

MAT237: Multivariable Calculus

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Contents

1	Limits, continuity, and related topics	2
2	Differentiation and related topics	2
2.1	.....	2
2.2	.....	2
2.3	.....	2
2.4	.....	2
2.5	.....	2
2.6	.....	2
2.7	.....	2
2.8	Optimization	2
3	The Implicit and Inverse Function Theorems	3
3.1	The Implicit Function Theorem I	3
3.2	Geometric content of the Implicit Function Theorem	3
3.3	Transformations, and the Inverse Function Theorem	4
4	Integration	5
4.1	Basics	5
4.2	Integration on Higher Dimensions	5
4.3	Iterated Integrals	7
4.4	Change of Variables	7
4.5	Further Aspects	8
4.5.1	Exchanging Differentiation and Integration	8
4.5.2	Improper Integrals	8
5	Vector Calculus	9
5.1	Line Integrals	9
5.1.1	Arc Length	9
5.1.2	Line Integrals of Scalar Functions	10
5.1.3	Line Integrals of Vector Fields	10
5.1.4	Rectifiable Curves	11
5.2	Green's Theorem	11
5.2.1	Preliminary Definitions	11
5.3	Surface Integrals	12
5.3.1	Surface Areas and Surface Integrals	12

5.3.2	An invariance property	13
5.3.3	Volume and Area	14
5.4	Divergence, Gradient and Curl	14
5.5	Divergence Theorem	14
5.6	Stokes Theorem	16
5.6.1	Stokes Theorem in \mathbb{R}^3	16
5.6.2	The Generalization	17

1 Limits, continuity, and related topics

2 Differentiation and related topics

2.1

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2.3

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2.6

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2.8 Optimization

Theorem 2.8.1. Let $S \subset \mathbb{R}^n$ be an open set and $f, g : S \rightarrow \mathbb{R}$ be C^1 functions. If \mathbf{x} is a *local extremal* satisfying $g(\mathbf{x}) = 0$, and $\nabla g(\mathbf{x}) \neq \mathbf{0}$, then

$$\exists \lambda \in \mathbb{R} \text{ s.t. } \begin{cases} \nabla f(\mathbf{x}) = \lambda \nabla g(\mathbf{x}) \\ g(\mathbf{x}) = 0 \end{cases} \quad (2.8.1)$$

Lemma 2.8.1. $\nabla g(\mathbf{x})$ is orthogonal to the constraint set $g^{-1}(0)$.

Proposition 2.8.1. Equations (2.8.1) $\implies \nabla f(\mathbf{x}) \perp g^{-1}(0)$ at \mathbf{x} .

Theorem 2.8.2. Let $S \subseteq \mathbb{R}^n$ be an open set, and $f, \{g_i\}_{i=1}^k : S \rightarrow \mathbb{R}$ be C^1 functions. Define $\mathbf{g}(\mathbf{x}) : \mathbb{R}^n \rightarrow \mathbb{R}^k \equiv (g_1(\mathbf{x}), g_2(\mathbf{x}), \dots, g_k(\mathbf{x}))$.

If $\mathbf{x} \in S$ is a *local extremal* of f such that $\mathbf{g}(\mathbf{x}) = \mathbf{0}$, and $\{\nabla g_i(\mathbf{x})\}$ are linearly independent (i.e. $\text{rank}(D\mathbf{g}(\mathbf{x})) = k$), then

$$\exists \boldsymbol{\lambda} \in \mathbb{R}^k \text{ s.t. } \begin{cases} \nabla f(\mathbf{x}) = \boldsymbol{\lambda}^T D\mathbf{g}(\mathbf{x}) \\ \mathbf{g}(\mathbf{x}) = \mathbf{0} \end{cases} \quad (2.8.2)$$

Remark 2.8.1. Procedure of optimization on *open sets*:

- (i) Find all critical points.
- (ii) Find optimizers among critical points.

Remark 2.8.2. Procedure of optimization with *inequality constraints*:

- (i) Find critical points without the constraints.
- (ii) Find critical points on the constraints.
- (iii) Find optimizers among candidates.

3 The Implicit and Inverse Function Theorems

3.1 The Implicit Function Theorem I

Theorem 3.1.1 (Implicit Function Theorem). Let $S \subseteq \mathbb{R}^{n+k}$ be an open set, and function $F : S \rightarrow \mathbb{R}^k$ be a C^1 function. Suppose there exists point $\mathbf{a} \in \mathbb{R}^n, \mathbf{b} \in \mathbb{R}^k$ such that

$$F(\mathbf{a}, \mathbf{b}) = \mathbf{0} \quad (3.1.1)$$

If

$$\det(D_{\mathbf{y}}(F(\mathbf{a}, \mathbf{b}))) \neq 0 \quad (3.1.2)$$

then there exists $r_0, r_1 > 0$ and a C^1 function $\mathbf{f} : \mathbb{R}^n \rightarrow \mathbb{R}^k$ such that

$$\forall \mathbf{x} \in \mathcal{B}(r_0, \mathbf{a}), \mathbf{f}(\mathbf{x}) \in \mathcal{B}(r_1, \mathbf{b}) \wedge F(\mathbf{x}, \mathbf{f}(\mathbf{x})) = \mathbf{0} \quad (3.1.3)$$

and define $\mathbf{y} \equiv \mathbf{f}(\mathbf{x})$, the derivative of \mathbf{f} can be found as

$$D\mathbf{f}(\mathbf{x}) = -[D_{\mathbf{y}}F(\mathbf{x}, \mathbf{y})]^{-1}D_{\mathbf{x}}F(\mathbf{x}, \mathbf{y}) \quad (3.1.4)$$

Remark 3.1.1. Procedure to prove solvability of non-linear equations

$$\mathbf{F}(\mathbf{x}, \mathbf{y}) = \mathbf{0} \quad (3.1.5)$$

near (\mathbf{a}, \mathbf{b}) .

(i) Verify $\mathbf{F}(\mathbf{a}, \mathbf{b}) = \mathbf{0}$.

(ii) Assert

$$\det(D_{\mathbf{y}}\mathbf{F}(\mathbf{a}, \mathbf{b})) \neq 0 \quad (3.1.6)$$

(iii) Approximate solution $\mathbf{y} = \mathbf{f}(\mathbf{x})$ using

$$\mathbf{f}(\mathbf{x} + \mathbf{h}) \approx \mathbf{a} + D\mathbf{f}(\mathbf{a})\mathbf{h} \quad (3.1.7)$$

$$= \mathbf{a} - [D_{\mathbf{y}}\mathbf{F}(\mathbf{a}, \mathbf{b})]^{-1}D_{\mathbf{x}}\mathbf{F}(\mathbf{a}, \mathbf{b}) \quad (3.1.8)$$

3.2 Geometric content of the Implicit Function Theorem

Definition 3.2.1. Let $S \subseteq \mathbb{R}^n$ and $\mathbf{a} \in S$. S is **singular** at \mathbf{a} if

$$\forall r > 0 \ S \cap \mathcal{B}(r, \mathbf{a}) \text{ cannot be represented as a } C^1 \text{ graph.} \quad (3.2.1)$$

S is **regular** at \mathbf{a} if it is not singular there.

Theorem 3.2.1 (k dimensional manifold as level set). Let $U \subseteq \mathbb{R}^n$ and let $\mathbf{F} : U \rightarrow \mathbb{R}^{n-k}$ be a C^1 function.

$$S \equiv \mathbf{F}^{-1}(\mathbf{0}) \quad (3.2.2)$$

Let $\mathbf{a} \in U$, if

$$\text{rank}(D\mathbf{F}(\mathbf{a})) = n - k \quad (3.2.3)$$

then $\exists r > 0$ such that the *level set of \mathbf{F} near \mathbf{a}*

$$\mathcal{B}(r, \mathbf{a}) \cap S \quad (3.2.4)$$

can be represented as a C^1 graph.

Theorem 3.2.2 (k dimensional manifold as parameterization). Let $T \subseteq \mathbb{R}^k$ and let $\mathbf{f} : U \rightarrow \mathbb{R}^n$ be a C^1 function.

$$S \equiv \mathbf{f}(T) \quad (3.2.5)$$

Let $\mathbf{t} \in T$, if

$$\text{rank}(\mathbf{f}(\mathbf{t})) = k \quad (3.2.6)$$

then $\exists r > 0$ such that the *parameterization of \mathbf{f} near \mathbf{t}*

$$\mathbf{f}(T \cap \mathcal{B}(r, \mathbf{t})) \quad (3.2.7)$$

can be represented as a C^1 graph.

3.3 Transformations, and the Inverse Function Theorem

Example 3.3.1 (Polar coordinate in \mathbb{R}^2). Let

$$U \equiv \{(r, \theta) : r > 0 \wedge \theta \in (-\pi, \pi)\} \quad (3.3.1)$$

$$V \equiv \mathbb{R}^2 \setminus \{(x, 0) : x \leq 0\} \quad (3.3.2)$$

Define $\mathbf{f} : U \rightarrow V$ as

$$\mathbf{f}(r, \theta) \equiv \begin{pmatrix} r \cos(\theta) \\ r \sin(\theta) \end{pmatrix} \quad (3.3.3)$$

Example 3.3.2 (Spherical coordinate in \mathbb{R}^3). Define

$$\mathbf{f}(r, \theta, \varphi) = \begin{pmatrix} r \cos(\theta) \sin(\varphi) \\ r \sin(\theta) \sin(\varphi) \\ r \cos(\varphi) \end{pmatrix} \quad (3.3.4)$$

Example 3.3.3 (Cylindrical coordinate in \mathbb{R}^3). Define

$$\mathbf{f}(r, \theta, z) = \begin{pmatrix} r \cos(\theta) \\ r \sin(\theta) \\ z \end{pmatrix} \quad (3.3.5)$$

Theorem 3.3.1 (Inverse Function Theorem). Let U and V be open subsets in \mathbb{R}^n , and $\mathbf{f} : U \rightarrow V$. Let $\mathbf{a} \in U$ and define $\mathbf{b} \equiv \mathbf{f}(\mathbf{a}) \in V$. If

$$\det(D\mathbf{f}(\mathbf{a})) \neq 0 \quad (3.3.6)$$

then there exists $M \subseteq U$ and $N \subseteq V$ such that

- (i) $\mathbf{a} \in M$ and $\mathbf{b} \in N$,
- (ii) \mathbf{f} is bijective between M and N ,
- (iii) $\mathbf{f}^{-1} : N \rightarrow M$ is C^1 ,

and **for all $\mathbf{x} \in M$** such $\mathbf{y} \equiv \mathbf{f}(\mathbf{x}) \in N$,

$$D\mathbf{f}^{-1}(\mathbf{y}) = [D\mathbf{f}(\mathbf{x})]^{-1} \quad (3.3.7)$$

4 Integration

4.1 Basics

Theorem 4.1.1 (**Properties of infimum and supremum**). Let $A \subseteq \mathbb{R}^n$ and $A \neq \emptyset$, and $f, g : A \rightarrow \mathbb{R}$ are bounded functions. Let m and M denote the infimum and supremum respectively, then

- (i) $m_A f + m_A g \leq m_A(f + g) \leq M_A(f + g) \leq M_A f + M_A g$
- (ii) If $A' \subseteq A$, then $m_A f \leq m_{A'} f \leq M_{A'} f \leq M_A f$
- (iii) If $f(\mathbf{x}) \leq g(\mathbf{x}) \forall \mathbf{x} \in A$, then $m_A f \leq m_A g$ and $M_A f \leq M_A g$
- (iv) $|M_A f| \leq M_A |f|$
- (v) $M_A |f| - m_A |f| \leq M_A f - m_A f$
- (vi) $\forall c \in \mathbb{R}, M_A(cf) - m_A(cf) = |c|(M_A f - m_A f)$
- (vii) $M_A f - m_A f = \sup\{f(x) - f(y) : x, y \in A\}$

4.2 Integration on Higher Dimensions

Definition 4.2.1. A rectangle $\mathcal{R} \subseteq \mathbb{R}^n$ is defined as

$$\mathcal{R} \equiv \prod_{i=1}^n [a_i, b_i] \quad (4.2.1)$$

where $a_i, b_i \in \mathbb{R}$ and $a_i < b_i$.

Definition 4.2.2. A **partition** P of rectangle $\mathcal{R} = \prod_{i=1}^n [a_i, b_i]$ is a list of n **finite** and increasing list of real numbers

$$P = \{L_1, L_2, \dots, L_n\} \quad (4.2.2)$$

where $L_i = \{e_j\}_{j=0}^{T_i}$ such that

$$a_i = e_0 < e_1 < \dots < e_{T_i} = b_i \quad (4.2.3)$$

and such partition induces a set of rectangles(boxes) $\mathcal{B}(P) \equiv \{B_j\}_{j=1}^J \subseteq \mathcal{R}$.

Definition 4.2.3. Let P and P' be two partitions of \mathcal{R} . Then P' is a **refinement** of P if

$$\forall B_j \in \mathcal{B}(P), B'_j \in \mathcal{B}(P') \quad B'_j \subseteq B_j \vee B'_j \cap B_j = \emptyset \quad (4.2.4)$$

Definition 4.2.4. Define the **volume** of rectangle $\mathcal{R} = \prod_{i=1}^n [a_i, b_i]$ as

$$V^n(\mathcal{R}) \equiv \prod_{i=1}^n (b_i - a_i) \quad (4.2.5)$$

Definition 4.2.5. The **lower Riemann sum** of f with partition P on \mathcal{R} is defined as

$$L_P f \equiv \sum_{B_j \in \mathcal{B}(P)} \inf_{\mathbf{x} \in B_j} f(\mathbf{x}) V^n(B_j) \quad (4.2.6)$$

and the **upper Riemann sum** is defined as

$$U_P f \equiv \sum_{B_j \in \mathcal{B}(P)} \sup_{\mathbf{x} \in B_j} f(\mathbf{x}) V^n(B_j) \quad (4.2.7)$$

Definition 4.2.6. The **upper integral** and **lower integral** of f on \mathcal{R} are defined as

$$\bar{I}_{\mathcal{R}}f \equiv \inf_P U_P f \quad (4.2.8)$$

$$\underline{I}_{\mathcal{R}}f \equiv \sup_P L_P f \quad (4.2.9)$$

Definition 4.2.7. A bounded real-valued function f defined on \mathcal{R} is **integrable** if

$$\underline{I}_{\mathcal{R}}f = \bar{I}_{\mathcal{R}}f \quad (4.2.10)$$

and the integral is defined as

$$\int \cdots \int_{\mathcal{R}} f \, dV^n \equiv \underline{I}_{\mathcal{R}}f = \bar{I}_{\mathcal{R}}f \quad (4.2.11)$$

Lemma 4.2.1. Let f be a bounded real-valued function defined on \mathcal{R} , f is integrable if and only if $\forall \epsilon > 0$, there exists a partition P of \mathcal{R} such that

$$U_P f - L_P f < \epsilon \quad (4.2.12)$$

Theorem 4.2.1. Let f and g be two integrable functions on $\mathcal{R} \subseteq \mathbb{R}^n$, let $c \in \mathbb{R}$,

- (i) $f + g : \mathcal{R} \rightarrow \mathbb{R}$ is integrable and $\int_{\mathcal{R}}(f + g) = \int_{\mathcal{R}} f + \int_{\mathcal{R}} g$
- (ii) $c \cdot f$ is integrable and $\int_{\mathcal{R}} c \cdot f = c \int_{\mathcal{R}} f$
- (iii) $f(\mathbf{x}) \geq g(\mathbf{x}) \, \forall \mathbf{x} \in \mathcal{R} \implies \int_{\mathcal{R}} f \geq \int_{\mathcal{R}} g$
- (iv) $|f|$ is integrable and $|\int_{\mathcal{R}} f| \leq \int_{\mathcal{R}} |f|$

Definition 4.2.8. Let $S \subseteq \mathbb{R}^n$ be a bounded set, and there exists rectangle \mathcal{R} covers S , the **indicator function** of S is $\chi_S : \mathcal{R} \rightarrow \{0, 1\}$, defined as

$$\chi_S(\mathbf{x}) \equiv \mathbb{I}(\mathbf{x} \in S) \quad (4.2.13)$$

Definition 4.2.9. Let $S \subseteq \mathbb{R}^n$ be a bounded set, and there exists rectangle \mathcal{R} covers S . Let $f : \mathcal{R} \rightarrow \mathbb{R}$ be a bounded function, then f is **integrable on S** if $\chi_S f$ is integrable on \mathcal{R} . And

$$\int \cdots \int_S f \, dV^n \equiv \int \cdots \int_{\mathcal{R}} \chi_S f \, dV^n \quad (4.2.14)$$

Definition 4.2.10. Let $Z \subseteq \mathbb{R}^n$, Z has **zero content** if for all $\epsilon > 0$, there exists a finite set of rectangles $\{R_\ell\}_{\ell=1}^L$ covers Z and

$$\sum_{\ell=1}^L V^n(R_\ell) < \epsilon \quad (4.2.15)$$

Proposition 4.2.1. Let $Z \subseteq \mathbb{R}^n$ has zero content, then

- (i) For any $Z' \subseteq Z$, Z' has zero content.
- (ii) Finite union of content zero sets has zero content.
- (iii) Let $f : [a, b] \rightarrow \mathbb{R}$ be an integrable function, it's graph $\{(x, f(x)) : x \in [a, b]\}$ has zero content.
- (iv) Let $\mathbf{f} : [a, b] \rightarrow \mathbb{R}^2$ be a C^1 function, the parameterization $\mathbf{f}([a, b])$ has zero content.

Theorem 4.2.2. Let \mathcal{R} be a rectangle in \mathbb{R}^n and f is integrable on \mathcal{R} if

$$\{\mathbf{x} \in \mathcal{R} : f \text{ is discontinuous at } \mathbf{x}\} \quad (4.2.16)$$

has zero content.

Proposition 4.2.2 (Folland 4.22). Suppose $Z \subseteq \mathbb{R}^n$ has zero content. If $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is bounded, then f is integrable on Z and $\int_Z f \, dV^n = 0$.

4.3 Iterated Integrals

Theorem 4.3.1 (Fubini's Theorem). Let $\mathcal{R} = [a, b] \times [c, d] \subseteq \mathbb{R}^2$ and $f : \mathcal{R} \rightarrow \mathbb{R}$ is bounded. Assuming that

- (i) f is integrable on \mathcal{R} .
- (ii) for each $y \in [c, d]$, the function $f_y(x) \equiv f(x, y)$ is integrable on $[a, b]$.
- (iii) Define $g(y) \equiv \int_a^b f(x, y) dx$ is integrable on $[c, d]$.

Then

$$\iint_{\mathcal{R}} f \, dA = \int_c^d \left(\int_a^b f(x, y) \, dx \right) dy \quad (4.3.1)$$

Proposition 4.3.1. Let $S \subseteq \mathbb{R}^n$ be an unbounded set, and $f : S \rightarrow \mathbb{R}$. Then improper integral $\int \cdots \int_S f \, d^n \mathbf{x}$ is absolutely convergent on \mathbb{R}^n if and only if $\int \cdots \int_{\mathbb{R}^n} \chi_S f \, d^n \mathbf{x}$ is absolutely convergent.

4.4 Change of Variables

Theorem 4.4.1 (Change of Variable). Let U and V be two open subsets of \mathbb{R}^n , and let $\mathbf{G} : U \rightarrow V$ be a C^1 bijection. Let $T \subset U$ and $S \subset V$. Suppose $\mathbf{G}(T) = S$, then

$$\int \cdots \int_S f \, d\Omega = \int \cdots \int_T f \circ \mathbf{G} \, |\det D\mathbf{G}| \, d\Theta \quad (4.4.1)$$

Corollary 4.4.1. Let S be a region in \mathbb{R}^n , suppose S can be parameterized by $\mathbf{G} : T \rightarrow S$. By the change of variable formula, consider the special case $f(\mathbf{x}) = 1$,

$$|S| = \int \cdots \int_S 1 \, d\Omega = \int \cdots \int_T 1 \, |\det D\mathbf{G}(\mathbf{u})| \, d\Theta \quad (4.4.2)$$

Example 4.4.1 (Polar Coordinate). Define the coordinate transformation mapping from polar to Cartesian,

$$\mathbf{P}(r, \theta) \equiv (x, y) = \begin{pmatrix} r \cos \theta \\ r \sin \theta \end{pmatrix}, \quad \theta \in [0, 2\pi] \quad r \in \mathbb{R}_+ \quad (4.4.3)$$

and $|\det D\mathbf{P}(r, \theta)| = r$.

Example 4.4.2 (Cylindrical Coordinate). Define the coordinate transformation mapping from cylindrical to Cartesian as

$$\mathbf{C}(r, \theta, z) \equiv (x, y, z) = \begin{pmatrix} r \cos \theta \\ r \sin \theta \\ z \end{pmatrix}, \quad \theta \in [0, 2\pi] \quad r \in \mathbb{R}_+ \quad z \in \mathbb{R} \quad (4.4.4)$$

and $|\det D\mathbf{C}(r, \theta, z)| = r$.

Example 4.4.3 (Spherical Coordinate). Define the coordinate transformation mapping from spherical to Cartesian as

$$\mathbf{S}(r, \theta, \varphi) = \begin{pmatrix} r \cos \theta \sin \varphi \\ r \sin \theta \sin \varphi \\ r \cos \varphi \end{pmatrix} \quad (4.4.5)$$

and $|\det D\mathbf{S}(r, \theta, \varphi)| = r^2 \sin \varphi$

4.5 Further Aspects

4.5.1 Exchanging Differentiation and Integration

Theorem 4.5.1 (Exchanging Differentiation and Integration). Let $f(\mathbf{x}, \mathbf{t}) : S \times T \rightarrow \mathbb{R}$ and define $F(\mathbf{x}) : S \rightarrow \mathbb{R}$ as

$$F(\mathbf{x}) \equiv \int \cdots \int_T f(\mathbf{x}, \mathbf{t}) \, d\Omega \quad (4.5.1)$$

If

- (i) S is open and T is compact and bounded;
- (ii) f and F are continuous on their domains;
- (iii) and $\forall x_j \in \mathbf{x}$, $\frac{\partial f(\mathbf{x}, \mathbf{t})}{\partial x_j}$ is continuous,

then F is C^1 in S and for every j ,

$$\frac{\partial F(\mathbf{x})}{\partial x_j} = \int \cdots \int_T \frac{\partial f(\mathbf{x}, \mathbf{t})}{\partial x_j} \, d\Omega \quad (4.5.2)$$

Corollary 4.5.1. By the definition of partial derivative, above theorem is equivalent to

$$\lim_{h \rightarrow 0} \int \cdots \int_T \frac{f(\mathbf{x} + h\mathbf{e}_j, \mathbf{t})}{h} \, d\Omega = \int \cdots \int_T \lim_{h \rightarrow 0} \frac{f(\mathbf{x} + h\mathbf{e}_j, \mathbf{t})}{h} \, d\Omega \quad (4.5.3)$$

4.5.2 Improper Integrals

Definition 4.5.1 (Unbounded Domains). An **improper integral** with unbounded domain $\int \cdots \int_{\mathbb{R}^n} f \, d\Omega$ is **absolutely convergent** if there exists $L \in \mathbb{R}$ such that

$$\forall \varepsilon > 0 \, \exists R > 0 \text{ s.t. } \forall S \subseteq \mathbb{R}^n \, B(R, \mathbf{0}) \subset S \implies \left| \int \cdots \int_S f \, d\Omega - L \right| < \varepsilon \quad (4.5.4)$$

Theorem 4.5.2. Let $f : \mathbb{R}^n \rightarrow \mathbb{R}$ be a continuous function, and that

$$\lim_{R \rightarrow \infty} \int \cdots \int_{B(R, \mathbf{0})} |f| \, d\Omega \text{ exists} \quad (4.5.5)$$

then $\int \cdots \int_{\mathbb{R}^n} f \, d\Omega$ is absolutely convergent.

Corollary 4.5.2 (Equivalence). Above improper integral $\int \cdots \int_{\mathbb{R}^n} f \, d\Omega$ is absolutely convergent if set

$$\left\{ \int \cdots \int_{B(R, \mathbf{0})} |f| \, d\Omega : R \in \mathbb{R}_{++} \right\} \quad (4.5.6)$$

is bounded.

Corollary 4.5.3. Let $f : \mathbb{R}^n \rightarrow \mathbb{R}$ be a continuous function, if

$$\exists p > n, \, C > 0 \text{ s.t. } |f(\mathbf{x})| \leq \frac{1}{\|\mathbf{x}\|^p} \, \forall \mathbf{x} \in \mathbb{R}^n \quad (4.5.7)$$

then $\int \cdots \int_{\mathbb{R}^n} f \, d\Omega$ is absolutely convergent.

Definition 4.5.2 (Unbounded Function). Let $S \subset \mathbb{R}^n$, $\mathbf{a} \in \mathbb{R}^n$. Consider a function $f : S \setminus \{\mathbf{a}\} \rightarrow \mathbb{R}$. Then the improper integral $\int \cdots \int_S f d\Omega$ is absolutely convergent if

$$\exists L \in \mathbb{R} \text{ s.t. } \forall \varepsilon > 0 \exists r > 0 \text{ s.t. } \forall U \subset S \text{ s.t. } \mathbf{a} \in U^{\text{int}} \wedge U \subset B(r, \mathbf{a}), \left| \int \cdots \int_{S \setminus U} f d\Omega - L \right| < \varepsilon \quad (4.5.8)$$

Theorem 4.5.3. Let $f : S \setminus \{\mathbf{a}\} \rightarrow \mathbb{R}$, if

$$\lim_{r \rightarrow 0} \int \cdots \int_{S \setminus B(r, \mathbf{a})} |f| d\Omega \text{ exists} \quad (4.5.9)$$

then $\int \cdots \int_S f d\Omega$ is absolutely convergent.

Corollary 4.5.4 (Equivalence). If the set

$$\left\{ \iint_{S \setminus B(r, \mathbf{a})} |f| d\Omega : r \in \mathbb{R}_{++} \right\} \quad (4.5.10)$$

is bounded, then $\int \cdots \int_S f d\Omega$ is absolutely convergent.

Corollary 4.5.5. Let $f : S \setminus \{\mathbf{a}\} \rightarrow \mathbb{R}$, if

$$\exists p < n, C > 0 \text{ s.t. } |f(\mathbf{x})| \leq \frac{C}{\|\mathbf{x} - \mathbf{a}\|^p} \quad \forall \mathbf{x} \in S \setminus \{\mathbf{a}\} \quad (4.5.11)$$

then the improper integral $\int \cdots \int_S f d\Omega$ is absolutely convergent.

5 Vector Calculus

5.1 Line Integrals

5.1.1 Arc Length

Definition 5.1.1. Let C be a smooth curve in \mathbb{R}^n parameterized by C^1 function \mathbf{g} such that $\mathbf{g}'(t) \neq \mathbf{0}$ for every appropriate t .

$$C \equiv \{\mathbf{g}(t) : t \in [a, b]\} \quad (5.1.1)$$

and the **arc length** of C is defined as

$$\int_C d^n \mathbf{x} \equiv \int_C ds \equiv \int_a^b \|\mathbf{g}'(t)\| dt \quad (5.1.2)$$

Proposition 5.1.1. The arc length of a curve C is an intrinsic property of the geometric object C and should not depend on the particular parameterization we use.

Proof. Let $\varphi : [c, d] \rightarrow [a, b]$ be a bijection, so that $\mathbf{h} \equiv \mathbf{g} \circ \varphi$ is also a valid parameterization of C such that

$$C \equiv \{\mathbf{h}(u) : u \in [c, d]\} \quad (5.1.3)$$

The arc length of C can be computed using

$$\int_C ds = \int_c^d \|\mathbf{h}'(u)\| du \quad (5.1.4)$$

$$= \int_c^d \|\mathbf{g}'(\varphi(u))\| \times \|\varphi'(u)\| du \quad (5.1.5)$$

$$= \int_a^b \|\mathbf{g}'(t)\| dt \text{ by change of variable formula.} \quad (5.1.6)$$

■

Remark 5.1.1 (Interpretations). Suppose \mathbf{g} is a parameterization of C .

- (i) $\int_a^b \mathbf{g}'(t) dt = \mathbf{g}(b) - \mathbf{g}(a)$ measures the distance between two endpoints of C .
- (ii) Choosing a parameterization is effectively choosing an **orientation** for the curve C .

Definition 5.1.2. A function $\mathbf{g} : [a, b] \rightarrow \mathbb{R}^n$ is called **piecewise smooth** if

- (i) it's *continuous*, and
- (ii) it's derivate exists and is continuous except at finitely many points t_j , at which the one-sided limits exists.

5.1.2 Line Integrals of Scalar Functions

Definition 5.1.3. Let smooth curve $C \subseteq \mathbb{R}^n$, $f : C \rightarrow \mathbb{R}$ and \mathbf{g} be a parameterization of C , then

$$\int_C f ds = \int_a^b f(\mathbf{g}(t)) \|\mathbf{g}'(t)\| dt \quad (5.1.7)$$

Remark 5.1.2. The line integrals of scalar functions are also independent from the choices of parameterizations.

Definition 5.1.4.

$$\text{Average of } f \text{ over } C \equiv \frac{\int_C f ds}{\int_C ds} \quad (5.1.8)$$

5.1.3 Line Integrals of Vector Fields

Definition 5.1.5. Let smooth $C \in \mathbb{R}^n$ with parameterization \mathbf{g} and $\mathbf{F} : C \rightarrow \mathbb{R}^n$ defined on it, the **line integral** of \mathbf{F} over C is defined as

$$\int_C \mathbf{F} \cdot d\mathbf{x} = \int_a^b \mathbf{F}(\mathbf{g}(t)) \cdot \mathbf{g}'(t) dt \quad (5.1.9)$$

Proposition 5.1.2. The line integral $\int_C \mathbf{F} \cdot d\mathbf{x}$ is independent of the parameterization *as long as the orientation is unchanged*.

Theorem 5.1.1 (The Fundamental Theorem of Line Integral). Let $f : C \rightarrow \mathbb{R}$ defined on smooth curve C parameterized by $\mathbf{g} : [a, b] \rightarrow \mathbb{R}^n$, then

$$\int_C \nabla f(\mathbf{x}) \cdot d^n \mathbf{x} = f(\mathbf{g}(b)) - f(\mathbf{g}(a)) \quad (5.1.10)$$

Proof.

$$\int_C \nabla f(\mathbf{x}) \cdot d^n \mathbf{x} = \int_a^b \frac{\partial f(\mathbf{g}(t))}{\partial \mathbf{g}(t)} \cdot \mathbf{g}'(t) dt \quad (5.1.11)$$

$$= \int_a^b \frac{\partial f(\mathbf{g}(t))}{\partial t} dt = f(\mathbf{g}(b)) - f(\mathbf{g}(a)) \quad (5.1.12)$$

■

5.1.4 Rectifiable Curves

Remark 5.1.3. Let C be a curve in \mathbb{R}^n parameterized by injection $\mathbf{g} : [a, b] \rightarrow \mathbb{R}^n$ such that $\mathbf{g}'(t) \neq \mathbf{0}$. Let P be a partition of $[a, b]$. Denote

$$L_P(C) \equiv \sum_j \|\mathbf{g}(t_j) - \mathbf{g}(t_{j-1})\| \quad (5.1.13)$$

Definition 5.1.6. A curve C is **rectifiable** if the set $\{L_P(C) : P\}$ is bounded. And the arc length of C is defined as

$$L(C) \equiv \sup\{L_P(C) : P\} \quad (5.1.14)$$

Theorem 5.1.2. The supremum found above, $L(C)$ is the precisely the arc length of C :

$$L(C) = \int_a^b \|\mathbf{g}'(t)\| dt \quad (5.1.15)$$

5.2 Green's Theorem

5.2.1 Preliminary Definitions

Definition 5.2.1. A **simple closed curve** is a curve with parameterization $\mathbf{g} : [a, b] \rightarrow \mathbb{R}^n$ where

- (i) \mathbf{g} is continuous;
- (ii) $\mathbf{g}(a) = \mathbf{g}(b)$;
- (iii) \mathbf{g} is injective with its domain restricted to (a, b) .

Definition 5.2.2. A *simple closed curve* is **piecewise smooth** if it has a parameterization \mathbf{g} such that

- (i) \mathbf{g} is continuously differentiable with $\mathbf{g}'(t) \neq \mathbf{0}$ except finitely many breakpoints;
- (ii) $\mathbf{g}'(t)$ is *one side continuous* at breakpoints of the curve.

Definition 5.2.3. A **regular region** $S \subseteq \mathbb{R}^n$ is a set satisfying both

- (i) S is compact;
- (ii) $\overline{S^{int}} = S$.

Definition 5.2.4. Let $S \subseteq \mathbb{R}^2$, S has **piecewise smooth boundary** if ∂S consists of one or more *disjoint, piecewise smooth, simple closed curve*.

Definition 5.2.5. Let $S \subseteq \mathbb{R}^2$, then **positive orientation** on ∂S is the orientation on each of the closed curves that make up the boundary such that the region is on the *left* with respect to the positive direction on the curve.

Theorem 5.2.1 (Green's Theorem). Suppose $S \subseteq \mathbb{R}^2$ is a regular region with piecewise smooth region ∂S . Suppose \mathbf{F} is a C^1 vector field defined on \overline{S} , then

$$\int_{\partial S} \mathbf{F} \cdot d\mathbf{x} = \iint_S \left(\frac{\partial F_2}{\partial x_1} - \frac{\partial F_1}{\partial x_2} \right) dA \quad (5.2.1)$$

Corollary 5.2.1. Suppose S is a regular region in \mathbb{R}^2 with piecewise smooth boundary ∂S , and let $\mathbf{n}(\mathbf{x})$ be the *unit outward normal* vector to ∂S at $\mathbf{x} \in \partial S$. Suppose also that \mathbf{F} is a vector field defined on \overline{S} , then

$$\int_{\partial S} \mathbf{F} \cdot \mathbf{n} \, ds = \iint_S \left(\frac{\partial F_1}{\partial x_1} + \frac{\partial F_2}{\partial x_2} \right) dA \quad (5.2.2)$$

Proof. Let $\mathbf{g}(t)$ be a parameterization of boundary ∂S . Then the tangent vector would be $\mathbf{g}'(t)$ and we can conclude the *outer normal vector* \mathbf{n} is $\frac{(g'_2(t), -g'_1(t))}{\|(g'_2(t), -g'_1(t))\|}$. Then

$$\int_{\partial S} \mathbf{F} \cdot \mathbf{n} \, ds = \int_T \mathbf{F} \circ \mathbf{g} \cdot \frac{(g'_2(t), -g'_1(t))}{\|(g'_2(t), -g'_1(t))\|} \|\mathbf{g}'(t)\| \, dt \quad (5.2.3)$$

$$= \int_T F_1 g'_2(t) - F_2 g'_1(t) \, dt \quad (5.2.4)$$

$$= \int_T \begin{pmatrix} -F_2 \\ F_1 \end{pmatrix} \cdot \begin{pmatrix} g'_1(t) \\ g'_2(t) \end{pmatrix} \, dt \quad (5.2.5)$$

$$= \int_{\partial S} \begin{pmatrix} -F_2 \\ F_1 \end{pmatrix} \cdot d^2 \mathbf{x} \quad (5.2.6)$$

$$= \iint_S \frac{\partial F_1}{\partial x} + \frac{\partial F_2}{\partial y} \, dA \text{ By Green's Theorem} \quad (5.2.7)$$

■

5.3 Surface Integrals

5.3.1 Surface Areas and Surface Integrals

Definition 5.3.1. Suppose S is a surface in \mathbb{R}^3 and parameterized by

$$\mathbf{G}(\mathbf{u}) : R \rightarrow S \quad (5.3.1)$$

where $\text{rank}(D\mathbf{G}(\mathbf{u})) = 2$ for every $\mathbf{u} \in R \setminus Z$ where Z is a probably empty set with zero content. If $\|\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v}\|$ is integrable, then

$$\text{Area}(S) \equiv \iint_R \left\| \frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v} \right\| d\Theta \quad (5.3.2)$$

Definition 5.3.2. Let $f : S \rightarrow \mathbb{R}$ be a real-valued continuous function defined on a super set of S , the **integral of a real-valued function on a surface** is defined as

$$\iint_S f(\mathbf{x}) \, dA \equiv \iint_R f(\mathbf{G}(\mathbf{u})) \left\| \frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v} \right\| d\Theta \quad (5.3.3)$$

Definition 5.3.3. Let $\mathbf{F} : S \rightarrow \mathbb{R}^3$ be a continuous vector field defined on a super set of S , the **integral of vector field on a surface** is defined as

$$\iint_S \mathbf{F}(\mathbf{x}) \cdot \mathbf{n} \, dA \equiv \iint_R \mathbf{F}(\mathbf{G}(\mathbf{u})) \cdot \left(\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v} \right) d\Theta \quad (5.3.4)$$

Remark 5.3.1. Surface integrals of **real-valued functions** are independent of the choice of parametrization.

Remark 5.3.2. But the choice of parameterization can change the sign of surface integrals of vector fields. We need to choose the direction of the normal, \mathbf{n} .

Definition 5.3.4. Let $S \subseteq \mathbb{R}^3$ be a two dimensional sub-manifold, and f is a real-valued function defined on a super set of S . Define the **average of f over S** as

$$\text{aver of } f \text{ over } S \equiv \frac{\iint_S f \, dA}{\iint_S 1 \, dA} \quad (5.3.5)$$

Remark 5.3.3. A note on the relation between integrals of a vector field and a real-valued function. The surface of vector field \mathbf{F} on S is defined by *reducing \mathbf{F} to a real-valued function $\mathbf{F} \cdot \mathbf{n}$* and then follow the definition of conventional real-valued function on S . Define $h \equiv \mathbf{F} \cdot \mathbf{n}$,

$$\iint_S \mathbf{F} \cdot \mathbf{n} \, dA = \iint_S h \, dA \quad (5.3.6)$$

$$\equiv \iint_R h(\mathbf{G}(\mathbf{u})) \left\| \frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v} \right\| d\Theta \quad (5.3.7)$$

$$= \iint_R \mathbf{F}(\mathbf{G}(\mathbf{u})) \cdot \mathbf{n}(\mathbf{G}(\mathbf{u})) \left\| \frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v} \right\| d\Theta \quad (5.3.8)$$

$$= \iint_R \mathbf{F}(\mathbf{G}(\mathbf{u})) \cdot \frac{\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v}}{\left\| \frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v} \right\|} \left\| \frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v} \right\| d\Theta \quad (5.3.9)$$

$$= \iint_R \mathbf{F}(\mathbf{G}(\mathbf{u})) \cdot \left(\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v} \right) d\Theta \quad (5.3.10)$$

5.3.2 An invariance property

Remark 5.3.4. As mentioned above, given $\mathbf{n}(\mathbf{x})$ fixed, we can define the surface integral of vector field as the surface integral of a real-valued function defined as $h(\mathbf{x}) \equiv \mathbf{F}(\mathbf{x}) \cdot \mathbf{n}(\mathbf{x})$. And as argued before, one \mathbf{n} is fixed (i.e. orientation is fixed), the value of integral is deterministic. Therefore we can conclude the integral of a vector field \mathbf{F} over a surface S depends on the orientation of S but otherwise independent of the parameterization.

Remark 5.3.5. Let $S \subseteq \mathbb{R}^3$ be a two dimensional sub-manifold parameterized by $\mathbf{G} : R \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}^3$ such that $\text{rank}(\mathbf{G}(\mathbf{u})) = 2$ for all but zero-content sets on its domain.

Let $\varphi : W \subseteq \mathbb{R}^2 \rightarrow R$ be a bijection such that $\mathbf{H} \equiv \mathbf{G} \circ \varphi : W \rightarrow \mathbb{R}^3$ is another parameterization of S .

Now consider the integral of vector field \mathbf{F} under parameterization \mathbf{H} ,

$$\iint_S \mathbf{F} \cdot \mathbf{u} \, dA = \iint_W \mathbf{F}(\mathbf{H}) \cdot \left(\frac{\partial \mathbf{H}}{\partial s} \times \frac{\partial \mathbf{H}}{\partial t} \right) d\Theta \quad (5.3.11)$$

$$= \iint_W \mathbf{F} \circ \mathbf{G} \circ \varphi \cdot \left(\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v} \right) \text{det } D\varphi \, d\Theta \quad (5.3.12)$$

$$= \pm \iint_R \mathbf{F} \circ \mathbf{G} \cdot \left(\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v} \right) d\Theta \text{ (change of variable)} \quad (5.3.13)$$

Theorem 5.3.1 (Invariance). Let $\mathbf{G} : R \rightarrow \mathbb{R}^3$ and $\mathbf{H} \equiv \mathbf{G} \circ \varphi : W \rightarrow \mathbb{R}^3$ be two parameterizations of S , then

$$\iint_R f \circ \mathbf{G} \left\| \frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v} \right\| d\Theta = \iint_W f \circ \mathbf{H} \left\| \frac{\partial \mathbf{H}}{\partial s} \times \frac{\partial \mathbf{H}}{\partial t} \right\| d\Theta \quad (5.3.14)$$

and

$$\iint_R \mathbf{F} \circ \mathbf{G} \cdot \left(\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v} \right) d\Theta = \pm \iint_W \mathbf{F} \circ \mathbf{H} \cdot \left(\frac{\partial \mathbf{H}}{\partial u} \times \frac{\partial \mathbf{H}}{\partial v} \right) d\Theta \quad (5.3.15)$$

5.3.3 Volume and Area

Theorem 5.3.2. Let R be an arbitrary regular region in \mathbb{R}^3 , and let S be the boundary surface of R , define

$$S_h \equiv \{\mathbf{x} + \delta \mathbf{n} : \mathbf{x} \in S \wedge \delta \in [0, h]\} \quad (5.3.16)$$

where S_h can be interpreted as *a shell of region R with thickness h* . Then the surface area of S is

$$\text{area}(S) = \lim_{h \rightarrow 0} \frac{|S_h|}{h} \quad (5.3.17)$$

5.4 Divergence, Gradient and Curl

Definition 5.4.1. Let $U \subseteq \mathbb{R}^n$ be an open set, and define real-valued function $f : U \rightarrow \mathbb{R}$ and vector field $\mathbf{F} : U \rightarrow \mathbb{R}^n$. Then we define

1. The **gradient** of f as ∇f ;
2. The **divergence** of \mathbf{F} as $\nabla \cdot \mathbf{F}$;
3. The **curl** of \mathbf{F} as $\nabla \times \mathbf{F}$.

Definition 5.4.2. Let $f : \mathbb{R}^n \rightarrow \mathbb{R}$ be a C^1 real-valued function, define the **Laplacian** of f as a mapping from *real-valued functional space* to *real-valued functional space* defined as

$$\text{div}(\text{grad})f \equiv \sum_j \partial_j^2 f = \Delta f = \nabla^2 f \quad (5.4.1)$$

Theorem 5.4.1. For every C^2 real valued function $f : \mathbb{R}^3 \rightarrow \mathbb{R}$,

$$\text{curl}(\text{grad}f) = \mathbf{0} \quad (5.4.2)$$

For every C^2 vector field defined in \mathbb{R}^3 or a subset of it,

$$\text{div}(\text{curl}\mathbf{F}) = 0 \quad (5.4.3)$$

Note that the domain of f and \mathbf{F} must be \mathbb{R}^3 or a subset of it, otherwise the curl operation is not well-defined.

Theorem 5.4.2 (Product rules).

$$\text{grad}(fg) = f \text{ grad}g + \text{grad}f \cdot g \quad (5.4.4)$$

$$\text{div}(f\mathbf{G}) = f \text{ div}\mathbf{G} + \text{grad}f \cdot \mathbf{G} \quad (5.4.5)$$

$$\text{curl}(f\mathbf{G}) = f \text{ curl}\mathbf{G} + \text{grad}f \times \mathbf{G} \quad (5.4.6)$$

5.5 Divergence Theorem

Remark 5.5.1. vector field integral on boundary (2-dimensional sub-manifold) of region in \mathbb{R}^3 ($\mathbf{F} \cdot \mathbf{n} \, dA$ 2-form) and scalar valued function ($\text{div}(\mathbf{F}) \, dV$ 3-form) in a region (3-dimensional sub-manifold).

Theorem 5.5.1 (Divergence Theorem). Let $R \subseteq \mathbb{R}^3$ be a *regular region* with *piece-wise smooth* boundary ∂S . And \mathbf{n} is the *outer normal vector* on ∂S , then,

$$\iint_{\partial S} \mathbf{F} \cdot \mathbf{n} \, dA = \iiint_S \operatorname{div}(\mathbf{F}) \, dV \quad (5.5.1)$$

Proof.

Definition 5.5.1. A region $R \subseteq \mathbb{R}^3$ is said to be *xy-simple* if and only if it can be expressed as the following form

$$R = \{(x, y, z) \in \mathbb{R}^3 : (x, y) \in W, \varphi_1(x, y) \leq z \leq \varphi_2(x, y)\} \quad (5.5.2)$$

Suppose S is simple in terms of all combinations of x, y, z .

Then

$$\iint_{\partial S} \mathbf{F} \cdot \mathbf{n} \, dA = \iint_{\partial S} F_1 n_1 + F_2 n_2 + F_3 n_3 \, dA \quad (5.5.3)$$

Consider $\iint_{\partial S} F_3 n_3 \, dA$, since R is *xy-simple*,

$$\iint_{\partial S} F_3 n_3 \, dA = \iint_{\partial S} F_3 \mathbf{k} \cdot \mathbf{n} \, dA \quad (5.5.4)$$

Note that except the bottom and top sides, which are parameterized by $\mathbf{G}_1(x, y) = (x, y, \varphi_1(x, y))$ and $\mathbf{G}_2(x, y) = (x, y, \varphi_2(x, y))$, the outer normal vector of those region has form $(\cdot, \cdot, 0)$, and therefore $\mathbf{n} \cdot \mathbf{k} = 0$ for every \mathbf{x} on those regions, and contribute nothing to the integral.

Therefore, to evaluate $\iint_{\partial S} F_3 \mathbf{k} \cdot \mathbf{n} \, dA$, we only need to consider the upper and bottom surfaces. Also note that \mathbf{n} has opposite z component on those two surfaces.

Moreover, the undirected \mathbf{n} on those two surfaces is

$$\tilde{\mathbf{n}} = \begin{pmatrix} 1 \\ 0 \\ \partial_x \varphi_i \end{pmatrix} \times \begin{pmatrix} 0 \\ 1 \\ \partial_y \varphi_i \end{pmatrix} = \begin{pmatrix} -\partial_x \varphi_i \\ \partial_x \varphi_i - \partial_y \varphi_i \\ 1 \end{pmatrix} \quad (5.5.5)$$

$$\implies \iint_{\partial S} F_3 \mathbf{k} \cdot \mathbf{n} \, dA = \iint_{\partial S} F_3 \, dA \quad (5.5.6)$$

$$= \iint_{\text{upper } \partial S} F_3 \, dA - \iint_{\text{lower } \partial S} F_3 \, dA \quad (5.5.7)$$

$$= \iint_W F_3(x, y, \varphi_2(x, y)) \, dx dy - \iint_W F_3(x, y, \varphi_1(x, y)) \, dx dy \quad (5.5.8)$$

$$= \iiint_W \int_{\varphi_1(x, y)}^{\varphi_2(x, y)} \partial_3 F_3 \, dz dx dy = \iiint_S \partial_3 F_3 \, dV \quad (5.5.9)$$

We can prove the equalities involving the other two components, and the proof is completed by the fact that any open set in \mathbb{R}^n can be written as a countable union of *almost disjoint* cubes, which are simple and the boundary of S has zero content. \blacksquare

Proposition 5.5.1 (Geometric Interpretation of Divergence). Let $S \subset \mathbb{R}^3$, $\mathbf{F} : S \rightarrow \mathbb{R}^3$, $\mathbf{a} \in S$,

$$\operatorname{div}(\mathbf{F})(\mathbf{a}) = \lim_{r \rightarrow 0} \frac{3}{4\pi r^2} \iiint_{\mathcal{B}(\mathbf{a}, r)} \operatorname{div}(\mathbf{F})(\mathbf{x}) \, d\mathbf{x} \quad (5.5.10)$$

$$= \lim_{r \rightarrow 0} \frac{3}{4\pi r^2} \underbrace{\iint_{\partial \mathcal{B}(\mathbf{a}, r)} \mathbf{F} \cdot \mathbf{n} \, d\mathbf{x}}_{\text{flux through boundary}} \quad (5.5.11)$$

thus $\operatorname{div}(\mathbf{F})(\mathbf{a}) > 0$ if and only if at point \mathbf{a} , matters are flowing away from this point.

Corollary 5.5.1 (Green's Formula). Suppose $R \subset \mathbb{R}^3$ and $f, g : R \rightarrow \mathbb{R}$ are C^2 functions, then

$$\iint_{\partial S} f \nabla g \cdot \mathbf{n} \, dA = \iiint_S \nabla f \cdot \nabla g + f \nabla^2 g \, dV \quad (5.5.12)$$

$$\iint_{\partial S} (f \nabla g - g \nabla f) \, dA = \iiint_S (f \nabla^2 g - g \nabla^2 f) \, dV \quad (5.5.13)$$

Proof.

$$\iint_{\partial S} f \nabla g \cdot \mathbf{n} \, dA = \iiint_S \operatorname{div}(f \nabla g) \, dV \quad (5.5.14)$$

$$= \iiint_S f \operatorname{div}(\nabla g) + \nabla f \cdot \nabla g \, dV = \iiint_S f \nabla^2 g + \nabla f \cdot \nabla g \, dV \quad (5.5.15)$$

The second formula can be proved directly using divergence theorem the first formula. ■

5.6 Stokes Theorem

5.6.1 Stokes Theorem in \mathbb{R}^3

Theorem 5.6.1 (Stokes Theorem, Special Case). Let S be a 2 dimensional sub-manifold in \mathbb{R}^3 , and let \mathbf{F} be a vector field defined on some neighbour of S , then

$$\int_{\partial S} \mathbf{F} \cdot d\mathbf{x} = \iint_S \operatorname{curl}(\mathbf{F}) \cdot \mathbf{n} \, dA \quad (5.6.1)$$

Remark 5.6.1. In above theorem, $\omega \equiv \mathbf{F} \cdot d\mathbf{x}$ is a 1-form in \mathbb{R}^3 and $d\omega \equiv \operatorname{curl}(\mathbf{F}) \cdot \mathbf{n} \, dA$ is a 2-form in \mathbb{R}^3 .

Corollary 5.6.1. Let S be a closed surface in \mathbb{R}^3 , that's, $\partial S = \emptyset$, and let \mathbf{n} denote the outer normal vector, and \mathbf{F} is a C^1 vector field. Then

$$\iint_S \operatorname{curl}(\mathbf{F}) \cdot \mathbf{n} \, dA = 0 \quad (5.6.2)$$

Proof. We can construct a *small* simple closed curve C on S and divide S into two regions sharing the same boundary. And note that given orientation fixed on S , the orientation on ∂S_1 and ∂S_2 are opposite. Then

$$\iint_S \operatorname{curl}(\mathbf{F}) \cdot \mathbf{n} \, dA = \iint_{S_1} \operatorname{curl}(\mathbf{F}) \cdot \mathbf{n} \, dA + \iint_{S_2} \operatorname{curl}(\mathbf{F}) \cdot \mathbf{n} \, dA \quad (5.6.3)$$

$$= \int_{\partial S_1} \mathbf{F} \cdot d\mathbf{x} - \int_{\partial S_2} \mathbf{F} \cdot d\mathbf{x} = \int_C \mathbf{F} \cdot d\mathbf{x} - \int_C \mathbf{F} \cdot d\mathbf{x} = 0 \quad (5.6.4)$$

■

Proposition 5.6.1 (Geometric Interpretation of Curl). Let $R \subset \mathbb{R}^3$ be a 2 dimensional sub-manifold with \mathbf{n} as outer normal vector on it, and $\mathbf{a} \in R$,

$$\operatorname{curl}(F)(\mathbf{a}) \cdot \mathbf{n}(\mathbf{a}) = \lim_{r \rightarrow 0} \frac{1}{2\pi r^2} \iint_{\mathcal{D}(\mathbf{a}, r)} \operatorname{curl}(F)(\mathbf{x}) \cdot \mathbf{n}(\mathbf{x}) \, dA \quad (5.6.5)$$

$$= \lim_{r \rightarrow 0} \frac{1}{2\pi r^2} \int_{\partial \mathcal{D}(\mathbf{a}, r)} \mathbf{F} \cdot d\mathbf{x} \quad (5.6.6)$$

$$(5.6.7)$$

If we think of \mathbf{F} as a force field, then $\int_{\partial\mathcal{D}(\mathbf{a},r)} \mathbf{F} \cdot d\mathbf{x}$ represents the work done by \mathbf{F} on a particle moves around $\partial\mathcal{D}(\mathbf{a},r)$. Thus $\text{curl}(\mathbf{F}) \cdot \mathbf{u}$ represents the **tendency of the force \mathbf{F} to push the particle around $\partial\mathcal{D}(\mathbf{a},r)$ in a direction compatible with \mathbf{n} .**

5.6.2 The Generalization

Proposition 5.6.2 (Properties of Exterior Products). Let α_1, α_2 and β be 1-forms on \mathbb{R}^n and f_1, f_2 are continuous functions defined on \mathbb{R}^n ,

1. Distributive

$$(f_1\alpha_1 + f_2\alpha_2) \wedge \beta = f_1(\alpha_1 \wedge \beta) + f_2(\alpha_2 \wedge \beta) \quad (5.6.8)$$

$$\beta \wedge (f_1\alpha_1 + f_2\alpha_2) = f_1(\beta \wedge \alpha_1) + f_2(\beta \wedge \alpha_2) \quad (5.6.9)$$

2. Anti-commutative

$$\beta \wedge \alpha = -\alpha \wedge \beta \quad (5.6.10)$$

Theorem 5.6.2 (Divergence Theorem in \mathbb{R}^n). Let R be a regular region in \mathbb{R}^n bounded by a piecewise smooth hyper-surface ∂R . Note here R is a n dimensional sub-manifold and ∂R is a $n-1$ dimension sub-manifold. Then

$$\int \cdots \int_{\partial R} \mathbf{F} \cdot \mathbf{n} dV^{n-1} = \iiint_R \text{div}(\mathbf{F}) dV^n \quad (5.6.11)$$

where if ∂R is parameterized by $\mathbf{G}(u_1, \dots, u_{n-1})$, then

$$\mathbf{n} dV^{n-1} = \det \begin{pmatrix} \mathbf{e}_1 & \cdots & \mathbf{e}_n \\ \partial_1 G_1 & \cdots & \partial_1 G_n \\ \vdots & & \vdots \\ \partial_{n-1} G_1 & \cdots & \partial_{n-1} G_n \end{pmatrix} \quad (5.6.12)$$

Definition 5.6.1. A 0-form on \mathbb{R}^n is a real valued function f .

Remark 5.6.2. While writing the basis elements $dx_i \wedge dx_j$ with the variables in *cyclic order*. That's dx before dy before dz before dx in \mathbb{R}^3 case.

Definition 5.6.2. A k -form in \mathbb{R}^n takes the expression of linear combination of $C(n, k)$ basis elements $\{\beta_i\}_i$.

Example 5.6.1. A 2-form ω in \mathbb{R}^3 can be expressed using a 3-element basis

$$\omega = \sum_{1 \leq i < j \leq 3} C_{ij}(\mathbf{x}) \beta_{ij} \quad (5.6.13)$$

$$\beta_{ij} \in \{dx \wedge dy, dy \wedge dz, dx \wedge dz\} \quad (5.6.14)$$

Definition 5.6.3. Let $\omega = \sum_{j=1}^{C(n,k)} f_j \beta_j$ be a k -form in \mathbb{R}^n , then it's **exterior derivative** is defined to be the $(k+1)$ -form in \mathbb{R}^n defined as

$$d\omega \equiv \sum_j df_j \wedge \beta_j \quad (5.6.15)$$

where df_j can be computed using *total derivative*.

Example 5.6.2. In \mathbb{R}^3 , the *exterior derivative* for a 0-form f is its **gradient**, which is a 1-form. And the exterior derivate of a 1-form in \mathbb{R}^3 is its curl

$$\omega := F_1 dx + F_2 dy + F_3 dz \quad (5.6.16)$$

$$\implies d\omega = dF_1 \wedge dx + dF_2 \wedge dy + dF_3 \wedge dz \quad (5.6.17)$$

$$= (\partial_1 F_1 dx + \partial_2 F_1 dy + \partial_3 F_1 dz) \wedge dx \quad (5.6.18)$$

$$+ (\partial_1 F_2 dx + \partial_2 F_2 dy + \partial_3 F_2 dz) \wedge dy \quad (5.6.19)$$

$$+ (\partial_1 F_3 dx + \partial_2 F_3 dy + \partial_3 F_3 dz) \wedge dz \quad (5.6.20)$$

$$= (\partial_1 F_2 - \partial_2 F_1) dx \wedge dy + (\partial_2 F_3 - \partial_3 F_2) dy \wedge dz + (\partial_3 F_1 - \partial_1 F_3) dz \wedge dx \quad (5.6.21)$$

$$= \text{curl}(\mathbf{F}) \quad (5.6.22)$$

The exterior derivate of a 2-form in \mathbb{R}^3 is its divergence

$$\omega := A dy \wedge dz + B dz \wedge dx + C dx \wedge dy \quad (5.6.23)$$

$$\implies d\omega = (\partial_1 A dx + \partial_2 A dy + \partial_3 A dz) \wedge dy \wedge dz \quad (5.6.24)$$

$$+ (\partial_1 B dx + \partial_2 B dy + \partial_3 B dz) \wedge dz \wedge dx \quad (5.6.25)$$

$$+ (\partial_1 C dx + \partial_2 C dy + \partial_3 C dz) \wedge dx \wedge dy \quad (5.6.26)$$

$$= (\partial_1 A + \partial_2 B + \partial_3 C) dx \wedge dy \wedge dz \quad (5.6.27)$$

$$= \text{div}(\mathbf{F}) \quad (5.6.28)$$

Theorem 5.6.3 (Stokes Theorem, 5.77). Let M be a smooth, oriented k dimensional sub-manifold of \mathbb{R}^n with a piecewise smooth boundary ∂M , and let ∂M carry the orientation that is (in a suitable sense) compatible with the one on M . If ω is a $(k-1)$ -form of class C^1 on an open set containing M , then

$$\int \cdots \int_{\partial M} \omega = \iint \cdots \int_M d\omega \quad (5.6.29)$$

Theorem 5.6.4. The *boundary* of a (smoothly bounded) region M in a k dimensional manifold is a $(k-1)$ dimensional manifold with no boundary.

That's let M be a k dimensional manifold with piecewise smooth boundary ∂M , then

$$\partial(\partial M) = \emptyset \quad (5.6.30)$$

Theorem 5.6.5. For any k -form ω on \mathbb{R}^n ,

$$d(d\omega) = 0 \quad (5.6.31)$$

Proof. Let M be a k dimensional sub-manifold in \mathbb{R}^n with piecewise smooth boundary, and ω is a $(k-2)$ -form on \mathbb{R}^n , so $d(d\omega)$ is a k -form on \mathbb{R}^n . And

$$\iiint \cdots \int_M d(d\omega) = \iint \cdots \int_{\partial M} d\omega \quad (5.6.32)$$

$$= \int \cdots \int_{\partial(\partial M)} \omega = \int \cdots \int_{\emptyset} \omega = 0 \quad (5.6.33)$$

■