R} \sin(9x^2 + 4y^2) \, dA, \]

where \( R \) is the region in the first quadrant bounded by the ellipse \( 9x^2 + 4y^2 = 1 \).

Solution.

\[ \text{Ans: } \frac{\pi(1-\cos 1)}{24} \]
A.7. (§16.2) Line Integrals

**Definition** A.26. If \( f \) is defined on a smooth curve \( C \) given by
\[
\mathbf{r}(t) = (x(t), y(t)), \quad a \leq t \leq b,
\] (A.12)
then line integral of \( f \) along \( C \) is
\[
\int_C f(x, y) \, ds = \lim_{n \to \infty} \sum_{i=1}^{n} f(x_i^*, y_i^*) \Delta s_i,
\] (A.13)
if this limit exists. Here \( \Delta s_i = \sqrt{\Delta x_i^2 + \Delta y_i^2} \).

The line integral defined in (A.13) can be evaluated as
\[
\int_C f(x, y) \, ds = \int_a^b f(x(t), y(t)) \sqrt{(x'(t))^2 + (y'(t))^2} \, dt
\] (A.14)

**Definition** A.27. Let \( F \) be a continuous vector field defined on a smooth curve \( C \) given by \( \mathbf{r}(t), a \leq t \leq b \). Then the line integral of \( F \) along \( C \) is
\[
\int_C \mathbf{F} \cdot d\mathbf{r} \stackrel{\text{def}}{=} \int_C \mathbf{F} \cdot \mathbf{T} \, ds = \int_a^b \mathbf{F}(\mathbf{r}(t)) \cdot \mathbf{r}'(t) \, dt.
\] (A.15)
We say that work is the line integral with respect to arc length of the tangential component of force.
Problem A.28. Evaluate the line integral \( \int_C x e^{y^2 - z^2} \, ds \), where \( C \) is the line segment from \((0,0,0)\) to \((2,-2,1)\).

Solution.

Ans: \( e^3 - 1 \)

Problem A.29. Find the work done by the vector field \( F(x, y) = (x, ye^x) \) on the particle that moves along the parabola \( x = y^2 + 1 \) from \((1,0)\) to \((2,1)\).

Solution.

Ans: \( \frac{3}{2} + \frac{e^2 - e}{2} \)
A.8. (§16.3) The Fundamental Theorem for Line Integrals

Let $C$ be a curve represented by

$$r(t) = \langle x(t), y(t) \rangle \quad \text{or} \quad r(t) = \langle x(t), y(t), z(t) \rangle, \quad a \leq t \leq b.$$ 

**Theorem A.30.**

1. Suppose that $F$ is continuous, and is a **conservative vector field**; that is, $F = \nabla f$ for some $f$. Then

$$\int_C F \cdot dr = \int_C \nabla f \cdot dr = f(r(b)) - f(r(a)). \quad \text{(A.16)}$$

2. $\int_C F \cdot dr$ is **independent of path** in $D$ if and only if $\int_C F \cdot dr = 0$ for every closed path in $D$.

3. Suppose $F$ is a vector field that is continuous on an **open connected domain** $D$. If $\int_C F \cdot dr$ is **independent of path** in $D$, then $F$ is **conservative** (i.e., there is $f$ such that $F = \nabla f$).

4. If $F = \langle P, Q \rangle$ is conservative, where $P$ and $Q$ have continuous partial derivatives, then

$$\frac{\partial Q}{\partial x} = \frac{\partial P}{\partial y}. \quad \text{(A.17)}$$

5. When $D$ is a simply-connected domain, the equality (A.17) implies conservativeness of $F$.

**Roughly speaking:** When $F = \langle P, Q \rangle$ is smooth enough,

$$\text{conservativeness} \iff \text{independence of path} \iff Q_x = P_y$$
A.8. (§16.3) The Fundamental Theorem for Line Integrals

Problem A.31. Find the work done by

\[ F = 2y^{3/2}i + 3x\sqrt{y}j \]

in moving an object from \( A(1, 1) \) to \( B(2, 4) \).

Solution. First, check if \( F \) is conservative: \( Q_x = 3\sqrt{y}, \ P_y = 2 \cdot \frac{3}{2}y^{1/2} = 3\sqrt{y} \).

\[ \text{Ans: 30} \]

Problem A.32. Given \( F(x, y) = \langle e^y + y \cos x, xe^y + \sin x \rangle \),

(a) Find a potential.

(b) Evaluate \( \int_C F \cdot dr \), where \( C \) is parameterized as

\[ r(t) = \langle e^t \cos t, e^t \sin t \rangle, \quad 0 \leq t \leq \pi. \]

Solution.

\[ \text{Ans: (a) } f(x, y) = xe^y + y \sin x + K \quad \text{(b) } -e^\pi - 1 \]
A.9. (§16.4) Green’s Theorem

**Theorem A.33. (Green’s Theorem).** Let $C$ be positively oriented, piecewise-smooth, simple closed curve in the plane and $D$ be the region bounded by $C$. If $F = \langle P, Q \rangle$ has continuous partial derivatives on an open region including $D$, then

$$\oint_C P \, dx + Q \, dy = \iint_D \left( \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) \, dA. \tag{A.18}$$

The theorem gives the following formulas for the area of $D$:

$$A(D) = \oint_C x \, dy = -\oint_C y \, dx = \frac{1}{2} \oint_C x \, dy - y \, dx \tag{A.19}$$

**Problem A.34.** Evaluate $\oint_C F \cdot dr$, where $F = \langle e^{-x} + y^2, e^{-y} + x^2 + 2xy \rangle$ and $C$ is the circle $x^2 + (y - 1)^2 = 1$ oriented clockwise.

**Solution.** Hint: Check the orientation of the curve.

*Ans*: 0
Problem A.35. Use the identity (an example of Green’s Theorem)

\[ A(D) = \iint_D dA = \oint_{\partial D} x \, dy \]

to show that the area of \( D \) (the shaded region) is 6. You have to compute the line integral for each of four line segments of the boundary. For the slant line segment, in particular, you should introduce an appropriate parameterization for the line integral.
Appendix A. Review for 12 Selected Sections

A.10. (§16.7) Surface Integrals

Suppose that the surface $S$ has a parametric representation

$$
r(u, v) = \langle x(u, v), y(u, v), z(u, v) \rangle, \quad (u, v) \in D.
$$

Then, surface integrals of scalar functions give

$$
\iint_{S} f(x, y, z) \, dS = \iint_{D} f(r(u, v)) |r_u \times r_v| \, dA. \quad (A.20)
$$

Remark A.36.

- $dS = |r_u \times r_v| \, dA$.
- For line integrals, $\int_{C} f(x, y, z) \, ds = \int_{a}^{b} f(r(t)) |r'(t)| \, dt$.
- When $z = g(x, y)$, $r_x \times r_y = \langle -g_x, -g_y, 1 \rangle$. Thus the formula (16.64) reads

$$
\iint_{S} f(x, y, z) \, dS = \iint_{D} f(x, y, g(x, y)) \sqrt{g_x^2 + g_y^2 + 1} \, dA. \quad (A.21)
$$

Surface Integrals of Vector Fields. Let $r$ be a parametric representation of $S$, from $D \subset \mathbb{R}^2$. The flux across the surface $S$ can be measured by

$$
\iint_{S} F \cdot dS \overset{\text{def}}{=} \iint_{S} F \cdot n \, dS
\quad = \quad \iint_{D} F(r) \cdot \left( \frac{r_u \times r_v}{|r_u \times r_v|} \right) |r_u \times r_v| \, dA
\quad = \quad \iint_{D} F(r) \cdot (r_u \times r_v) \, dA. \quad (A.22)
$$

Note that $F \cdot n$ and $F(r) \cdot (r_u \times r_v)$ are scalar functions.
A.37. Line integrals of vector fields is defined to measure quantities along the curve. That is, for $C$ parametrized by $\mathbf{r} : [a, b] \to C$,
\[
\int_C \mathbf{F} \cdot d\mathbf{r} \overset{\text{def}}{=} \int_C \mathbf{F} \cdot \mathbf{T} \, ds = \int_a^b \mathbf{F}(\mathbf{r}(t)) \cdot \frac{\mathbf{r}'(t)}{|\mathbf{r}'(t)|} \, |\mathbf{r}'(t)| \, dt = \int_a^b \mathbf{F}(\mathbf{r}(t)) \cdot \mathbf{r}'(t) \, dt.
\] (A.23)

Surfaces defined by $z = g(x, y)$:

- A vector representation: $\mathbf{r}(x, y) = (x, y, g(x, y))$.
- Normal vector: $\mathbf{r}_x \times \mathbf{r}_y = (-g_x, -g_y, 1)$.
- Thus, when $\mathbf{F} = (P, Q, R)$,
\[
\iint_S \mathbf{F} \cdot d\mathbf{S} = \iint_D \mathbf{F} \cdot (\mathbf{r}_x \times \mathbf{r}_y) \, dA = \iint_D (-P \, g_x - Q \, g_y + R) \, dA.
\] (A.24)

Problem A.38. Evaluate $\iint_S (x^2 + y^2 + z) \, dS$, where $S$ is the surface whose side $S_1$ is given by the cylinder $x^2 + y^2 = 1$, whose bottom $S_2$ is the disk $x^2 + y^2 \leq 1$ in the plane $z = 0$, and whose top $S_3$ is the disk $x^2 + y^2 \leq 1$ in the plane $z = 1$.

Solution. Hint: Use (A.19). Clue: $S_1 : x = \cos \theta, \ y = \sin \theta, \ z = z; \ (\theta, z) \in D \equiv [0, 2\pi] \times [0, 1]$. Then $|\mathbf{r}_\theta \times \mathbf{r}_z| = 1$.

Ans: $3\pi + \frac{1}{2}\pi + \frac{3}{2}\pi = 5\pi$
Problem A.39. Find the flux of $F = \langle x, y, 1 \rangle$ across a upward helicoid: $r(u, v) = \langle u \cos v, u \sin v, v \rangle$, $0 \leq u \leq 2$, $0 \leq v \leq \pi$.

Solution. **Hint:** Use (A.22). **Clue:** $r_u \times r_v = \langle \sin v, -\cos v, u \rangle$.

\[\text{Ans: } 2\pi\]
Problem A.40. Evaluate \( \iint_S F \cdot dS \), where \( F = \langle x, y, z \rangle \) and \( S \) is the boundary of the solid region \( E \) enclosed by the paraboloid \( z = 1 - x^2 - y^2 \) and the plane \( z = 0 \).

Solution. Clue: For \( S_1 \) (the upper part), use the formula in (A.24). For \( S_2 \) (the bottom: \( z = 0 \)), you may try to get \( F \cdot n \), where \( n = -\mathbf{k} \).

Ans: \( \frac{3\pi}{2} + 0 = \frac{3\pi}{2} \)
A.11. (§16.8) Stokes’s Theorem

Stokes’s Theorem is a high-dimensional version of Green’s Theorem studied in § 16.4.

Recall: (Green’s Theorem, p. 274). Let \( C \) be positively oriented, piecewise-smooth, simple closed curve in the plane and \( D \) be the region bounded by \( C \). If \( F = \langle P, Q \rangle \) have continuous partial derivatives on an open region including \( D \), then

\[
\oint_C F \cdot dr \overset{\text{def}}{=} \int_C P \, dx + Q \, dy = \iint_D \left( \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) \, dA = \iiint_D (\text{curl } F) \cdot k \, dA. \tag{A.25}
\]

Theorem A.41. (Stokes’s Theorem) Let \( S \) be an oriented piecewise-smooth surface that is bounded by a simple, closed, piecewise-smooth curve \( C \) with positive orientation. Let \( F = \langle P, Q, R \rangle \) be a vector field whose components have continuous partial derivatives on an open region in \( \mathbb{R}^3 \) that contains \( S \). Then

\[
\oint_C F \cdot dr = \iint_S (\text{curl } F) \cdot dS \tag{A.26}
\]

Remark A.42.

- See Figure 16.29(left) on p. 216, for an oriented surface of which the boundary has positive orientation.
- Computation of the surface integral: for \( r : D \to S \),

\[
\iint_S (\text{curl } F) \cdot dS \overset{\text{def}}{=} \iint_S (\text{curl } F) \cdot n \, dS = \iint_D (\text{curl } F) \cdot (ru \times rv) \, dA. \tag{A.27}
\]

- Green’s Theorem is a special case in which \( S \) is flat and lies on the \( xy \)-plane (\( n = k \)). Compare the last terms in (A.25) and (A.27).

Try to solve problems in Section 16.8, once more.
A.12. (§16.9) The Divergence Theorem

**Theorem** A.43. (Divergence Theorem) Let $E$ be a simple solid region and $S$ be the boundary surface of $E$, given with positive (outward) orientation. Let $\mathbf{F} = \left\langle P, Q, R \right\rangle$ have continuous partial derivatives on an open region that contains $E$. Then

$$\iiint_S \mathbf{F} \cdot d\mathbf{S} = \iiint_E \nabla \cdot \mathbf{F} \, dV.$$  \hspace{1cm} (A.28)

**Problem** A.44. Use the Divergence Theorem to evaluate the (total) flux $\iint_S \mathbf{F} \cdot dS$, where

$$\mathbf{F}(x, y, z) = (x + y^2 + \cos z) \mathbf{i} + [\sin(\pi z) + xe^{-z}] \mathbf{j} + z \mathbf{k}$$

and $S$ is a part of the cylinder $x^2 + y^2 = 4$ that lies between $z = 0$ and $z = 1$.

**Solution.**

**Ans:** $8\pi$
Problem A.45. Use the Divergence Theorem to evaluate

\[ \iiint_S \left( x^2 + y \sin x + \frac{z^2}{2} \right) dS, \]

where \( S \) is the unit sphere \( x^2 + y^2 + z^2 = 4 \).

Solution. Clue: What is \( n \)?

Answer: \( 32\pi \)
Bibliography


Index

CAS, 30, 64, 111, 115, 154, 221, 256
3D plots in Maple, 74

absolute extrema, 63
absolute maximum value, 59
absolute minimum value, 59
adaptive step length, 252
arc length, 112, 156
average value, 87

backtracking line search, 252
boundary, finite, 188
boundary, oriented, 188

calculus of variations, 240
Cauchy, Augustin-Louis, 247
center of mass, 107, 160, 169
chain rule, 45
change of variables, 132, 209
circle, 3
circular helix, 165
circular slice, 144
Clairaut's theorem, 37, 152
closed curve, 172
comparison function, 242
computer algebra, 31
connected set, 174
conservative vector field, 151, 170, 236, 272
constraint, 65
constraint set, 247
continuous function, 28
contourplot, 64
convert, in Maple, 64
critical point, 59
cross product, 7
curl, 192
curvature, 245
cylinder, 14
cylindrical coordinate system, 123
definite integral, 80
del, 192
delta-epsilon argument, 25
denoising, 241
density, 106
dependent variable, 18
Descartes, René, 97
determinant, 268
differentiable, 32, 42, 44
differentials, 43
directed distance, 107
directional derivative, 51, 260
distance, 2
divergence, 195
Divergence Theorem, 219, 226, 237, 281
domain, 18, 247
dot product, 6
double integral, 81
END, 246
energy descent direction, 245
epsilon-delta argument, 25
equalized net diffusion, 246
Euclidean inner product, 6
Euler-Lagrange equation, 242, 243
existence of absolute extrema, 63
expected values, 110
ezsurf, in Matlab, 31

fastest increasing direction, 23
feasible solution, 239
fieldplot, Maple, 154, 155
First Derivative Test, 59
first moment, 107
flux, 217
Fubini’s Theorem, 84, 116
function of three variables, 23
function of two variables, 18
Fundamental Theorem for Line Integrals, 170
Fundamental Theorem of Calculus, 80, 170

Gaussian homotopy continuation, 254
Gaussian smoothing, 254
GD.m, 255
gd1D.m, 255
generalized Green’s Theorem, 188
gradient, 54
gradient descent method, 247
gradient vector field, 151
graph, 19
Green’s Theorem, 182, 230, 236, 274

heart-data.txt, 230, 231
heart.m, 230
helicoid, 218, 221
helix, 165
hypervolume, 104

ID function, 76
image, 133, 268
image processing, 241, 245
implicit differentiation, 35, 48
implicitplot3d, 35
improved TV model, 246
incompressible, 196
independence of path, 172
independent variable, 18
integration by parts, 243
Introduction to Linear Algebra, 268
iterated integral, 84, 99, 264
ITV model, 246

Jacobian, 134, 135, 209, 268
Jacobian, higher order, 139
joint density function, 109

Lagrange multiplier, 65, 240, 262
land-grant research university, 39
Laplace operator, 196

learning rate, 249
length, 4
level curve, 20
level surface, 23
limit, 25
line integral, 157, 270
line integral in 3D, 164
line integral of vector fields, 167, 270
linear algebra, 268
linear approximation, 41, 77, 258
linearization, 41, 77
local extrema, 59
local maximum, 59
local minima problem, 254
local minimum, 59

magnitude, 4
Maple 3D plots, 74
Maple script for $V_0$, 146
mass, 106, 160, 169
mathematical denoising, 241
MATLAB, 256
mean, 110
method of Lagrange multipliers, 240
mid-point approximation, 231
mid-point formula, 230
midpoint rule, 82
Mississippi State University, 39
moment, 107
multiple integral, 79
multiple local minima problem, 254

n-Ball, 104
n-dimensional ball, 104
negative orientation of curves, 182
Newton’s method, 75
Newton, Isaac, 97
nonconservative, 152
norm, 4
normal line, 57, 260
normal vector, outward unit, 197

objective function, 247
one-to-one, 133, 135, 268
open connected region, 174
open set, 174
optimization, 239
optimization problem, 239, 247
orientable, 216
orientation of curves, 163
oriented surface, 216
parametric equations, 156
parametric surface, 199
parametrization of line, 10
parametrization of line segment, 10
partial derivative, 33
partial integral w.r.t \( x \), 83
partial integral w.r.t \( y \), 83
peak signal-to-noise ratio, 246
piecewise smooth curve, 159
plane, 12, 205
plane curve, 156
plot3d, 64
polar point, 97
polar rectangle, 99
polar region, 102
position vector, 4
positive orientation, 216
positive orientation of curves, 182
potential, 151, 170
potential function, 151, 170
probability, 109
probability density function, 109
Projects, 72, 143, 230
PSNR, 246
quadratic approximation, 77
quadric surface, 15
range, 18
Riemann Sum, 80
right-hand rule, 8
root-finding, 75
Rosenbrock function, 248
sample point, 81
scalar multiplication, 5
scaling factor, 209
Second Derivative Test, 59, 60
second partial derivative, 37
sectors, 98
separable function, 86
simple curve, 172
simply-connected region, 175
smooth surface, 205
spherical coordinates, 127
spherical Fubini’s Theorem, 130
spherical slice, 144
spherical wedge, 128
square_sum.m, 232
squeeze theorem, 28
staircasing, 245
standard deviation, 240
standard unit vectors, 5
steepest descent, 249
steepest descent method, 247
step length, 249
Stokes’ Theorem, 237
Stokes’s Theorem, 222, 280
sufficient decrease condition, 252
surface area, 112, 207, 208
surface integral, 217
surface of revolution, 204
symbolic computation, 31
symmetry, 87
tangent line, 40
tangent plane, 40, 41, 57, 205, 258, 260
tangent plane approximation, 258
tangent vector, 134
tangential component, 167, 270
Taylor polynomial of degree \( n \), 72
Taylor polynomial, first-degree, 77
Taylor polynomial, second-degree, 77
Taylor series, 72
Taylor’s Theorem, with integral remainder, 250
taylor, in Maple, 72
tornado, 192
total differential, 43
total variation, 241
total variation model, 245
trace, 15
transformation, 132, 133, 268
transformation, \( C^1 \), 135
trigonometric formulas, 98
triple integral, 116
triple integral on spherical wedges, 129
TV model, 245

unit ball, 143
unit circle, 104
unit interval, 104
unit sphere, 104
unit vector, 5

variational calculus, 240
vector, 4

vector addition, 4
vector differential operator del, 192
vector equation, 156
vector field, 148
volume, 120
volume of n-Ball, 104
volume scaling factor, 268
work, 157, 166

X-mean, 110
Y-mean, 110