

MAT237 Multivariable Calculus

Lecture Notes 2018-19

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1 Limits, Continuity, and Related Topics

1.1 Open, Closed, and other subsets of \mathbb{R}^n

Definition - Open Ball Assume $\mathbf{a} \in \mathbb{R}^n$ and $r > 0$.

The open ball with centre \mathbf{a} and radius r is the set denoted $B(r, \mathbf{a})$, defined

by

$$B(r, \mathbf{a}) = \{\mathbf{x} \in \mathbb{R}^n : |\mathbf{x} - \mathbf{a}| < r\}$$

Definition - Sphere The sphere with centre \mathbf{a} and radius r is the set of points whose distance from \mathbf{a} exactly equals r :

$$\{\mathbf{x} \in \mathbb{R}^n : |\mathbf{x} - \mathbf{a}| = r\}$$

Set Terminologies

1. A set $S \subset \mathbb{R}^n$ is bounded if there exists some $r > 0$ such that $S \subset B(r, \mathbf{0})$
2. A set is unbounded if and only if it is not bounded.
3. If $S \subset \mathbb{R}^n$, then the complement of S , denoted S^c , is the set defined by

$$S^c = \{x \in \mathbb{R}^n : \mathbf{x} \notin S\}$$

Interior, Boundary, and Closure

1. We say that \mathbf{x} belongs to the interior of S , and we write $\mathbf{x} \in S^{int}$, if

$$\exists \varepsilon > 0 \text{ such that } B(\varepsilon, \mathbf{x}) \subset S$$
2. We say that \mathbf{x} belongs to the boundary of S , and we write $\mathbf{x} \in \partial S$, if

$$\forall \varepsilon > 0, B(\varepsilon, \mathbf{x}) \cap S \neq \emptyset \text{ and } B(\varepsilon, \mathbf{x}) \cap S^c \neq \emptyset$$
3. We say that \mathbf{x} belongs to the closure of S , and we write $\mathbf{x} \in \bar{S}$, if

$$\forall \varepsilon > 0, B(\varepsilon, \mathbf{x}) \cap S \neq \emptyset$$

$$\text{Equivalently, } \bar{S} = S^{int} \cup \partial S$$

Theorem 1 For any $S \subset \mathbb{R}^n$,

$$S^{int} \subset S \subset \bar{S}$$

Theorem 2 For any $S \subset \mathbb{R}^n$,

$$\partial S = \partial(S^c)$$

Definition - Open and Closed Sets

1. A set S is open if $S = S^{int}$
2. A set S IS closed if $S = \bar{S}$

Remark It is possible for a set $S \subset \mathbb{R}^n$ to be “both open and closed”, or “neither open nor closed”.

Examples

1. Both open and closed: \mathbb{R}^n
2. Neither open nor closed: A ball with partial boundary; $[0, 1)$

Theorem 3 S is open \iff every point of S is an interior point
 $\iff \forall \mathbf{x} \in S, \exists \varepsilon > 0$ such that $B(\varepsilon, \mathbf{x}) \subset S$

Theorem 4 S is closed \iff every boundary point of S belongs to S
 $\iff S^c$ is open

1.2 Limits and Continuity

Homework 1.1 Theorem Consider limits such as

$$\lim_{(x,y) \rightarrow (0,0)} \frac{|x|^{r_1} |y|^{r_2}}{|x|^{s_1} + |y|^{s_2}}$$

where r_1, r_2, s_1, s_2 are positive numbers.

The limit **exists and equals 0** if and only if

$$\frac{r_1}{s_1} + \frac{r_2}{s_2} > 1$$

Basic Property of Limits

1. The sum of two limits that do not exist can still exist.
2. The sum of two limits, one exist, one does not exist, must not exist.
3. The product of two limits that do not exist can still exist.
4. The product of two limits, one exist, one does not exist, can still exist.

Definition of Limit Assume that $S \subset \mathbb{R}^n$, and that $\mathbf{F} : S \rightarrow \mathbb{R}^k$ is a function. The statement

$$\lim_{\mathbf{x} \rightarrow \mathbf{a}} \mathbf{F}(\mathbf{x}) = \mathbf{L}$$

is defined to mean

$$\forall \varepsilon > 0, \exists \delta > 0 \text{ such that } \mathbf{x} \in S \wedge 0 < |\mathbf{x} - \mathbf{a}| < \delta \implies |\mathbf{F}(\mathbf{x}) - \mathbf{L}| < \varepsilon$$

In order for the definition to make sense, we need to assume that \mathbf{a} satisfies

$$\forall \delta > 0, \exists \mathbf{x} \in S, 0 < |\mathbf{x} - \mathbf{a}| < \delta \quad (1)$$

For example, this always holds if $\mathbf{a} \in S^{int}$, or if $\mathbf{a} \in \overline{S^{int}}$ (the closure of S^{int})

Theorem 1: Limit Laws Assume that $S \subset \mathbb{R}^n$ and that \mathbf{a} is a point in \mathbb{R}^n satisfying (1). Further assume that $f, g : S \rightarrow \mathbb{R}$ are functions and L, M are numbers such that $\lim_{\mathbf{x} \rightarrow \mathbf{a}} f(\mathbf{x}) = L, \lim_{\mathbf{x} \rightarrow \mathbf{a}} g(\mathbf{x}) = M$. Then

$$\lim_{\mathbf{x} \rightarrow \mathbf{a}} [f(\mathbf{x}) + g(\mathbf{x})] = L + M, \quad \lim_{\mathbf{x} \rightarrow \mathbf{a}} [f(\mathbf{x})g(\mathbf{x})] = LM$$

Theorem 2: Squeeze Theorem Assume that $S \subset \mathbb{R}^n$ and that \mathbf{a} is a point in \mathbb{R}^n satisfying (1). Further assume that $f, g, h : S \rightarrow \mathbb{R}$ are functions and $p > 0$ and L are numbers such that $f(\mathbf{x}) \leq g(\mathbf{x}) \leq h(\mathbf{x})$ for all $\mathbf{x} \in S$ such that $|\mathbf{x} - \mathbf{a}| < p$ and

$$\lim_{\mathbf{x} \rightarrow \mathbf{a}} f(\mathbf{x}) = \lim_{\mathbf{x} \rightarrow \mathbf{a}} h(\mathbf{x}) = L$$

Then $\lim_{\mathbf{x} \rightarrow \mathbf{a}} g(\mathbf{x}) = L$

Remark These theorems are only for real-valued functions, because with vector-valued functions it is not clear how to generalize the hypothesis $f \leq g \leq h$ and we have several choices for the definition of a product of functions.

Corollary of the Squeeze Theorem Assume that $S \subset \mathbb{R}^n$ and that \mathbf{a} is a point in \mathbb{R}^n satisfying (1). Further assume that $g, h : S \rightarrow \mathbb{R}$ are functions such that

$$|g(\mathbf{x})| \leq h(\mathbf{x}) \text{ for all } \mathbf{x} \in S, \lim_{\mathbf{x} \rightarrow \mathbf{a}} h(\mathbf{x}) = 0$$

Then

$$\lim_{\mathbf{x} \rightarrow \mathbf{a}} g(\mathbf{x}) = 0$$

proof: The conclusion follows directly from the Squeeze Theorem with $-h(\mathbf{x})$ playing the role of $f(\mathbf{x})$. ■

Theorem 3 Assume that $S \subset \mathbb{R}^n$ and that \mathbf{a} is a point in \mathbb{R}^n satisfying (1). If $\mathbf{F} = (f_1, \dots, f_k)$ is a vector-valued function $S \rightarrow \mathbb{R}^k$, then

$$\lim_{\mathbf{x} \rightarrow \mathbf{a}} \mathbf{F}(\mathbf{x}) = \mathbf{L} \text{ if and only if } \lim_{\mathbf{x} \rightarrow \mathbf{a}} f_j(\mathbf{x}) = L_j \forall j = 1, \dots, k$$

Question Type: Determine whether a limit exist

1. For a limit that does not exist, find two y functions that yield different limits.
2. For a limit that does exist, an explanation must involve using the squeeze theorem.

Definition of Continuity If $S \subset \mathbb{R}^n$, then a function $\mathbf{F} : S \rightarrow \mathbb{R}^k$ is continuous at $\mathbf{a} \in S$ if

$$\lim_{\mathbf{x} \rightarrow \mathbf{a}} f(\mathbf{x}) = f(\mathbf{a})$$

or

$$\forall \varepsilon > 0, \exists \delta > 0 \text{ such that } \mathbf{x} \in S \wedge |\mathbf{x} - \mathbf{a}| < \delta \implies |\mathbf{F}(\mathbf{x}) - \mathbf{F}(\mathbf{a})| < \varepsilon$$

If \mathbf{F} is continuous at every point in S , then we say simply that \mathbf{F} is continuous.

Theorem 4: Basic properties of Continuity Assume that $S \subset \mathbb{R}^n$ and that $\mathbf{a} \in S$

1. If $\mathbf{F} : S \rightarrow \mathbb{R}^k$ is a vector-valued function with components (f_1, \dots, f_k) , then \mathbf{F} is continuous at \mathbf{a} if and only if every component function f_j is continuous at \mathbf{a} .
2. If $\mathbf{F}, \mathbf{G} : S \rightarrow \mathbb{R}^k$ are continuous at \mathbf{a} , then the sum $\mathbf{F} + \mathbf{G}$ is continuous at \mathbf{a} .
3. If $f, g : S \rightarrow \mathbb{R}$ are continuous at \mathbf{a} , then the product fg is continuous at \mathbf{a} . If in addition $g(\mathbf{a}) \neq 0$ then the quotient f/g is continuous at \mathbf{a} .
4. A composition of continuous functions is continuous. That is, assume that $S \subset \mathbb{R}^n$ and $T \subset \mathbb{R}^k$, and that $\mathbf{F} : S \rightarrow \mathbb{R}^k$ and $\mathbf{G} : T \rightarrow \mathbb{R}^l$ are functions such that $\mathbf{G} \circ \mathbf{F}$ is well-defined. (Thus, the image of \mathbf{F} is a subset of T). If \mathbf{F} is continuous at \mathbf{a} and \mathbf{G} is continuous at $\mathbf{F}(\mathbf{a})$, then $\mathbf{G} \circ \mathbf{F}$ is continuous at \mathbf{a} .

5. The elementary functions of a single variable (trigonometric functions and their inverses, polynomials, exponentials and log) are continuous on their domains.

Theorem 5 Assume that \mathbf{F} is a function $\mathbb{R}^n \rightarrow \mathbb{R}^k$. Then the following are equivalent:

1. \mathbf{F} is continuous.
2. For every open set $U \subset \mathbb{R}^k$, the set $\{\mathbf{x} \in \mathbb{R}^n : \mathbf{F}(\mathbf{x}) \in U\}$ is open.
3. For every closed set $K \subset \mathbb{R}^k$, the set $\{\mathbf{x} \in \mathbb{R}^n : \mathbf{F}(\mathbf{x}) \in K\}$ is closed.

1.3 Sequences and Completeness

Theorem 1: Bounded Sequence Theorem Every bounded sequence in \mathbb{R}^n has a subsequence that converges to a limit.

Basic of Sequences

1. A sequence in \mathbb{R}^n may be written as

$$\{\mathbf{a}_j\}_{j=1}^{\infty}, \quad \{\mathbf{a}_j\}_j, \quad \{\mathbf{a}_j\}, \quad \dots$$

2. We say that a sequence $\{\mathbf{a}_j\}_j$ in \mathbb{R}^n converges to the limit $L \in \mathbb{R}^n$ if

$$\forall \varepsilon > 0, \exists J > 0 \text{ such that } j \geq J \implies |\mathbf{a}_j - \mathbf{L}| < \varepsilon$$

Theorem 2 Let $\{\mathbf{a}_j\}_j$ be a sequence in \mathbb{R}^n , and let $\mathbf{L} = (L_1, \dots, L_n) \in \mathbb{R}^n$. Then

$$\lim_{j \rightarrow \infty} \mathbf{a}_j = \mathbf{L} \iff \lim_{j \rightarrow \infty} a_{jk} = L_k \forall k = 1, \dots, n$$

Theorem 3: Monotone Sequence Theorem Every bounded nondecreasing sequence of real numbers converges to a limit.

Definition of Subsequences A subsequence of a sequence $\{\mathbf{a}_j\}_{j \geq j_0}$ in \mathbb{R}^n , is a new sequence, denoted $\{\mathbf{a}_{k_j}\}_j$, where $\{k_j\}$ is an increasing sequence of integers such that $k_j \geq j_0$ for every j . Thus, the j th term \mathbf{a}_{k_j} of the subsequence is the k_j th term of the original sequence.

Fact If $\{\mathbf{a}_j\}_j$ is a sequence in \mathbb{R}^n that converges to a limit $\mathbf{L} \in \mathbb{R}^n$, then any subsequence of $\{\mathbf{a}_j\}_j$ converges to the same limit.

1.4 Compactness

Definition A set $S \subset \mathbb{R}^n$ is said to be compact if **every** sequence in S has a subsequence that converges to a limit in S .

Theorem 1: Bolzano-Weierstrass Theorem $S \subset \mathbb{R}^n$ is compact \iff S is closed and bounded.

Proposition 1 if $\{\mathbf{x}_j\}_j$ is a convergent sequence in a **closed** set $S \subset \mathbb{R}^n$, then the limit of the sequence must belong to S .

Theorem 2: The Extreme Value Theorem Assume that K is a compact subset of \mathbb{R}^n , and that $f : K \rightarrow \mathbb{R}$ is continuous. Then

the set $\{f(\mathbf{x}) : \mathbf{x} \in K\}$ is compact

and there exists \mathbf{x}^* and \mathbf{x}_* in K such that

$$f(\mathbf{x}^*) = \sup\{f(\mathbf{x}) : \mathbf{x} \in K\}, \quad f(\mathbf{x}_*) = \inf\{f(\mathbf{x}) : \mathbf{x} \in K\}$$

When there exists \mathbf{x}^* , we say that f attains its supremum, and when there exists \mathbf{x}_* , we say that f attains its infimum.

Notation We often use the abbreviations

$$\inf_S f := \inf\{f(\mathbf{x}) : \mathbf{x} \in S\}, \quad \sup_S f := \sup\{f(\mathbf{x}) : \mathbf{x} \in S\}$$

Application of the EVT It can sometimes guarantee that an optimization problem **must have a solution**. (It does not given any indication how to find the solution, when it exists.)

Proposition 2 Assume that $\{\mathbf{z}_j\}_j$ is a sequence in a set $S \subset \mathbb{R}^k$ for some $k \geq 1$ and that $\mathbf{z}_j \rightarrow \mathbf{z} \in S$ as $j \rightarrow \infty$. Assume also that f is a continuous function on S . Then $f(\mathbf{z}_j) \rightarrow f(\mathbf{z})$ as $j \rightarrow \infty$.

Proposition 3 If S is a compact subset of \mathbb{R}_I then $\sup S \in S$ and $\inf S \in S$

Definition of Uniformly Continuous Functions A function $\mathbf{F} : S \rightarrow \mathbb{R}^k$ (for some $S \subset \mathbb{R}^n$) is uniformly continuous if

$$\forall \varepsilon > 0, \exists \delta > 0, \mathbf{x}, \mathbf{y} \in S \wedge |\mathbf{x} - \mathbf{y}| < \delta \implies |\mathbf{F}(\mathbf{x}) - \mathbf{F}(\mathbf{y})| < \varepsilon$$

Remark Uniform continuity will be important for us when we begin to look at integration of functions of several variables.

The difference between continuity and uniform continuity is that if a function is continuous, then the choice of δ may depend on \mathbf{x} , whereas if it is uniformly continuous, then given $\varepsilon > 0$ we can find a $\delta > 0$ that "works" for all $\mathbf{x} \in S$ simultaneously.

Examples Sine and cosine functions

Theorem 3 If K is a compact subset of \mathbb{R}^n and $f : K \rightarrow \mathbb{R}^k$ is continuous, then f is uniformly continuous.

Corollary If S_1 and S_2 are path-connected, and $S_1 \cap S_2 \neq \emptyset$, then $S := S_1 \cup S_2$ is path-connected.

1.5 The Intermediate Value Theorem

Definition of Path-connectedness A set $S \subset \mathbb{R}^n$ is path-connected if, for every pair of points \mathbf{x} and \mathbf{y} in S ,

$$\exists \text{ continuous } \gamma : [0, 1] \rightarrow S, \gamma(0) = \mathbf{x}, \gamma(1) = \mathbf{y}$$

Theorem 1: the Intermediate Value Theorem Assume that S is a path-connected subset of \mathbb{R}^n and that $f : S \rightarrow \mathbb{R}$ is continuous. If \mathbf{a}, \mathbf{b} are points in S and either

$$f(\mathbf{a}) < t < f(\mathbf{b})$$

or

$$f(\mathbf{b}) < t < f(\mathbf{a})$$

then there exists a point $\mathbf{c} \in S$ such that $f(\mathbf{c}) = t$.

2 Differentiation and related topics

2.1 Differentiation of Real-valued Functions

Definition of Linearity A function $l : \mathbb{R}^n \rightarrow \mathbb{R}^m$ is linear if it has the form

$$l(\mathbf{x}) = M\mathbf{x}$$

where M is a $m \times n$ matrix. Alternatively, a function $l : \mathbb{R}^n \rightarrow \mathbb{R}^m$ is linear if

$$l(a\mathbf{x} + b\mathbf{y}) = al(\mathbf{x}) + bl(\mathbf{y})$$

for all $a, b \in \mathbb{R}$ and $\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$.

If a function has the form $f(\mathbf{x}) = M\mathbf{x} + \mathbf{b}$, we may say that it is affine. We may also sometimes call it a “first-order polynomial” or a “polynomial of degree 1”.

Definition of Differentiability - Single Variable Function $f : (a, b) \rightarrow \mathbb{R}$ is differentiable at x if $x \in (a, b)$ and

$$\lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h}$$

exists.

Equivalently, Function $f : (a, b) \rightarrow \mathbb{R}$ is differentiable at x if $x \in (a, b)$ and there exists a number m such that

$$\lim_{h \rightarrow 0} \frac{f(x+h) - f(x) - mh}{h}$$

and the number m is the derivative of f at x , denoted $f'(x)$.

Interpretation Temporarily fix x , and view h as a variable, and view $f(x+h) - f(x)$ as a function of h . Then f is differentiable at x if the linear function mh approximates $f(x+h) - f(x)$, with errors that are **smaller than linear** as $h \rightarrow 0$. When this holds, $f'(x) = m$. **Alternatively**, Function $f : (a, b) \rightarrow \mathbb{R}$ is differentiable at x if $x \in (a, b)$ and there exists a number m and a function $E(h)$ such that

$$f(x+h) = f(x) + mh + E(h), \quad \text{and} \quad \lim_{h \rightarrow 0} \frac{E(h)}{h} = 0$$

and the number m is the derivative of f at x , denoted $f'(x)$.

Definition of Differentiability - Multi Variable Assume that f is a function $S \rightarrow \mathbb{R}$, where S is an open subset of \mathbb{R}^n . We say that f is differentiable at a point $\mathbf{x} \in S$ if there exists a **vector** $\mathbf{m} \in \mathbb{R}^n$ such that

$$\lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{f(\mathbf{x} + \mathbf{h}) - f(\mathbf{x}) - \mathbf{m} \cdot \mathbf{h}}{|\mathbf{h}|} = 0$$

When this holds, we say that the vector \mathbf{m} (**which is uniquely determined by the above condition**) is the gradient of f at \mathbf{x} , which is denoted $\nabla f(\mathbf{x})$. Thus, the gradient ∇f (when it exists) is characterized by the property that

$$\lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{f(\mathbf{x} + \mathbf{h}) - f(\mathbf{x}) - \nabla f(\mathbf{x}) \cdot \mathbf{h}}{|\mathbf{h}|} = 0$$

Alternatively, f is differentiable at \mathbf{x} if there exists a vector \mathbf{m} such that

$$f(\mathbf{x} + \mathbf{h}) = f(\mathbf{x}) + \mathbf{m} \cdot \mathbf{h} + E(\mathbf{h})$$

where $\lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{E(\mathbf{h})}{|\mathbf{h}|} = 0$. When this holds, we define $\nabla f(\mathbf{x}) = m$.

Theorem 1 Assume that $f : S \rightarrow \mathbb{R}$, where S is an open subset of \mathbb{R}^n , and that $\mathbf{x} \in S$. If f is differentiable at \mathbf{x} , then f is continuous at \mathbf{x} .

Definition of Partial Derivatives If f is a function defined on an open subset $S \subset \mathbb{R}^n$, then at a point $\mathbf{x} \in S$, we define

$$\frac{\partial f}{\partial x_j}(\mathbf{x}) := \lim_{h \rightarrow 0} \frac{f(\mathbf{x} + h\mathbf{e}_j) - f(\mathbf{x})}{h}$$

This is called the *j th partial derivative of f , the partial derivative of f in the x_j direction*, or the *partial derivative of f with respect to x_j* .

Theorem 2 Let f be a function $S \rightarrow \mathbb{R}$, where S is an open subset of \mathbb{R}^n . If f is differentiable at a point $\mathbf{x} \in S$, then $\frac{\partial f}{\partial x_j}$ exists at \mathbf{x} for all $j = 1, \dots, n$, and in addition,

$$\nabla f(\mathbf{x}) = \left(\frac{\partial f}{\partial x_1}, \dots, \frac{\partial f}{\partial x_n} \right)$$

That is, the partial derivatives are the components of the gradient vector.

The converse is not true: It can happen that all partial derivatives $\frac{\partial f}{\partial x_j}$ exist at \mathbf{x} but that f is not differentiable at \mathbf{x} .

Question Type - Determine whether a function f is differentiable at a point \mathbf{x}

1. If any partial derivatives $\partial f / \partial x_j$ fail to exist at \mathbf{x} , then f is not differentiable there, and
2. If all partial derivatives exist, then the vector $\mathbf{m} = (\partial f / \partial x_1, \dots, \partial f / \partial x_n)$ is the **only** possible vector that can “work” in the definition of differentiability.

Theorem 3 Assume f is a function $S \rightarrow \mathbb{R}$ for some open $S \subset \mathbb{R}^n$. If all partial derivatives of f exist and are continuous at every point of S , then f is differentiable at every point of S .

Definition of Class C^1 A function $f : S \rightarrow \mathbb{R}$ is said to be "of class C^1 ", or simply " C^1 " for short, if all partial derivatives of f exist and are continuous at every point of S .

Definition of Directional Derivatives A direction in \mathbb{R}^n is naturally represented by a unit vector.

Given a unit vector \mathbf{u} and a point $\mathbf{x} \in \mathbb{R}^n$, the point $\mathbf{x} + h\mathbf{u}$ is the point reached by starting at \mathbf{x} and traveling a distance h in the direction \mathbf{u} . So $f(\mathbf{x} + h\mathbf{u}) - f(\mathbf{x})$ represents the change in f if we start at \mathbf{x} and move at a distance h in the direction \mathbf{u} .

The directional derivative of f at \mathbf{x} in the direction \mathbf{u} is defined to be

$$\partial_{\mathbf{u}}f(\mathbf{x}) := \lim_{h \rightarrow 0} \frac{f(\mathbf{x} + h\mathbf{u}) - f(\mathbf{x})}{h}$$

whenever the limit exists.

Remark

1. $\partial_{\mathbf{u}}f(\mathbf{x})$ represents the instantaneous rate of change of f if we move in the direction \mathbf{u} through the point \mathbf{x} .
2. $\forall j \in 1, \dots, n$,

$$\frac{\partial f}{\partial x_j} = \partial_{\mathbf{e}_j}f$$

Theorem 4 If f is differentiable at a point \mathbf{x} , then $\partial_{\mathbf{u}}f(\mathbf{x})$ exists for every unit vector \mathbf{u} and moreover

$$\partial_{\mathbf{u}}f(\mathbf{x}) = \mathbf{u} \cdot \nabla f(\mathbf{x})$$

Fundamental Principle When it not equal to zero, $\nabla f(\mathbf{x})$ points in the direction in which f is increasing most rapidly at \mathbf{x} .

2.2 Differentiation (continued)

2.2.1 Differentiation of vector-valued functions

Suppose that S is an open subset of \mathbb{R}^n , and consider a vector-valued function $\mathbf{f}: S \rightarrow \mathbb{R}^m$.

Idea: \mathbf{f} is differentiable at a point $\mathbf{a} \in S$ if \mathbf{f} can be approximated by a linear map $\mathbb{R}^n \rightarrow \mathbb{R}^m$ near \mathbf{a} , with errors that are “smaller than linear”.

Definition Assume that S is an open subset of \mathbb{R}^n . Given a function $\mathbf{f}: S \rightarrow \mathbb{R}^m$, we say that \mathbf{f} is differentiable at a point $\mathbf{a} \in S$ if there exists a $m \times n$ matrix M such that

$$\mathbf{f}(\mathbf{a} + \mathbf{h}) = \mathbf{f}(\mathbf{a}) + M\mathbf{h} + \mathbf{E}(\mathbf{h}), \quad \text{where } \lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{\mathbf{E}(\mathbf{h})}{|\mathbf{h}|} = \mathbf{0} \in \mathbb{R}^m$$

or

$$\lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{\mathbf{f}(\mathbf{x} + \mathbf{h}) - \mathbf{f}(\mathbf{x}) - M\mathbf{h}}{|\mathbf{h}|} = 0$$

When this holds, we say that M is the derivative of \mathbf{f} at \mathbf{a} , and we write $M = D\mathbf{f}(\mathbf{a})$.

Definition of Jacobian Matrix When M satisfy the above definition of differentiability, we say that M is a *Jacobian* matrix.

2.2.2 The differential

Definition Given a differentiable function $f: S \rightarrow \mathbb{R}$, where S is an open subset of \mathbb{R}^n , at a point $\mathbf{a} \in S$ we define $df|_{\mathbf{a}}$ to be the linear map $\mathbb{R}^n \rightarrow \mathbb{R}$ given by

$$df|_{\mathbf{a}}(\mathbf{h}) = \nabla f(\mathbf{a}) \cdot \mathbf{h}$$

Notation for differentials

$$df = \frac{\partial f}{\partial x_1} dx_1 + \dots + \frac{\partial f}{\partial x_n} dx_n$$

linear approximation The definition of the differential implies that if f is differentiable at \mathbf{a} , then

$$f(\mathbf{a} + \mathbf{h}) \approx f(\mathbf{a}) + df|_{\mathbf{a}}(\mathbf{h})$$

for \mathbf{h} small.

2.3 the Chain Rule

Theorem 1: the Chain Rule Assume that S and T are open subsets of \mathbb{R}^n and \mathbb{R}^m , and that we are given functions $\mathbf{g} : S \rightarrow \mathbb{R}^m$ and $\mathbf{f} : T \rightarrow \mathbb{R}^l$. Assume also that $\mathbf{a} \in S$ is a point such that $\mathbf{g}(\mathbf{a}) \in T$; thus $\mathbf{f} \circ \mathbf{g}(\mathbf{x}) = \mathbf{f}(\mathbf{g}(\mathbf{x}))$ is well-defined for all \mathbf{x} close to \mathbf{a} .

$$D(\mathbf{f} \circ \mathbf{g})(\mathbf{a}) = D\mathbf{f}(\mathbf{g}(\mathbf{a})) D\mathbf{g}(\mathbf{a})$$

Equivalently,

$$\frac{\partial}{\partial x_j}(f_k \circ \mathbf{g})(\mathbf{a}) = \sum_{i=1}^m \frac{\partial f_k}{\partial y_i}(\mathbf{g}(\mathbf{a})) \frac{\partial g_i}{\partial x_j}(\mathbf{a})$$

for $k = 1, \dots, l$ and $j = 1, \dots, n$

Different Notation Write $\mathbf{u} = (u_1, \dots, u_l)$ to denote a typical point in \mathbb{R}^l . If we suppose that the \mathbf{x}, \mathbf{y} and \mathbf{u} variables are related by

$$\mathbf{y} = \mathbf{g}(\mathbf{x}), \quad \mathbf{u} = \mathbf{f}(\mathbf{y}) = \mathbf{f}(\mathbf{g}(\mathbf{x}))$$

Then the Chain Rule becomes

$$\frac{\partial u_k}{\partial x_j} = \frac{\partial u_k}{\partial y_1} \frac{\partial y_1}{\partial x_j} + \dots + \frac{\partial u_k}{\partial y_m} \frac{\partial y_m}{\partial x_j}$$

for $k = 1, \dots, l$ and $j = 1, \dots, n$

Examples

1. $f(\mathbf{x}) = |\mathbf{x}| \implies \nabla f(\mathbf{x}) = \frac{\mathbf{x}}{|\mathbf{x}|}$ for $\mathbf{x} \neq \mathbf{0}$

2. **homogeneous functions**

A function $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is said to be homogeneous of degree α if

$$f(\lambda \mathbf{x}) = \lambda^\alpha f(\mathbf{x})$$

for all $\mathbf{x} \neq \mathbf{0}$ and $\lambda > 0$.

2.3.1 Level Sets and the Gradient

Assume that S is an open subset of \mathbb{R}^n and that $f : S \rightarrow \mathbb{R}$ is differentiable at \mathbf{a} . Then

$\nabla f(\mathbf{a})$ is orthogonal to the level set of f that passes through \mathbf{a} .

Tangent plane to a level set Suppose S is an open subset of \mathbb{R}^3 and that $f : S \rightarrow \mathbb{R}$ is a function that is differentiable at a point $\mathbf{a} \in S$. Assume also that

$$\nabla f(\mathbf{a}) \neq \mathbf{0}$$

We define the tangent plane to C at \mathbf{a} $:= \{\mathbf{x} \in \mathbb{R}^3 : (\mathbf{x} - \mathbf{a}) \cdot \nabla f(\mathbf{a}) = 0\}$.

2.4 The Mean Value Theorem

Theorem 1: the Mean Value Theorem Assume that f is a real-valued function of class C^1 defined on an open set $S \subset \mathbb{R}^n$. For two points $\mathbf{a}, \mathbf{b} \in S$, let $L_{\mathbf{a}, \mathbf{b}}$ denote the line segment that connects them. If $L_{\mathbf{a}, \mathbf{b}} \subset S$, then there exists $\mathbf{c} \in L_{\mathbf{a}, \mathbf{b}}$ such that

$$f(\mathbf{b}) - f(\mathbf{a}) = (\mathbf{b} - \mathbf{a}) \cdot \nabla f(\mathbf{c})$$

Applications

1. If a function f has the property that $f'(t) = 0$ for all t in an interval (a, b) , then f is constant on (a, b) .
2. If a function f has the property that $|f'(t)| \leq M$ for all t in an interval (a, b) , then the slope of f between any two points is at most M . More precisely,

$$|f'(t)| \leq M \text{ for all } t \in (a, b) \implies |f(t) - f(s)| \leq M|t - s| \text{ for all } s, t \in (a, b)$$

Theorem 2 Assume that S is an open, convex subset of \mathbb{R}^n and that $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is a function that is differentiable in S , and moreover that there exists $M \geq 0$ such that $|\nabla f(\mathbf{x})| \leq M$ for all $\mathbf{x} \in S$. Then for every $\mathbf{a}, \mathbf{b} \in S$,

$$|f(\mathbf{b}) - f(\mathbf{a})| \leq M|\mathbf{b} - \mathbf{a}|$$

Theorem 3 Assume that S is an open, convex subset of \mathbb{R}^n and that $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is a function that is differentiable in S . If $\nabla f(\mathbf{x}) = \mathbf{0}$ for every $\mathbf{x} \in S$, then f is constant on S .

Theorem 4 Assume that S is an open, **path-connected** subset of \mathbb{R}^n and that $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is a function that is differentiable on S . If $\nabla f(\mathbf{x}) = \mathbf{0}$ for every $\mathbf{x} \in S$, then f is constant on S .

2.5 Higher Order Derivatives

Theorem 1 Assume that S is an open subset of \mathbb{R}^n . If $f : S \rightarrow \mathbb{R}$ is C^2 ,

$$\frac{\partial^2 f}{\partial x_i \partial x_j} = \frac{\partial^2 f}{\partial x_j \partial x_i}$$

for all $i, j = 1, \dots, n$ everywhere in S .

Theorem 2 Assume that S is an open subset of \mathbb{R}^n . If $f : S \rightarrow \mathbb{R}$ is C^k . For any integers i_1, \dots, i_k between 1 and n , if j_1, \dots, j_k is a reordering of i_1, \dots, i_k , then

$$\frac{\partial}{\partial x_{i_k}} \cdots \frac{\partial}{\partial x_{i_1}} = \frac{\partial}{\partial x_{j_k}} \cdots \frac{\partial}{\partial x_{j_1}}$$

everywhere in S .

The Hessian Matrix If f is a C^2 function of n variables, then it is customary to arrange the second derivatives of f into a $n \times n$ matrix, called the Hessian matrix (or sometimes just the Hessian and denote H :

$$H = \begin{pmatrix} \partial_1 \partial_1 f & \cdots & \partial_n \partial_1 f \\ \vdots & \ddots & \vdots \\ \partial_1 \partial_n f & \cdots & \partial_n \partial_n f \end{pmatrix}$$

2.6 Taylor's Theorem

2.6.1 Review of Taylor's Theorem in 1 Dimension

Definition of Taylor polynomials Assume $I \subset \mathbb{R}$ is an open interval and that $f : I \rightarrow \mathbb{R}$ is a function of class C^k on I .

For a point $a \in I$, the k th order Taylor polynomial of f at a is the unique polynomial of order at most k , denoted $P_{a,k}(h)$ such that

$$\begin{aligned} f(a) &= P_{a,k}(0) \\ f'(a) &= P'_{a,k}(0) \\ &\vdots \\ f^{(k)}(a) &= P^{(k)}_{a,k}(0) \end{aligned}$$

$$\begin{aligned}
P_{a,k}(h) &= f(a) + hf'(a) + \frac{h^2}{2}f''(a) + \dots + \frac{h^k}{k!}f^{(k)}(a) \\
&= \sum_{j=0}^k \frac{h^j}{j!}f^{(j)}(a)
\end{aligned}$$

Remark Taylor's Theorem guarantees that $P_{a,k}(h)$ is a very good approximation of $f(a+h)$, and that **the quality of the approximation increases as k increases.**

Theorem 1: Taylor's Theorem in 1D Assume $I \subset \mathbb{R}$ is an open interval and that $f : I \rightarrow \mathbb{R}$ is a function of class C^k on I . For $a \in I$ and $h \in \mathbb{R}$ such that $a+h \in I$, let $P_{a,k}(h)$ denote the k th-order Taylor polynomial at a and define the remainder

$$R_{a,k}(h) := f(a+h) - P_{a,k}(h)$$

Then

$$\lim_{h \rightarrow 0} \frac{R_{a,k}(h)}{h^k} = 0$$

2.6.2 Taylor's Theorem in higher dimensions

Assume $S \subset \mathbb{R}^n$ is an open set and that $f : S \rightarrow \mathbb{R}$ is a function of class C^k on S . For a point $a \in S$, the k th order Taylor polynomial of f at a is the unique polynomial of order at most k , denoted $P_{a,k}(\mathbf{h})$ such that

$$\begin{aligned}
f(\mathbf{a}) &= P_{\mathbf{a},k}(\mathbf{0}) \\
\partial^\alpha f(\mathbf{a}) &= \partial^\alpha P_{\mathbf{a},k}(\mathbf{0})
\end{aligned}$$

for all partial derivatives of order up to k .

Theorem 2: Taylor's Theorem in n Dimensions Assume $S \subset \mathbb{R}^n$ is an open interval and that $f : S \rightarrow \mathbb{R}$ is a function of class C^k on I . For $a \in S$ and $h \in \mathbb{R}^n$ such that $a+h \in S$, let $P_{a,k}(h)$ denote the k th-order Taylor polynomial at a and define the remainder

$$R_{\mathbf{a},k}(\mathbf{h}) := f(\mathbf{a} + \mathbf{h}) - P_{\mathbf{a},k}(\mathbf{h})$$

Then

$$\lim_{\mathbf{h} \rightarrow \mathbf{0}} \frac{R_{\mathbf{a},k}(\mathbf{h})}{|\mathbf{h}|^k} = 0$$

c

2.6.3 The Quadratic case

A Taylor polynomial formula for $k = 2$

$$P_{\mathbf{a},2}(\mathbf{h}) = f(\mathbf{a}) + \nabla f(\mathbf{a}) \cdot \mathbf{h} + \frac{1}{2}(H(\mathbf{a})\mathbf{h}) \cdot \mathbf{h}$$

where we remember that $\mathbf{h} = \mathbf{x} - \mathbf{a}$ if we want the result in terms of x, y .

2.7 Critical Points

Definition A symmetric $n \times n$ matrix A is

1. **positive definite** if $\mathbf{x}^T A \mathbf{x} > 0$ for all $\mathbf{x} \in \mathbb{R}^n \setminus \{\mathbf{0}\}$
2. **nonnegative definite** if $\mathbf{x}^T A \mathbf{x} \geq 0$ for all $\mathbf{x} \in \mathbb{R}^n$

In addition, we say that A is

1. **negative definite** if $-A$ is positive definite
2. **nonpositive definite** if $-A$ is nonnegative definite

A matrix A is **indefinite** if none of the above holds. Equivalently, A is indefinite if there exist $\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$ such that $\mathbf{x}^T A \mathbf{x} < 0 < \mathbf{y}^T A \mathbf{y}$

Theorem 1 Assume that A is a symmetric matrix. Then

1. A is positive definite \iff all its eigenvalues are positive
 $\iff \exists \lambda_1 > 0$ such that $\mathbf{x}^T A \mathbf{x} \geq \lambda_1 |\mathbf{x}|^2$ for all $\mathbf{x} \in \mathbb{R}^n$
2. A is nonnegative definite \iff all its eigenvalues are nonnegative
3. A is indefinite $\iff A$ has both positive and negative eigenvalues

Remark If A is a symmetric matrix then

The smallest eigenvalue of $A = \min_{\{\mathbf{u} \in \mathbb{R}^n: |\mathbf{u}|=1\}} \mathbf{u}^T A \mathbf{u}$

Theorem 2 For the matrix $A = \begin{pmatrix} \alpha & \beta \\ \beta & \gamma \end{pmatrix}$,

1. if $\det A < 0$, then A is indefinite
2. if $\det A > 0$, then
 - if $\alpha > 0$ then A is positive definite
 - if $\alpha < 0$ then A is negative definite
3. if $\det A = 0$ then at least one eigenvalue equals zero.

Definition A critical point \mathbf{a} of C^2 function \mathbf{f} is degenerate if $\det(D\mathbf{H}(\mathbf{a})) = 0$

Theorem 3 - first derivative test If $\mathbf{f} : S \subset \mathbb{R}^n \rightarrow \mathbb{R}$ is differentiable, then every local extremum is a critical point.

Theorem 4 - second derivative test

1. If $f : S \rightarrow \mathbb{R}$ is C^2 and \mathbf{a} is a local minimum point for f , then \mathbf{a} is a critical point of f and $H(\mathbf{a})$ is nonnegative definite.
2. If \mathbf{a} is a critical point and $H(\mathbf{a})$ is positive definite, then \mathbf{a} is a local minimum point.

Corollary Assume that f is C^2 and $\nabla f(\mathbf{a}) = \mathbf{0}$

1. If $H(\mathbf{a})$ is positive definite, then \mathbf{a} is a local min;
2. If $H(\mathbf{a})$ is negative definite, then \mathbf{a} is a local max;
3. If $H(\mathbf{a})$ is indefinite, then \mathbf{a} is a saddle point;
4. If none of the above hold, then we cannot determine the character of the critical point without further thought.

E.Knight's approach to critical points. In solving a question of $f : \mathbb{R}^2 \rightarrow \mathbb{R}$ we could use the following “quick check” approach:

1. Calculate the gradient of F , equating it to zero to find the critical points

2. Calculate the Hessian of F , find the corresponding matrices for each critical points, where the Hessian is defined as

$$H(f) = \begin{bmatrix} \partial_{xx}f & \partial_{xy}f = \partial_{yx}f \\ \partial_{xy}f = \partial_{yx}f & \partial_{yy}f \end{bmatrix}$$

3. Calculate the determinant of the hessian, and there are the following cases to consider
- (a) $\det H < 0$, then $\text{sig}(H) = (1, 1)$ and the point is a saddle point
 - (b) $\det H > 0$, then
 - i. $\text{tr}(H) < 0 \implies \text{sig}(H) = (2, 0)$ and the point is a local minimum
 - ii. $\text{tr}(H) > 0 \implies \text{sig}(H) = (0, 2)$ and the point is a local maximum
 - (c) $\det H = 0$, then the test is inconclusive. We have to do this case by starring at it.

2.8 Lagrange Multipliers

2.8.1 One constraint

Consider the problem

$$\begin{cases} \text{minimize/maximize} & f(\mathbf{x}) \\ \text{subject to the constraint:} & g(\mathbf{x}) = 0 \end{cases}$$

Theorem 1 Assume that f and g are functions $S \rightarrow \mathbb{R}$ of class C^1 , where S is an open subset of \mathbb{R}^n .

If \mathbf{x} is a local minimum point or local maximum point of f subject to the constraint $g = 0$, and if $\nabla g(\mathbf{x}) \neq \mathbf{0}$ then there exists $\lambda \in \mathbb{R}$ such that the following system of equations is satisfied by \mathbf{x} and λ :

$$\begin{cases} \nabla f(\mathbf{x}) + \lambda \nabla g(\mathbf{x}) & = \mathbf{0} \\ g(\mathbf{x}) & = 0 \end{cases}$$

Proposition the Lagrange multiplier equations $\implies \nabla f(\mathbf{x})$ is orthogonal at \mathbf{x} to the set of points satisfying the constraint.

2.8.2 Two constraints

Assume that f, g_1 and g_2 are functions $\mathbb{R}^n \rightarrow \mathbb{R}$ of class C^1 . Assume also that $\{\nabla g_1(\mathbf{x}), \nabla g_2(\mathbf{x})\}$ are **linearly independent** at all \mathbf{x} where $g_1(\mathbf{x}) = g_2(\mathbf{x}) = 0$. Then if x is any solution to the optimization problem, there exists $\lambda_1, \lambda_2 \in \mathbb{R}$ such that the following system of equations is satisfied by \mathbf{x}, λ_1 and λ_2 :

$$\begin{cases} \nabla f(\mathbf{x}) + \lambda_1 \nabla g_1(\mathbf{x}) + \lambda_2 \nabla g_2(\mathbf{x}) &= \mathbf{0} \\ g_1(\mathbf{x}) &= 0 \\ g_2(\mathbf{x}) &= 0 \end{cases}$$

2.8.3 Inequality Constraints

Consider the problem

$$\begin{cases} \text{minimize/maximize } f(\mathbf{x}) \\ \text{subject to the constraint: } g(\mathbf{x}) \leq 0 \end{cases}$$

where we assume that g is C^2 , say, and that $\nabla g(\mathbf{x}) \neq 0$ on the set $\{\mathbf{x} \in \mathbb{R}^n : g(\mathbf{x}) = 0\}$.

We can reduce this to problems we already know how to solve. EVT guarantees that the problem has a solution.

Case 1 The max or min occurs in the set $\{x \in \mathbb{R}^n : g(\mathbf{x}) < 0\}$. Then it is a critical point, which we know how to find and classify.

Case 2 The max or min occurs in the set $\{x \in \mathbb{R}^n : g(\mathbf{x}) = 0\}$. Then we can find it by the Lagrange Multiplier technique.

Finally we can choose the smallest/largest value of f and the point where that value is attained from among all the candidates found in steps 1 and 2 above.

3 The Implicit and Inverse Function Theorems

3.1 The Implicit Function Theorem

Assume that S is an open subset of \mathbb{R}^{n+k} and that $F : S \rightarrow \mathbb{R}^k$ is a function of class C^1 . Assume also that (\mathbf{a}, \mathbf{b}) is a point in S such that

$$\mathbf{F}(\mathbf{a}, \mathbf{b}) = \mathbf{0} \text{ and } \det D_{\mathbf{y}}\mathbf{F}(\mathbf{a}, \mathbf{b}) \neq 0$$

1. Then there exists $r_0, r_1 > 0$ such that for every $\mathbf{x} \in \mathbb{R}^n$ such that $|\mathbf{x} - \mathbf{a}| < r_0$, there exists a unique $\mathbf{y} \in \mathbb{R}^k$ such that $|\mathbf{y} - \mathbf{b}| < r_1$

$$\mathbf{F}(\mathbf{x}, \mathbf{y}) = \mathbf{0} \quad (2)$$

In other words, equation (2) implicitly defines a function $\mathbf{y} = \mathbf{f}(\mathbf{x})$ for $x \in \mathbb{R}^n$ near \mathbf{a} , with $\mathbf{y} = \mathbf{f}(\mathbf{x})$ close to \mathbf{b} . Note in particular that $\mathbf{b} = \mathbf{f}(\mathbf{a})$.

2. Moreover, the function $\mathbf{f} : B(r_0, \mathbf{a}) \rightarrow B(r_1, \mathbf{b}) \subset \mathbb{R}^k$ from part (1) above is of class C^1 , and its derivatives may be determined by differentiating the identity

$$\mathbf{F}(\mathbf{x}, \mathbf{f}(\mathbf{x})) = \mathbf{0}$$

and solving to find the partial derivatives of \mathbf{f} .

Analytic Content of the Theorem Suppose we want to solve the equation $\mathbf{F}(\mathbf{x}, \mathbf{y}) = \mathbf{0}$ for \mathbf{y} as a function of \mathbf{x} , say $\mathbf{y} = \mathbf{f}(\mathbf{x})$. If we have a solution $\mathbf{b} = \mathbf{f}(\mathbf{a})$, then in principle it is possible to solve for \mathbf{x} near \mathbf{a} , **if the crucial hypothesis $\det D_{\mathbf{y}}\mathbf{F}(\mathbf{a}, \mathbf{b}) \neq 0$ holds.** Thus it is a theorem about the possibility of solving systems of (in general nonlinear) equations.

Remark Differentiating $\mathbf{F}(\mathbf{x}, \mathbf{f}(\mathbf{x})) = \mathbf{0}$:

$$D_{\mathbf{y}}\mathbf{F}|_{(\mathbf{x}, \mathbf{f}(\mathbf{x}))} D\mathbf{f}(\mathbf{x}) = -D_{\mathbf{x}}\mathbf{F}|_{(\mathbf{x}, \mathbf{f}(\mathbf{x}))}$$

Substituting $(\mathbf{x}, \mathbf{f}(\mathbf{x})) = (\mathbf{a}, \mathbf{b})$ we get

$$D_{\mathbf{y}}\mathbf{F}(\mathbf{a}, \mathbf{b}) D\mathbf{f}(\mathbf{a}) = -D_{\mathbf{x}}\mathbf{F}(\mathbf{a}, \mathbf{b})$$

We need to solve for $D\mathbf{f}(\mathbf{a})$ in terms of derivatives of \mathbf{F} evaluated at (\mathbf{a}, \mathbf{b}) , which leads to

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

Limitations

1. We have to start by knowing one solution $\mathbf{y} = \mathbf{b}$ for some specific $\mathbf{x} = \mathbf{a}$.
2. It only gives **local** information near point (\mathbf{a}, \mathbf{b}) .

3. It does not give a formula for $\mathbf{y} = \mathbf{f}(\mathbf{x})$ solving $\mathbf{F}(\mathbf{x}, \mathbf{y}) = 0$. It does however, tell us how to compute $D\mathbf{f}(\mathbf{a})$, and this allows us to approximate the solution

$$\mathbf{f}(\mathbf{a} + \mathbf{h}) \approx \mathbf{f}(\mathbf{a}) + D\mathbf{f}(\mathbf{a})\mathbf{h} = \mathbf{b} + D\mathbf{f}(\mathbf{a})\mathbf{h}$$

for \mathbf{h} small.

3.2 Geometric Contents of the Implicit Function Theorem

k-Dimensional Manifolds in \mathbb{R}^n

3.2.1 The General Case

Fix $k < n$. For a k-dimensional manifold M in \mathbb{R}^n , we say that M has "degrees of freedom" k . There are 3 natural ways to represent M (be careful with the dimensions!!!):

1. As a graph:

$$\mathbf{f}: U \subset \mathbb{R}^k \rightarrow \mathbb{R}^{n-k}$$

where U is open.

$$S = \{(\mathbf{x}, \mathbf{f}(\mathbf{x})) \in \mathbb{R}^n : \mathbf{x} \in U\}$$

2. As a level set:

$$\mathbf{F}: U \subset \mathbb{R}^n \rightarrow \mathbb{R}^{n-k}$$

where U is open.

$$S = \{\mathbf{x} \in U : \mathbf{F}(\mathbf{x}) = \mathbf{c}\}$$

for some $\mathbf{c} \in \mathbb{R}^{n-k}$.

This is also called the "zero locus" of \mathbf{F} when $\mathbf{c} = \mathbf{0}$

Remark 1 The regularity conditions that guarantees that S is smooth is that

1. $\nabla F_1(\mathbf{x}), \dots, \nabla F_{n-k}(\mathbf{x})$ are linearly independent at each $\mathbf{x} \in S$. Or equivalently,
2. the matrix $D\mathbf{F}(\mathbf{x})$ has rank $n - k$ at every $\mathbf{x} \in S$.

Remark 2 It can happen that S is smooth but the above conditions are not satisfied. Example: The square of a smooth set $\mathbf{F}(x, y, z) = (x^2 + y^2 - 1)^2$, $\mathbf{c} = \mathbf{0}$

3. Parametrically

$$\mathbf{f} : U \subset \mathbb{R}^k \rightarrow \mathbb{R}^n$$

where U is open.

$$S = \{\mathbf{f}(\mathbf{u}) : \mathbf{u} \in U\}$$

Remark The regularity conditions that guarantees that S is smooth is that

1. $\partial_{u_1} \mathbf{f}(\mathbf{u}), \dots, \partial_{u_k} \mathbf{f}(\mathbf{u})$ are linearly independent at each $\mathbf{u} \in U$. Or equivalently,
2. the matrix $D\mathbf{f}(\mathbf{u})$ has rank k at every $\mathbf{u} \in U$.

Notes We can prove that if the above conditions are satisfied, then S is smooth. Construct $\mathbf{F} : \mathbb{R}^{2k} \rightarrow \mathbb{R}^k$, then use IFT (the proof is hard but worthwhile to think about since the general case implies every specific case).

3.2.2 The Specific Cases

Theorem 1 - When is a curve regular? Assume that $\mathbf{F} : \mathbb{R}^2 \rightarrow \mathbb{R}$ is C^1 , and let

$$S := \{\mathbf{x} \in \mathbb{R}^2 : F(\mathbf{x}) = 0\}$$

If $\mathbf{a} \in S$ and $\nabla F(\mathbf{a}) \neq 0$, then there exists some $r > 0$ such that $B(r, \mathbf{a}) \cap S$ is a C^1 graph.

(Prove directly using IFT)

Theorem 2 - When is the parametrization regular? Assume that $\mathbf{f} : (a, b) \rightarrow \mathbb{R}^2$ is C^1 , and let

$$S := \{\mathbf{f}(t) : t \in (a, b)\}$$

If $\mathbf{f}'(c) \neq 0$ for some $c \in (a, b)$, then there exists some $r > 0$ such that $\{\mathbf{f}(t) : |t - c| < r\}$ is a C^1 graph.

Remark It says only that the parametrization is regular near $t = c$, it does not say that S is regular near $\mathbf{f}(c)$. What it means is that when increasing/decreasing t , we have no control over the path of $f(t)$.

Theorem 3- When is a surface regular? conditions: $\mathbf{a} \in S$ and $\nabla F(\mathbf{a}) \neq 0$

Theorem 4 - When is the parametrization regular? conditions: $Df(c)$ has rank 2 at some c

3.2.3 Remarks on smoothness of a parametric smooth curve

Definition. If $I \subseteq \mathbb{R}$ is an interval, a \mathcal{C}^1 map $\gamma : I \rightarrow \mathbb{R}^2$ is said to be

1. A *regular curve* if $\gamma'(t) \neq 0, \forall t \in I$
2. A *simple curve* if γ is injective on the interior of I .

Hence if γ is regular, then there is a neighbourhood of each point whose image looks like a graph of a \mathcal{C}^1 -function. Simplicity guarantees that no funny overlaps can happen, and this is what is needed for the curve to be smooth. **As a conclusion, we say a parametric curve is smooth if and only if it is *regular* and *simple*.** Equivalently we could also convert such parametrization into a zero locus of a F to use the good old method of gradient directly.

3.2.4 Remarks on Smoothness of a Set S

1. S is smooth $:= S$ can be represented as a \mathcal{C}^1 graph
2. Jacobian of a level set has full rank $\implies S$ is smooth
3. A parametrization of S is smooth \wedge parametrization is injective $\implies S$ is smooth
4. S is smooth $\not\implies$ Jacobian of any level set has full rank
5. S is smooth $\not\implies$ any parametrization of S is smooth
6. A parametrization of S is smooth $\not\implies S$ is smooth

3.3 The Inverse Function Theorem

Let U and V be open sets in \mathbb{R}^n , and assume that $\mathbf{f} : U \rightarrow V$ is a mapping of class C^1 .

Assume that $\mathbf{a} \in U$ is a point such that $D\mathbf{f}(\mathbf{a})$ is invertible.

and let $\mathbf{b} := \mathbf{f}(\mathbf{a})$. Then there exist open sets $M \subset U$ and $N \subset V$ such that

1. $\mathbf{a} \in M$ and $\mathbf{b} \in N$
2. \mathbf{f} is one-to-one from M onto N (hence invertible), and
3. the inverse function $f^{-1} : N \rightarrow M$ is of class C^1

Moreover, if $x \in M$ and $y = \mathbf{f}(\mathbf{x}) \in N$, then

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

In particular,

$$D(\mathbf{f}^{-1})(\mathbf{b}) = [D\mathbf{f}(\mathbf{a})]^{-1}$$

Remarks The theorem tells us when a transformation of class C^1 has a **local** inverse of class C^1

It says: Suppose we are given n nonlinear equations in n unknowns. Given $\mathbf{f} : U \rightarrow V$ and $\mathbf{y} \in V$, and we want to find \mathbf{x} solving

$$\mathbf{f}(\mathbf{x}) = \mathbf{y}$$

If we know that $\mathbf{f}(\mathbf{a}) = \mathbf{b}$, then for \mathbf{y} near \mathbf{b} , the solvability of the system can be established by considering whether the matrix $D\mathbf{f}(\mathbf{a})$ is invertible.

3.3.1 Some Important Coordinate Systems

Polar Coordinates in \mathbb{R}^2

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} r \cos \theta \\ r \sin \theta \end{pmatrix} = \mathbf{f}(r, \theta)$$

For \mathbf{f} to be a bijection between open sets, we have to restrict its domain and range. A common choice is to specify that \mathbf{f} is a function $U \rightarrow V$ where

$$U := \{(r, \theta) : r > 0, |\theta| < \pi\}, V := \mathbb{R}^2 \setminus \{(x, 0) : x \leq 0\}$$

(Note that there is a half of the x-axis missing)

Spherical Coordinates in \mathbb{R}^3

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} r \cos \theta \sin \varphi \\ r \sin \theta \sin \varphi \\ r \cos \varphi \end{pmatrix} = \mathbf{f}(r, \theta, \varphi)$$

If we want \mathbf{f} to be a bijection between open sets U and V , it is necessary to restrict the domain and range in some appropriate way.

Cylindrical Coordinates in \mathbb{R}^3

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

4 Integration**4.1 Zero content**

Zero content in 1-D A set $S \subset \mathbb{R}$ is said to have zero content if

$$\forall \epsilon > 0, \exists \text{ intervals } I_1, \dots, I_n \text{ s.t. } S \subseteq \bigcup_{i=1}^n I_i \wedge \sum_{i=1}^n \text{Len}(I_i) < \epsilon$$

Multidimensional zero content. A set $S \subset \mathbb{R}^n$ is said to have zero content if

$$\forall \epsilon > 0, \exists \text{ boxes } B_1, \dots, B_n \text{ s.t. } S \subseteq \bigcup_{i=1}^n B_i \wedge \sum_{i=1}^n \text{Area}(B_i) < \epsilon$$

Consequence of zero content. If a set Z has zero content, then

$$\forall \epsilon > 0, \exists \text{ boxes } B_1, \dots, B_n \text{ s.t. } S \subseteq \bigcup_{i=1}^n B_i^{\text{int}} \wedge \sum_{i=1}^n \text{Area}(B_i) < \epsilon$$

Notice the extra *int*.

Proposition on zero content

1. If $Z \subset \mathbb{R}^2$ has zero content and $U \subset Z$, then U has zero content.
2. If Z_1, \dots, Z_k have zero content, then so does $\bigcup_1^k Z_j$
3. $\mathbf{f} : (a_0, b_0) \rightarrow \mathbb{R}^2$ is of class C_1 , then $\mathbf{f}([a, b])$ has zero content whenever $a_0 < a < b < b_0$

4.2 Theorems of 1-D Integral Calculus

Lemma: Refined partitions give better approximations Let P be some partition over an interval and let P' be a refinement of P , then

$$LS_{P'}f \geq LS_Pf \wedge US_{P'}f \leq US_Pf$$

Where LS and US stands for lower sum and upper sum respectively.

Lemma: Lower sum is always less then or equal to upper sum If P and Q are any partitions of $[a, b]$, then $LS_Pf \leq US_Qf$. The essence of this proof is to consider the common refinement of these two partitions.

Lemma. $\epsilon - \delta$ definition of integrability If f is a bounded function on $[a, b]$, the following conditions are equivalent:

1. f is integrable on $[a, b]$
2. $\forall \epsilon > 0, \exists P$ of $[a, b]$ such that $US_Pf - LS_Pf < \epsilon$

Theorem: Integration is “Linear”

1. Suppose $a < b < c$. If f is integrable on $[a, b]$ and on $[b, c]$, then f is integrable on $[a, c]$, further more

$$\int_a^c f(x)dx = \int_a^b f(x)dx + \int_b^c f(x)dx$$

2. If f and g are integrable on $[a, b]$, then so is $f + g$, further more

$$\int_a^b [f(x) + g(x)]dx = \int_a^b f(x)dx + \int_a^b g(x)dx$$

Theorem. Suppose f is integrable on $[a, b]$.

1. If $c \in \mathbb{R}$, the cf is integrable on $[a, b]$, and $\int_a^b cf(x) = c \int_a^b f(x)dx$
2. If $[c, d] \subset [a, b]$, then f is integrable on $[c, d]$.
3. If g is integrable on $[a, b]$ and $f(x) \leq g(x), \forall x \in [a, b]$, then $\int_a^b f(x)dx \leq \int_a^b g(x)dx$
4. $|f|$ is integrable on $[a, b]$, and $\left| \int_a^b f(x)dx \right| \leq \int_a^b |f(x)|dx$

Theorem: Bounded + monotone \implies integrable If f is bounded and monotone on $[a, b]$, then f is integrable on $[a, b]$. The proof of this uses the $\epsilon - \delta$ definition of integrability

Theorem: Continuous \implies integrable If f is continuous on $[a, b]$, then f is integrable on $[a, b]$. Note that continuous is a sufficient but not necessary condition of integrability

Theorem: discontinuous at only finite pts \implies integrable If f is bounded on $[a, b]$ and continuous at all except finitely many points in $[a, b]$, then f is integrable on $[a, b]$. A easy example of this would be any \mathbb{R} function that has a hole in it.

Theorem: Discontinuous at only zero content \implies integrable If f is bounded on $[a, b]$ and the set of points in $[a, b]$ at which f is discontinuous has zero content, then f is integrable on $[a, b]$.

Proposition. Suppose f and g are integrable on $[a, b]$ and $f(x) = g(x)$ for all except finitely many points $x \in [a, b]$. Then $\int_a^b f(x)dx = \int_a^b g(x)dx$.

The Fundamental Theorem Of Calculus

1. Let f be an integrable function on $[a, b]$. For $x \in [a, b]$, let $F(x) = \int_a^x f(t)dt$. Then F is continuous on $[a, b]$; more-over, $F'(x)$ exists and equals $f(x)$ at every x at which f is continuous,
2. Let F be a continuous function on $[a, b]$ that is differentiable except perhaps at finitely many points in $[a, b]$, and let f be a function on $[a, b]$ that agrees with F' at all points where the latter is defined. If f is integrable on $[a, b]$, then $\int_a^b f(t)dt = F(b) - F(a)$

Proposition. Suppose f is integrable on $[a, b]$. Given $\epsilon > 0, \exists \delta > 0$ such that if $P = \{x_0, \dots, x_J\}$ is any partition of $[a, b]$ satisfying

$$\max\{x_j - x_{j-1} | 1 \leq j \leq J\} < \delta$$

the sums $LS_P f$ and $US_P f$ differ from $\int_a^b f(x)dx$ by at most ϵ .

4.3 Generalized Integral Calculus

Theorems of double integrals

1. If f_1 and f_2 are integrable on the bounded set S and $c_1, c_2 \in \mathbb{R}$, then $c_1 f_1 + c_2 f_2$ is integrable on S , and

$$\iint_S [c_1 f_1 + c_2 f_2] dA = c_1 \iint_S f_1 dA + c_2 \iint_S f_2 dA$$

2. Let S_1 and S_2 be bounded sets with no points in common (intersection $= \emptyset$), and let f be a bounded function. If f is integrable on S_1 and on S_2 , then f is integrable on $S_1 \cup S_2$, in which case

$$\iint_{S_1 \cup S_2} f dA = \iint_{S_1} f dA + \iint_{S_2} f dA$$

3. If f and g are integrable on S and $f(\mathbf{x}) \leq g(\mathbf{x})$ for $\mathbf{x} \in S$, then $\iint_S f dA \leq \iint_S g dA$
4. If f is integrable on S , then so is $|f|$, and

$$\left| \iint_S f dA \right| \leq \iint_S |f| dA$$

Theorem. Suppose f is a bounded function on the rectangle R . If the set of points in R at which f is discontinuous has zero content, then f is integrable on R .

Discontinuity of characteristic function The function χ_S is discontinuous at \mathbf{x} if and only if \mathbf{x} is in the boundary of S .

Theorem. Let S be a measurable subset of \mathbb{R}^2 . Suppose $f : \mathbb{R}^2 \rightarrow \mathbb{R}$ is bounded and the set of points in S at which f is discontinuous has zero content. Then f is integrable on S .

Remark on this theorem: The only points where f_{χ_S} can be discontinuous are those points in the closure of S where either f or χ_S is discontinuous. Both of these cases are discontinuity on a set of zero content. And we can definitely fix S inside of a rectangle, then by the previously stated theorem (The theorem directly above), such function is integrable.

Proposition: Integration on a set of zero content evaluates to zero.

Suppose $Z \subset \mathbb{R}^2$ has zero content. If $f : \mathbb{R}^2 \rightarrow \mathbb{R}$ is bounded, then f is integrable on Z and $\int_Z f dA = 0$

Corollary

1. Suppose that f is integrable on the set $S \subset \mathbb{R}^2$. If $g(\mathbf{x}) = f(\mathbf{x})$ except for \mathbf{x} in a set of zero content, then g is integrable on S and $\int_S g dA = \int_S f dA$
2. Suppose that f is integrable on S and on T , and $S \cap T$ has zero content. Then f is integrable on $S \cup T$, and $\int_{S \cup T} f dA = \int_S f dA + \int_T f dA$

Fubini's Theorem Let $R = \{(x, y) : a \leq x \leq b, c \leq y \leq d\}$, and let f be an integrable function on R . Suppose that, for each $y \in [c, d]$, the function f_y defined by $f_y(x) = f(x, y)$ is integrable on $[a, b]$, and the function $g(y) = \int_a^b f(x, y) dx$ is integrable on $[c, d]$. Then

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

Likewise, if $f^x(y) = f(x, y)$ is integrable on $[c, d]$ for each $x \in [a, b]$, and $h(x) = \int_c^d f(x, y) dy$ is integrable on $[a, b]$, then

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

4.4 Change of Variables

Change of Variable formula 1D If g is a one-to-one function of class C^1 on the interval $[a, b]$, then for any continuous function f ,

$$\int_{[a, b]} f(g(u)) |g'(u)| du = \int_{g([a, b])} f(x) dx$$

In practice it is often more convenient to have all the g 's on one side of the equation. If we set $I = g([a, b])$, we have $[a, b] = g^{-1}(I)$, and

$$\int_I f(x) dx = \int_{g^{-1}(I)} f(g(u)) |g'(u)| du$$

Goal: find the analogous formula for multiple integrals. The question is: How does the volume of a tiny piece of n -space change when one applies the transformation G ?

Theorem - Change of Variable for linear mappings Let A be an invertible $n \times n$ matrix, and let $\mathbf{G}(\mathbf{u}) = A\mathbf{u}$ be the corresponding linear transformation of \mathbb{R}^n . Suppose S is a measurable region in \mathbb{R}^n and f is an integrable function on S . Then $G^{-1}(S) = \{A^{-1}\mathbf{x} : \mathbf{x} \in S\}$ is measurable and $f \circ \mathbf{G}$ is integrable on $\mathbf{G}^{-1}(S)$, and

$$\int \dots \int_S f(\mathbf{x}) d^n \mathbf{x} = |\det A| \int \dots \int_{\mathbf{G}^{-1}(S)} f(A\mathbf{u}) d^n \mathbf{u}$$

Theorem - Change of Variable for general functions Given open sets U and V in \mathbb{R}^n , let $\mathbf{G} : U \rightarrow V$ be a one-to-one transformation of class C^1 whose derivative $D\mathbf{G}(\mathbf{u})$ is invertible for all $\mathbf{u} \in U$. Suppose that $T \subset U$ and $S \subset V$ are measurable sets such that $\mathbf{G}(T) = S$. If f is an integrable function on S , then $f \circ \mathbf{G}$ is integrable on T , and

$$\int \dots \int_S f(\mathbf{x}) d^n \mathbf{x} = \int \dots \int_T f(\mathbf{G}(\mathbf{u})) |\det D\mathbf{G}(\mathbf{u})| d^n \mathbf{u}$$

Some important determinants

1. polar coordinates: factor = r
2. cylindrical coordinates: factor = $|\det(Dg)| = r$
3. spherical coordinates: factor = $r^2 \sin \varphi$

4.5 Functions Defined by Integrals

Question

$$F(\mathbf{x}) = \int \dots \int_S f(\mathbf{x}, \mathbf{y}) d^n \mathbf{y}$$

What condition on f guarantee that F behaves well?

Theorem 1 - Continuity of F Suppose S and T are compact subsets of \mathbb{R}^n and \mathbb{R}^m , respectively, and S is measurable. If $f(\mathbf{x}, \mathbf{y})$ is continuous on the set $T \times S = \{(\mathbf{x}, \mathbf{y}) : \mathbf{x} \in T, \mathbf{y} \in S\}$, then the function F defined by

$$F(\mathbf{x}) = \int \dots \int_S f(\mathbf{x}, \mathbf{y}) d^n \mathbf{y}$$

is continuous on T .

Theorem 2 - Differentiability of F Suppose $S \subset \mathbb{R}^n$ is compact and measurable, and $T \subset \mathbb{R}^m$ is open. If f is a continuous function on $T \times S$ that is of class C^1 as a function of $\mathbf{x} \in T$ for each $\mathbf{y} \in S$, then the function F defined by

$$F(\mathbf{x}) = \int \dots \int_S f(\mathbf{x}, \mathbf{y}) d^n \mathbf{y}$$

is of class C^1 on T , and

$$\frac{\partial F}{\partial x_j}(\mathbf{x}) = \int \dots \int_S \frac{\partial f}{\partial x_j}(\mathbf{x}, \mathbf{y}) d^n \mathbf{y} (\mathbf{x} \in T)$$

Remark Situation often occur in which the variable \mathbf{x} occurs in the limits of integration as well as the integrand. For simplicity we consider the case where x and y are scalar variables:

$$F(x) = \int_a^{\varphi(x)} f(x, y) dy (*)$$

We suppose that f is continuous in x and y and of class C^1 in x for each y , and that φ is of class C^1 . If f does not depend on x , the derivative of F can be computed by the fundamental theorem of calculus together with the chain rule:

$$\frac{d}{dx} \int_a^{\varphi(x)} f(y) dy = f(\varphi(x)) \varphi'(x)$$

For the more general case (*), we can differentiate F by combining this result with Theorem 2: Differentiate with respect to each x in (*) while treating the others as constants, and add the results

$$F'(x) = f(\varphi(x)) \varphi'(x) + \int_a^{\varphi(x)} \frac{\partial f}{\partial x}(x, y) dy$$

4.6 Improper Multiple Integrals

There are many situations where one needs to integrate functions over infinite intervals (e.g. half-space or the whole space) or functions that are unbounded near some point in the region of integration.

4.6.1 Bounded Functions on Unbounded Domains

Suppose, for example, that f is a continuous function on \mathbb{R}^2 and we wish to define $\iint_{\mathbb{R}^2} f dA$. The obvious idea is to set

$$\iint_{\mathbb{R}^2} f dA = \lim_{r \rightarrow \infty} \iint_{S_r} f dA$$

where the S_r 's are a family of measurable sets that fill out \mathbb{R}^2 as $r \rightarrow \infty$. For example, we could take S_r to be

1. the disc of radius r about the origin
2. the square of side length r centered at the origin
3. the rectangle of side lengths r and r^2 centered at the origin
4. the disc of radius r centered at $(15, -37)$
5. ...

No rationale for choosing one over another and no guarantee that different families S_r will yield the same limit.

Definition 1 We will say the **improper integral** $\int \dots \int_{\mathbb{R}^n} f(\mathbf{x}) d^n \mathbf{x}$ is **absolutely convergent** (or sometimes just "the improper integral exists") if there exists $L \in \mathbb{R}$ s.t.

$$\forall \varepsilon > 0, \exists R > 0 \text{ such that } \forall S \subset \mathbb{R}^n$$

if $B(R, \mathbf{0}) \subset S$, then $|\int \dots \int_S f(\mathbf{x}) d^n \mathbf{x} - L| < \varepsilon$

Theorem 2 Assume that $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is continuous, and that

$$\lim_{R \rightarrow \infty} \int \dots \int_{B(R)} |f(\mathbf{x})| d^n \mathbf{x} =: M \in [0, \infty) \text{ exists.}$$

Then the improper integral $\int \dots \int_{\mathbb{R}^n} f(\mathbf{x}) d^n \mathbf{x}$ is absolutely convergent.

Corollary 1 Suppose $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is bounded and integrable on any bounded set and satisfies $|f(\mathbf{x})| \leq C \cdot \frac{1}{\|\mathbf{x}\|^p}$ whenever $\|\mathbf{x}\| > R$, for some constants $C, R > 0$.

If $p > n$ then $\int \dots \int_{\mathbb{R}^n} f d^n \mathbf{x}$ exists.

proof: (n=2) Suppose there exist a $p > 2$ such that the hypothesis of the theorem is satisfied. Consider $B(\mathbf{0}, R)$.

Then

$$\int \dots \int_{\mathbb{R}^n} f d^n \mathbf{x} = \int \dots \int_{B(\mathbf{0}, R)} f d^n \mathbf{x} + \int \dots \int_{\mathbb{R}^n \setminus B(\mathbf{0}, R)} f d^n \mathbf{x}$$

(if it exists)

It's sufficient to show both (1) and (2) exist for all $R > 0$.

By the hypothesis of the theorem (that f is integrable on any bounded set), (1) exists.

Consider (2)

Convert to polar coordinates:

$$\begin{aligned}
 \int \dots \int_{\mathbb{R}^2 \setminus B(\mathbf{0}, R)} f d^n \mathbf{x} &= \int_0^{2\pi} \int_R^\infty f r dr d\theta \\
 &\leq \int_0^{2\pi} \int_R^\infty |f| r dr d\theta \\
 &= 2\pi \int_R^\infty |f| r dr \\
 &\leq 2\pi \int_R^\infty C \frac{1}{\|\mathbf{x}\|^p} r dr \\
 &= 2\pi \int_R^\infty C \frac{1}{r^p} r dr & (\|\mathbf{x}\| = r) \\
 &= 2\pi C \int_R^\infty r^{1-p} dr
 \end{aligned}$$

$$\lim_{d \rightarrow \infty} 2\pi C (d^{1-p} - R^{1-p})$$

exists iff

$$p - 1 > 1 \iff p > 2$$

■

4.6.2 Unbounded Functions on Bounded Domains

Now let S be a measurable subset of \mathbb{R}^n , and for a point $\mathbf{a} \in S^{int}$, and consider a continuous but unbounded function $f : S \setminus \{\mathbf{a}\} \rightarrow \mathbb{R}$.

Example

$$f(x) = |\mathbf{x} - \mathbf{a}|^{-p}$$

for some $p > 0$.

Definition 2 For continuous $f : S \setminus \{\mathbf{a}\} \rightarrow \mathbb{R}$, we say the **improper integral** $\int \dots \int_{S \setminus \{\mathbf{a}\}} f(\mathbf{x}) d^n \mathbf{x}$ is **absolutely convergent** (or sometimes just "the improper integral exists") if there exists $L \in \mathbb{R}$ s.t.

$$\forall \varepsilon > 0, \exists r > 0 \text{ such that } \forall U \subset S \text{ with } \mathbf{a} \in U^{int}$$

if $U \subset B(r, \mathbf{a})$, then $|\int \dots \int_{S \setminus U} f(\mathbf{x}) d^n \mathbf{x} - L| < \varepsilon$

Theorem 3 Assume that $f : S \setminus \{\mathbf{a}\} \rightarrow \mathbb{R}$ is continuous, and that

$$\lim_{r \rightarrow 0} \int \dots \int_{S \setminus B(r, \mathbf{a})} |f(\mathbf{x})| d^n \mathbf{x} \text{ exists (and is finite)}$$

Then the improper integral $\int \dots \int_S f(\mathbf{x}) d^n \mathbf{x}$ is absolutely convergent.

Corollary 2 Assume that S is a bounded measurable subset of \mathbb{R}^n that contains the origin, and that $f : S \setminus \{\mathbf{0}\}$ is continuous. If

$$\exists C > 0 \text{ and } p < n \text{ such that } |f(\mathbf{x})| \leq C|\mathbf{x}|^{-p}$$

for all $\mathbf{x} \in S \setminus \{\mathbf{0}\}$, then

the improper integral $\int \dots \int_S f(\mathbf{x}) d^n \mathbf{x}$ is absolutely convergent.

Proposition For $p > 0$, define f_p on $\mathbb{R}^n \setminus \{\mathbf{0}\}$ by $f_p(\mathbf{x}) = |\mathbf{x}|^{-p}$. The integral of f_p over a ball $\{\mathbf{x} : |\mathbf{x}| < a\}$ is finite if and only if $p < n$; the integral of f_p over the complement of a ball, $\{\mathbf{x} : |\mathbf{x}| > a\}$, is finite if and only if $p > n$.

Proposition

$$\int_{-\infty}^{\infty} e^{-x^2} dx = \sqrt{\pi}$$

5 Vector Calculus

Let \mathbf{F} be an \mathbb{R}^n -valued function defined on some subset of \mathbb{R}^n . In this chapter, we think of such an \mathbf{F} as a function that assigns to each point \mathbf{x} in its domain a vector $\mathbf{F}(\mathbf{x})$, represented pictorially as an arrow based at \mathbf{x} , and we therefore call it a **vector field**.

5.1 Arc Length and Line Integrals

line integrals: integrals over curves

Given a smooth curve C , how to compute its length?

Based on the idea of cutting up the curve into many tiny pieces, forming appropriate Riemann sums, and passing to the limit

5.1.1 Differentials on Curve; Arc Length

Suppose C is a smooth curve in \mathbb{R}^n . We consider two nearby points \mathbf{x} and $\mathbf{x} + d\mathbf{x}$ on the curve; here

$$d\mathbf{x} = (dx_1, \dots, dx_n)$$

is the vector difference between the two points, and we imagine it as being infinitely small. We may, however, be more interested in the distance between the two points, traditionally denoted by ds , which is

$$ds = |d\mathbf{x}| = \sqrt{dx_1^2 + \dots + dx_n^2} (*)$$

Arc length of C = result of “adding up all the ds ’s” = $\int_C ds$

To give these differentials a precise meaning that can be used for calculations, the best procedure is to parametrize the curve. Thus, we assume that C is given by parametric equations $\mathbf{x} = \mathbf{g}(t)$, $a \leq t \leq b$, where \mathbf{g} is of class C^1 and $\mathbf{g}'(t) \neq \mathbf{0}$. Then the neighboring points \mathbf{x} and $\mathbf{x} + d\mathbf{x}$ are given by $\mathbf{g}(t)$ and $\mathbf{g}(t + dt)$, so

$$d\mathbf{x} = \mathbf{g}(t + dt) - \mathbf{g}(t) = \mathbf{g}'(t)dt = \left(\frac{dx_1}{dt}, \dots, \frac{dx_n}{dt}\right)dt$$

Moreover,

$$|d\mathbf{x}| = |\mathbf{g}'(t)|dt = \sqrt{\left(\frac{dx_1}{dt}\right)^2 + \dots + \left(\frac{dx_n}{dt}\right)^2}dt$$

which is just what one gets by formally multiplying and dividing the expression on the right of (*) by dt

Integration of the vector increments $d\mathbf{x}$ just gives the total vector increment, that is, the vector difference between the initial and final points on the curve:

$$\int_C d\mathbf{x} = \int_a^b \mathbf{g}'(t)dt = \mathbf{g}(b) - \mathbf{g}(a)$$

Definition of arc length for a smooth curve ds is the *arc length* of the bit of curve between $d\mathbf{x}$ and $\mathbf{x} + d\mathbf{x}$. Adding these up gives the total arc length of the curve

$$\text{Arc length} = \int_C ds = \int_a^b |\mathbf{g}'(t)| dt$$

Notes The arc length and the vector difference between the two endpoints of the curve should not depend on the particular parametrization we use. The issue here is that a parametrization $\mathbf{x} = \mathbf{g}(t)$ determines an **orientation** for the curve C , that is, a determination of which direction along the curve is “forward” (the direction in which the point $\mathbf{g}(t)$ moves as t increases) and which direction is “backward”.

5.1.2 Line Integrals of Scalar Functions

Definition of Piecewise Smoothness of a Function The function $\mathbf{g} : [a, b] \rightarrow \mathbb{R}^n$ is called **piecewise smooth** if

1. It is continuous
2. Its derivative exists and is continuous except perhaps at finitely many points t_j , at which the one-sided limits $\lim_{t \rightarrow t_j \pm} \mathbf{g}'(t)$ exist.

Line Integrals of Scalar Functions If f is a continuous function whose domain includes a smooth (or piecewise smooth) curve C in \mathbb{R}^n , we can integrate f over the curve, taking the differential in the integral to be the element of arc length ds . Thus, if C is parametrized by $\mathbf{x} = \mathbf{g}(t)$, $a \leq t \leq b$, we define

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

This is independent of the parametrization and the orientation.

Definition of Average of f over C

$$\text{Average of } f \text{ over } C = \frac{\int_C f ds}{\int_C ds}$$

integral of f over C = (arclength of C) \times (average of f over C)

5.1.3 Rectifiable Curves

Let C be a curve in \mathbb{R}^n parametrized by injection $\mathbf{g} : [a, b] \rightarrow \mathbb{R}^n$ such that $\mathbf{g}'(t) \neq 0$. Let $P = \{t_0, \dots, t_J\}$ be any partition of $[a, b]$. The length of C may be approximated by the sum of the lengths of the line segments connecting $\mathbf{g}(t_{j-1})$ to $\mathbf{g}(t_j)$ for $j = 1, \dots, J$:

$$L_P(C) := \sum_{j=1}^J |\mathbf{g}(t_j) - \mathbf{g}(t_{j-1})|$$

We say that C is rectifiable if

$$\{L_P(C) : P \text{ is a partition of } [a, b]\} \text{ is bounded}$$

and in this case, we define

$$\text{arclength of } C := L(C) := \sup\{L_P(C) : P \text{ is a partition of } [a, b]\}$$

Theorem If $\mathbf{g} : [a, b] \rightarrow \mathbb{R}^n$ is C^1 , then

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

5.1.4 The Line Integral of a Vector Field

Vector-Valued Line Integrals of Vector Fields We can define the integral of an \mathbb{R}^m -valued function over a curve in \mathbb{R}^n , simply by integrating each component separately; that is, if $\mathbf{F} = (F_1, \dots, F_m)$, then $\int_C \mathbf{F} ds = (\int_C F_1 ds, \dots, \int_C F_m ds)$

Scalar-Valued Line Integrals for Vector Fields If C is a smooth (or piecewise smooth) curve in \mathbb{R}^n and \mathbf{F} is a continuous vector field defined on some neighborhood of C in \mathbb{R}^n , the **line integral** of \mathbf{F} over C is

$$\int_C \mathbf{F} \cdot d\mathbf{x} = \int_C (F_1 dx_1 + F_2 dx_2 + \dots + F_n dx_n)$$

That is, if C is described parametrically by $\mathbf{x} = \mathbf{g}(t)$, $a \leq t \leq b$, then

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

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

5.1.5 Tangential Component

Definition of unit tangent vector Since we have assumed that $\mathbf{g}'(t) \neq 0$, it makes sense to define $\mathbf{t}(\mathbf{g}(t)) := \frac{\mathbf{g}'(t)}{|\mathbf{g}'(t)|}$, which is the unit tangent vector to the curve C at $\mathbf{g}(t)$, pointing to the direction given by the orientation.

Definition of tangential component

$$F_{tang}(\mathbf{x}) := \mathbf{F}(\mathbf{x}) \cdot \mathbf{t}(\mathbf{x})$$

Interpretation of line integral of a vector field using \mathbf{F}_{tang}

$$\int_C \mathbf{F} \cdot d\mathbf{x} = \int_a^b \mathbf{F}(\mathbf{g}(t)) \cdot \left(\frac{\mathbf{g}'(t)}{|\mathbf{g}'(t)|} \right) |\mathbf{g}'(t)| dt = \int_C F_{tang} ds$$

We can interpret $\int_C \mathbf{F} \cdot d\mathbf{x}$ as the scalar integral of the tangential component of \mathbf{F} over the curve C .

5.1.6 Fundamental Theorem of Line Integrals

If C is a curve that starts at $\mathbf{p} \in \mathbb{R}^n$ and ends at $\mathbf{q} \in \mathbb{R}^n$, then

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

where $\mathbf{g}(a) = \mathbf{p}$ and $\mathbf{g}(b) = \mathbf{q}$ and the line integral around any closed path is 0.

5.2 Green's Theorem

“The integral of something over the boundary of a region equals the integral of something else over the region itself.”

Let $R \subset \mathbb{R}^2$ be a region such that $R = \overline{R^{int}}$. Assume that R is bounded. We say that ∂R is piecewise smooth if:

$$\partial R = \bigcup_{i=1}^n C_i \text{ with } C_i \text{ being smooth, } \forall i$$

Simple-Closed curve. A Jordan Simple-Closed curve is a curve in \mathbb{R}^2 that is closed and non-self-overlapping. Such curve divides the region of \mathbb{R}^2 into two portions: those that are inside this curve, and those that are outside. More precisely, a simple closed curve is one that can be parametrized by a continuous map $\mathbf{x} = \mathbf{g}(t)$, $a \leq t \leq b$, such that $\mathbf{g}(a) = \mathbf{g}(b)$ but $\mathbf{g}(s) \neq \mathbf{g}(t)$ unless $\{s, t\} = \{a, b\}$

Positive/ Natural Orientation The **positive orientation** on ∂S is the orientation on each of the closed curves that make up the boundary such that the region S is on the *left* with respect to the positive direction on the curve

Regular Region A compact set in \mathbb{R}^n that is the closure of its interior.

Statement of the Green's Theorem - Textbook Version Suppose S is a regular region in \mathbb{R}^2 with piecewise smooth boundary ∂S . Suppose also that \mathbf{F} is a vector field of class C^1 on \bar{S} . Then

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

In the more common notation, if we set $\mathbf{F} = (P, Q)$ and $\mathbf{x} = (x, y)$,

$$\int_{\partial S} P dx + Q dy = \iint_S \left(\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) dA$$

The sum of line integrals over all curves that make up ∂S

Statement of the Green's Theorem - E.Knight's Version Let C be a positively oriented, piece-wise smooth, simple closed curve in a plane, and let D be the region bounded by C . If $L(\cdot)$ and $M(\cdot)$ are functions of (x, y) defined on an open region containing D and have continuous partial derivatives there, then

$$\oint_C (Ldx + Mdy) = \iint_D \left(\frac{\partial M}{\partial x} - \frac{\partial L}{\partial y} \right) dxdy$$

where the path of integration along C is anticlockwise.

Notes

1. Green's Theorem implies that

$$\int_{\partial S} x dy = - \int_{\partial S} y dx = \int_{\partial S} \frac{1}{2} (x dy - y dx) = \iint_S 1 dA = \text{area}(S)$$

Reformulation of Green's Theorem Let $S \subset \mathbb{R}^2$ be a regular domain with piecewise smooth boundary. If \mathbf{F} is a C^1 vector field defined on an open set that contained S , then

$$\iint_S \left(\frac{\partial F_1}{\partial x} + \frac{\partial F_2}{\partial y} \right) dA = \int_{\partial S} \mathbf{F} \cdot \mathbf{n} ds$$

where $\mathbf{n}(t) = (t_2, -t_1) \perp \partial S$.

5.3 Surface Integrals

5.3.1 Surface Area and Surface Integrals

On a curve the orientation is a matter of deciding which direction along a curve is “positive”; on a surface it is a matter of deciding which side of the surface is the “positive” side.

Not every surface can be oriented. Counterexample: Mobius band

However, if a surface forms part of the boundary of a regular region in \mathbb{R}^3 , it is always orientable, and the positive normal vector is defined to be the one pointing out of the region.

Element of Area

$$dA = \left| \frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v} \right| du dv$$

Area for a parametrized surface If R is a measurable subset of W in the uv -plane and $\mathbf{G}(R)$ is the corresponding region in the surface S ,

$$\text{Area of } \mathbf{G}(R) = \iint_R \left| \frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v} \right| du dv$$

Surface Integrals of scalar Functions If S admits a parametrization $\mathbf{x} = \mathbf{G}(u, v)$ with $(u, v) \in W$, where W is tacitly assumed to be measurable,

$$\iint_S f dA = \iint_W f(\mathbf{G}(u, v)) \left| \frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v} \right| du dv$$

If S is the graph of a function $z = \varphi(x, y)$, $(x, y) \in W$, the result is

$$\iint_S f dA = \iint_W f(x, y, \varphi(x, y)) \sqrt{1 + (\partial_x \varphi)^2 + (\partial_y \varphi)^2} dx dy$$

Surface Integrals of Vector Fields It is natural to regard the vector $(\partial_u \mathbf{G} \times \partial_v \mathbf{G}) du dv$ itself as a “vector element of area” for S : its magnitude gives the area of a small bit of S , and its direction, namely the normal direction to S , specifies how that bit is oriented in space. That is, we have

$$\left(\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v}\right) du dv = \mathbf{n} dA$$

where \mathbf{n} is a unit normal vector to the surface S .

dA is independent of the parametrization, and clearly so is \mathbf{n} up to a factor of ± 1 (using a different parametrization might result in replacing \mathbf{n} by $-\mathbf{n}$). Suppose S is a surface with a specified orientation, and \mathbf{F} is a continuous vector field defined on a neighborhood of S . The **surface integral** of \mathbf{F} over S is defined to be

$$\iint_S \mathbf{F} \cdot \mathbf{n} dA$$

Thus, if S is parametrized by $\mathbf{x} = \mathbf{G}(u, v)$, $(u, v) \in W$, we have

$$\iint_S \mathbf{F} \cdot \mathbf{n} dA = \iint_W \mathbf{F}(\mathbf{G}(u, v)) \cdot \left(\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v}\right) du dv$$

5.3.2 Normal Component

Definition of Unit Normal Vector Since $\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v}$ is orthogonal to S ,

$$\frac{\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v}}{\left|\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v}\right|} \text{ and } -\frac{\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v}}{\left|\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v}\right|}$$

are unit normal vectors to S .

Therefore, we write $\mathbf{n}(\mathbf{G}(\mathbf{u})) := \frac{\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v}}{\left|\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v}\right|}$. With this notation,

$$\begin{aligned} \iint_S \mathbf{F} \cdot \mathbf{n} dA &= \iint_R \mathbf{F}(\mathbf{G}(\mathbf{u})) \cdot \left(\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v}\right) du dv \\ &= \iint_R \mathbf{F}(\mathbf{G}(\mathbf{u})) \cdot \mathbf{n}(\mathbf{G}(\mathbf{u})) \left|\frac{\partial \mathbf{G}}{\partial u} \times \frac{\partial \mathbf{G}}{\partial v}\right| du dv \\ &= \text{surface integral of the scalar function } (\mathbf{F} \cdot \mathbf{n}) \text{ over } S \end{aligned}$$

5.4 Vector Derivatives

$$\nabla = (\partial_1, \dots, \partial_n)$$

$$\text{grad } f = \nabla f = (\partial_1 f, \dots, \partial_n f)$$

$$\operatorname{div} \mathbf{F} = \nabla \cdot \mathbf{F} = \partial_1 F_1 + \dots + \partial_n F_n$$

Suppose $n = 3$. If \mathbf{F} is a C^1 vector field on an open subset of \mathbb{R}^3 , the **curl** of \mathbf{F} is the vector field defined by

$$\operatorname{curl} \mathbf{F} = \nabla \times \mathbf{F} = (\partial_2 F_3 - \partial_3 F_2)\mathbf{i} + (\partial_3 F_1 - \partial_1 F_3)\mathbf{j} + (\partial_1 F_2 - \partial_2 F_1)\mathbf{k}$$

Product Rules

$$\operatorname{grad}(fg) = f \operatorname{grad} g + g \operatorname{grad} f \quad (3)$$

$$\operatorname{grad}(\mathbf{F} \cdot \mathbf{G}) = (\mathbf{F} \cdot \nabla)\mathbf{G} + (\operatorname{curl} \mathbf{G}) \times \mathbf{F} + (\mathbf{G} \cdot \nabla)\mathbf{F} + \mathbf{G} \times (\operatorname{curl} \mathbf{F}) \quad (4)$$

$$\operatorname{curl}(f\mathbf{G}) = f \operatorname{curl} \mathbf{G} + (\operatorname{grad} f) \times \mathbf{G} \quad (5)$$

$$\operatorname{curl}(\mathbf{F} \times \mathbf{G}) = (\mathbf{G} \cdot \nabla)\mathbf{F} + (\operatorname{div} \mathbf{G})\mathbf{F} - (\mathbf{F} \cdot \nabla)\mathbf{G} - (\operatorname{div} \mathbf{F})\mathbf{G} \quad (6)$$

$$\operatorname{div}(f\mathbf{G}) = f \operatorname{div} \mathbf{G} + (\operatorname{grad} f) \cdot \mathbf{G} \quad (7)$$

$$\operatorname{div}(\mathbf{F} \times \mathbf{G}) = \mathbf{G} \cdot (\operatorname{curl} \mathbf{F}) - \mathbf{F} \cdot (\operatorname{curl} \mathbf{G}) \quad (8)$$

Combined Operations

$$\operatorname{curl}(\operatorname{grad} f) = (\partial_2 \partial_3 f - \partial_3 \partial_2 f)\mathbf{i} + (\partial_3 \partial_1 f - \partial_1 \partial_3 f)\mathbf{j} + (\partial_1 \partial_2 f - \partial_2 \partial_1 f)\mathbf{k} = \mathbf{0} \quad (9)$$

$$\operatorname{div}(\operatorname{curl} \mathbf{F}) = \partial_1(\partial_2 F_3 - \partial_3 F_2) + \partial_2(\partial_3 F_1 - \partial_1 F_3) + \partial_3(\partial_1 F_2 - \partial_2 F_1) = 0 \quad (10)$$

$$(11)$$

Laplacian

$$\nabla^2 f = \Delta f = \operatorname{div}(\operatorname{grad} f) = \partial_1^2 f + \dots + \partial_n^2 f$$

Other two combinations together yield the Laplacian for vector fields in \mathbb{R}^3 :

$$\operatorname{grad}(\operatorname{div} \mathbf{F}) - \operatorname{curl}(\operatorname{curl} \mathbf{F}) = \nabla^2 \mathbf{F} = (\nabla^2 F_1)\mathbf{i} + (\nabla^2 F_2)\mathbf{j} + (\nabla^2 F_3)\mathbf{k}$$

5.5 The Divergence Theorem

The 3-dimensional analogue of Green's theorem; Relates surface integrals over the boundary of a regular region in \mathbb{R}^3 to volume integrals over the region itself; valid for regions with piece-wise smooth boundaries.

The Divergence Theorem Suppose R is a regular region in \mathbb{R}^3 with piecewise smooth boundary ∂R , oriented so that the positive normal points out of R . Suppose also that \mathbf{F} is a vector field of class C^1 on R . Then

$$\iint_{\partial R} \mathbf{F} \cdot \mathbf{n} \, dA = \iiint_R \operatorname{div} \mathbf{F} \, dV$$

proof:

Begin by considering a class of simple regions.

We say that R is xy -simple if it has the form

$$R = \{(x, y, z) : (x, y) \in W, \varphi_1(x, y) \leq z \leq \varphi_2(x, y)\}$$

where W is a regular region in the xy -plane and φ_1 and φ_2 are piecewise smooth functions on W . We define the notions of yz -simple and xz -simple similarly, and we say that R is simple if it is xy -simple, yz -simple and xz -simple. Next, show $\iint_{\partial R} F_3 \mathbf{k} \cdot \mathbf{n} \, dA = \iiint_R \partial_3 F_3 \, dV$

The proof for $F_1 i$ and $F_2 j$ is the same.

It now follows that the divergence theorem is valid for regions that can be cut up into finitely many simple regions R_1, \dots, R_k

5.5.1 Geometric Interpretation of div

Suppose \mathbf{F} is a C^1 vector field on some open set containing the point \mathbf{a} . For $r > 0$, let B_r be the ball of radius r about \mathbf{a} . If r is very small, the average value of $\operatorname{div} \mathbf{F}(\mathbf{x})$ on the ball B_r is very nearly equal to $\operatorname{div} \mathbf{F}(\mathbf{a})$. Therefore, by the divergence theorem,

$$\operatorname{div} \mathbf{F}(\mathbf{a}) \approx \frac{3}{4\pi r^3} \iiint_{B_r} \operatorname{div} \mathbf{F} \, dV = \frac{3}{4\pi r^3} \iint_{\partial B_r} \mathbf{F} \cdot \mathbf{n} \, dA$$

This approximation becomes better and better as $r \rightarrow 0$, and hence

$$\operatorname{div} \mathbf{F}(\mathbf{a}) = \lim_{r \rightarrow 0} \frac{3}{4\pi r^3} \iint_{|\mathbf{x}-\mathbf{a}|=r} \mathbf{F} \cdot \mathbf{n} \, dA$$

The flux of \mathbf{F} across ∂B_r from the inside (B_r) to the outside (the complement of B_r)

Corollary (Green's Formulas) Suppose R is a regular region in \mathbb{R}^3 with piecewise smooth boundary, and f and g are functions of class C^2 on \bar{R} . Then

$$\iint_{\partial R} f \nabla g \cdot \mathbf{n} \, dA = \iiint_R (\nabla f \cdot \nabla g + f \nabla^2 g) \, dV$$

$$\iint_{\partial R} (f\nabla g - g\nabla f) \cdot \mathbf{n} dA = \iiint_R (f\nabla^2 g - g\nabla^2 f) dV$$

The directional derivative $\nabla f \cdot \mathbf{n}$ that occurs in these formulas is called the **outward normal derivative** of f on ∂R and is often denoted by $\frac{\partial f}{\partial n}$.

5.6 Stokes's Theorem

“the generalization of Green's theorem in which the plane is replaced by a curved surface”

Statement of Stokes's Theorem Suppose S_0 is a smooth surface in \mathbb{R}^3 , and S is a region in S_0 bounded by a piecewise curve ∂S . Assume S has an orientation given by \mathbf{n} and ∂S is positively oriented with respect to this orientation.

Let \mathbf{F} be a C^1 vector field defined on some neighborhood of S in \mathbb{R}^3 . Then

$$\int_{\partial S} \mathbf{F} \cdot d\mathbf{x} = \iint_S (\text{curl } \mathbf{F}) \cdot \mathbf{n} dA$$

Special case If S is a region in the xy -plane, then $\mathbf{n} = \mathbf{k} = (0, 0, 1)$; moreover, $\mathbf{F} \cdot d\mathbf{x}$ involves only the x - and y -components of \mathbf{F} , i.e., F_1 and F_2 , and $(\text{curl } \mathbf{F}) \cdot \mathbf{n} = \partial_1 F_2 - \partial_2 F_1$. Hence Stokes's theorem reduces to Green's theorem in this case.

Note A closed curve in \mathbb{R}^3 is the boundary of infinitely many surfaces in \mathbb{R}^3 . Stokes's theorem says that if C is a closed curve in \mathbb{R}^3 and S is **any** oriented surface bounded by C , then

$$\int_{\partial S} \mathbf{F} \cdot d\mathbf{x} = \iint_S (\text{curl } \mathbf{F}) \cdot \mathbf{n} dA$$

for any C^1 vector field \mathbf{F} , provided that the orientations on C and S are compatible.

Example Use Stokes's Theorem twice to let the complicated integral vanish

Definition of a closed surface A piecewise smooth surface S in \mathbb{R}^3 is closed if there exist subsets S_1, S_2 such that $\partial S_1 = \partial S_2 = S_1 \cap S_2$, and $\partial S_1, \partial S_2$ have opposite orientations.

Remark One can check that if $R \subset \mathbb{R}^3$ is a regular region with piecewise smooth boundary, then $S := \partial R$ is a closed surface.

Corollary If S is a closed surface (i.e., a surface with no boundary) in \mathbb{R}^3 with unit outward normal \mathbf{n} , and \mathbf{F} is a C^1 vector field on S , then

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

proof:

If \mathbf{F} is differentiable on the region R inside S , this follows from the divergence theorem since $\operatorname{div}(\operatorname{curl} \mathbf{F}) = 0$ for any \mathbf{F} . More generally, draw a simple closed curve C in S that divides S into two regular regions S_1 and S_2 , and we have

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

On the other hand, if we give C the orientation compatible with S_1 , Stokes's theorem gives

$$\iint_S (\operatorname{curl} \mathbf{F}) \cdot \mathbf{n} dA = \int_C \mathbf{F} \cdot d\mathbf{x} = - \iint_{S_2} (\operatorname{curl} \mathbf{F}) \cdot \mathbf{n} dA$$

Hence the terms on the right cancel.

5.6.1 Moving the Surface

It follows immediately from Stokes' Theorem that if S and S' are two (oriented) surfaces such that $\partial S = \partial S'$ (with the same orientation), then

$$\iint_S \operatorname{curl} \mathbf{F} \cdot \mathbf{n} dA = \int_{\partial S} \mathbf{F} \cdot d\mathbf{x} = \int_{\partial S'} \mathbf{F} \cdot d\mathbf{x} = \iint_{S'} \operatorname{curl} \mathbf{F} \cdot \mathbf{n} dA$$

This means that to evaluate an integral

$$\int_S \operatorname{curl} \mathbf{F} \cdot \mathbf{n} dA$$

we can *move the surface* to a (suitable and simpler) new surface S' .

5.6.2 Geometric Interpretation of Curl

Suppose \mathbf{F} is a C^1 vector field on some open set containing the point \mathbf{a} .

Fix a unit vector \mathbf{u} .

Let D_ϵ be the disc of radius ϵ centered at \mathbf{a} in the plane perpendicular to \mathbf{u} , oriented so that \mathbf{u} is the positive normal for D_ϵ .

As $\epsilon \rightarrow 0$, the average value of $(\text{curl} \mathbf{F}) \cdot \mathbf{u}$ over D_ϵ approaches its value at \mathbf{a} :

$$(\text{curl} \mathbf{F}(\mathbf{a})) \cdot \mathbf{u} = \lim_{\epsilon \rightarrow 0} \frac{1}{\pi \epsilon^2} \iint_{D_\epsilon} (\text{curl} \mathbf{F}) \cdot \mathbf{u} \, dA$$

Since \mathbf{u} is the normal to D_ϵ , Stokes's theorem gives

$$(\text{curl} \mathbf{F}(\mathbf{a})) \cdot \mathbf{u} = \lim_{\epsilon \rightarrow 0} \frac{1}{\pi \epsilon^2} \int_{C_\epsilon} \mathbf{F} \cdot d\mathbf{x}$$

where C_ϵ is the circle of radius ϵ about \mathbf{a} in the plane perpendicular to \mathbf{u} , traversed counterclockwise as viewed from the side on which \mathbf{u} lies.

Think of \mathbf{F} as a force field, $\int_{C_\epsilon} \mathbf{F} \cdot d\mathbf{x}$ is the [work done by \$\mathbf{F}\$ on a particle that moves around \$C_\epsilon\$](#) . Thus $(\text{curl} \mathbf{F}(\mathbf{a})) \cdot \mathbf{u}$ represents the [tendency of the force \$\mathbf{F}\$ to push the particle around \$C_\epsilon\$](#) .

5.7 Vector Fields That Are Gradients or Curls

“Inverse” question of computing $\text{grad } f$ or $\text{curl } \mathbf{F}$:

- does there exist some function f such that $\mathbf{G} = \text{grad } f$? If so, can we find f ?
- does there exist some vector field \mathbf{F} such that $\mathbf{G} = \text{curl } \mathbf{F}$? If so, can we find \mathbf{F} ?

5.7.1 Vector Field that are Gradients

Proposition Suppose \mathbf{G} is a continuous vector field on an open set R in \mathbb{R}^n . The following 3 conditions are equivalent:

1. There exists a function $f : U \rightarrow \mathbb{R}$ of class C^1 such that $\mathbf{G} = \nabla f$
2. If C_1 and C_2 are any two oriented curves in R with the same initial point and the same final point, then $\int_{C_1} \mathbf{G} \cdot d\mathbf{x} = \int_{C_2} \mathbf{G} \cdot d\mathbf{x}$
3. If C is any closed curve in R , $\int_C \mathbf{G} \cdot d\mathbf{x} = 0$

proof: see textbook p258

Conservative Vector Field A vector field \mathbf{G} is called conservative in the region R if it satisfies the above conditions.

Geometric Interpretation \mathbf{G} a force field, the force does no net work on a particle that returns to its starting point.

Proposition A continuous vector field \mathbf{G} in an open set $R \subset \mathbb{R}^n$ is conservative \iff there is a C^1 function f on R such that $\mathbf{G} = \nabla f$.

proof:

\leftarrow : If $\mathbf{G} = \nabla f$ and C is a closed curve parametrized by $\mathbf{x} = \mathbf{g}(t)$, $a \leq t \leq b$, by the chain rule we have

$$\int_C \nabla f \cdot d\mathbf{x} = \int_a^b \nabla f(\mathbf{g}(t)) \cdot \mathbf{g}'(t) dt = \int_a^b \frac{d}{dt} f(\mathbf{g}(t)) dt = f(\mathbf{g}(b)) - f(\mathbf{g}(a)) = 0$$

\rightarrow : If \mathbf{G} is conservative in R . Need to construct a function f such that $\nabla f = \mathbf{G}$. Assume R is (piecewise) connected, pick $\mathbf{a} \in R$. For any $\mathbf{x} \in R$, let C be a curve in R from \mathbf{a} to \mathbf{x} . We shall show $G_i = \partial_j f$ for each j .

For case $j = 1$:

Let $\mathbf{h} = (h, 0, \dots, 0)$. Suppose h is small enough so that the line segment L from \mathbf{x} to $\mathbf{x} + \mathbf{h}$ lies entirely in R . We define $f(x) = \int_C \mathbf{G} \cdot d\mathbf{x}$ where C is a curve from \mathbf{a} to \mathbf{x} .

Make a curve from \mathbf{a} to $\mathbf{x} + \mathbf{h}$ by joining L onto the end of C , so that

$$f(\mathbf{x} + \mathbf{h}) = \int_C \mathbf{G} \cdot d\mathbf{x} + \int_L \mathbf{G} \cdot d\mathbf{x}$$

But then

$$\frac{f(\mathbf{x} + \mathbf{h}) - f(\mathbf{x})}{h} = \frac{1}{h} \int_L \mathbf{G} \cdot d\mathbf{x} = \frac{1}{h} \int_0^h G_1(x_1 + t, x_2, \dots, x_n) dt$$

By letting $h \rightarrow 0$ we obtain $\partial_1 f(\mathbf{x}) = G_1(\mathbf{x})$ ■

Theorem 1

1. If \mathbf{G} is a conservative vector field of class C^1 on an open set $U \subset \mathbb{R}^3$, then $\text{curl } \mathbf{G} = \mathbf{0}$.
2. If U is convex, then the converse is true: if $\mathbf{G} : U \rightarrow \mathbb{R}^3$ is a C^1 vector field and $\text{curl } \mathbf{G} = \mathbf{0}$, then \mathbf{G} is conservative.

3. However, on some non-convex sets, there exist **non-conservative** vector fields \mathbf{G} that satisfy $\text{curl } \mathbf{G} = \mathbf{0}$.

proof:

Similar as previous proof.

By Stokes's Theorem,

$$\int_{\partial S} \mathbf{G} \cdot d\mathbf{x} = \iint_S (\text{curl } \mathbf{G}) \mathbf{n} dA = 0$$

(since $\text{curl } \mathbf{G} = \mathbf{0}$)

$$f(\mathbf{x} + \mathbf{h}) - f(\mathbf{x}) = \int_{L(\mathbf{a}, \mathbf{x})} \mathbf{G} \cdot d\mathbf{x} - \int_{L(\mathbf{a}, \mathbf{x} + \mathbf{h})} \mathbf{G} \cdot d\mathbf{x} = \int_{L(\mathbf{x}, \mathbf{x} + \mathbf{h})} \mathbf{G} \cdot d\mathbf{x}$$

Now the same argument applies.

5.7.2 Vector Field that are Curls

Theorem 2

1. If $\mathbf{G} : U \rightarrow \mathbb{R}^3$ is a vector field of class C^1 and $\mathbf{G} = \text{curl } \mathbf{F}$ for some vector field $\mathbf{F} : U \rightarrow \mathbb{R}^3$ of class C^2 , then $\text{div } \mathbf{G} = 0$
2. Suppose \mathbf{G} is a C^1 vector field in an open set $U \subset \mathbb{R}^3$ such that $\text{div } \mathbf{G} = 0$.
 - a. If U is convex, then there exists a vector field \mathbf{F} such that $\text{curl } \mathbf{F} = \mathbf{G}$.
 - b. However, if U is not convex, it may be the case that no such vector field exists.

Definition If $\text{div } \mathbf{G} = 0$, a vector field \mathbf{F} such that $\text{curl } \mathbf{F} = \mathbf{G}$ is called a vector potential for \mathbf{G} .

6 Fourier Series

Definition Infinite series that use the trigonometric functions $\cos n\theta$ and $\sin n\theta$, or, equivalently, $e^{in\theta}$ and $e^{-in\theta}$, as the basic building blocks.

Piecewise Continuity of Functions A function f defined on an interval $[a, b]$ is piecewise continuous on $[a, b]$ if it is continuous except at finitely many points in $[a, b]$, and at each such point the one-sided limits

$$f(x+) = \lim_{\epsilon \rightarrow 0+} f(x + \epsilon), \quad f(x-) = \lim_{\epsilon \rightarrow 0+} f(x - \epsilon)$$

exist (and are finite)

By making the change of variable $\theta = \frac{2\pi x}{P}$, we can convert any P -periodic function into a 2π -periodic function.

Basic Idea An arbitrary piecewise continuous 2π -periodic function $f(\theta)$ can be expanded as an infinite linear combination of the functions $e^{in\theta}$ ($n = 0, \pm 1, \pm 2, \dots$), of the form

$$f(\theta) = \sum_{-\infty}^{\infty} c_n e^{in\theta}$$

(advantage: exponentials tend to be easier to manipulate than trig functions)

Since $e^{\pm in\theta} = \cos n\theta \pm i \sin n\theta$, then $c_n e^{in\theta} + c_{-n} e^{-in\theta} = (c_n + c_{-n}) \cos n\theta + i(c_n - c_{-n}) \sin n\theta = a_n \cos n\theta + b_n \sin n\theta$

$$f(\theta) = \frac{1}{2}a_0 + \sum_1^{\infty} (a_n \cos n\theta + b_n \sin n\theta)$$

(advantage: $\cos n\theta$ and $\sin n\theta$ are real-valued and are respectively even and odd)

f may be either real-valued or complex-valued

Question Given a 2π -periodic function f , can it be expanded in a series of the form as above? If so, how do we find the coefficients c_n in this series?

Fourier coefficients It can be derived that (see textbook p358)

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(\theta) \cos n\theta \, d\theta$$

$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(\theta) \sin n\theta \, d\theta$$

$$c_n = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(\theta) e^{-in\theta} \, d\theta$$

Fourier Series

$$\sum_{-\infty}^{\infty} c_n e^{in\theta} = \frac{1}{2}a_0 + \sum_1^{\infty} (a_n \cos n\theta + b_n \sin n\theta)$$

f may be either real-valued or complex-valued

E.Knight's Version of Fourier Series, A Reformulation To simplify our calculations, let's reformat the above mentioned form of Fourier Series into the following:

$$f(\theta) = a_0 + \sum_{n \geq 1} b_n \cos n\theta + \sum_{m \geq 1} c_m \sin m\theta$$

where the Fourier coefficients are to be calculated by

$$\begin{aligned} a_0 &= \frac{1}{2\pi} \int_0^{2\pi} f(\theta) d\theta \\ b_n &= \frac{1}{\pi} \int_0^{2\pi} f(\theta) \cos n\theta d\theta \\ c_m &= \frac{1}{\pi} \int_0^{2\pi} f(\theta) \sin m\theta d\theta \end{aligned}$$

notice that we here are integrating over the region $[0, 2\pi]$, but in fact any region of length 2π would do, since we are assuming a 2π -periodicity. We simplify our calculation in this reformulation in the way that a_0 now is just the average value of the original function $f(\theta)$ in some interval of length 2π .

Convergence of Fourier Series Decomposition. We shall study the convergence of such series since all of these would be pointless if we can not write down an converging series at the end of the day. We shall first look at the following question: "What can we say about the Fourier coefficients b_n, c_n as $n \rightarrow \infty$ "? To answer, we look at the following theorem:

$$\text{Theorem: } \sum_{n=1}^{\infty} b_n^2 < \infty \wedge \sum_{n=1}^{\infty} c_n^2 < \infty$$

In paticular, we have $\lim_{n \rightarrow \infty} b_n = \lim_{n \rightarrow \infty} c_n = 0$.

proof: Let $N \in \mathbb{N}$, and define $f_N(x) = \sum_{n=1}^N (b_n \cos(nx) + c_n \sin(nx))$, then

we consider

$$\begin{aligned} \int_0^{2\pi} f^2(x) dx &= \int_0^{2\pi} f_N(x) dx \\ &+ 2 \int_0^{2\pi} f_N(x)(f(x) - f_N(x)) dx + \int_0^{2\pi} (f(x) - f_N(x))^2 dx \end{aligned} \quad (12)$$

using brute force, we will find that $\int_0^{2\pi} f_N(x) dx = \sum_{n=1}^N (b_n^2 \pi + c_n^2 \pi)$, and that $b_n = 0$. We look at our equation (10) above, and see that

$$\int_0^{2\pi} (f(x) - f_N(x))^2 dx \geq 0$$

since we are integrating a non-negative function. So rearranging what we have yields us

$$\sum_{n=1}^N (b_n^2 \pi + c_n^2 \pi) = \pi \sum_{n=1}^N (b_n^2 + c_n^2) \leq \frac{1}{\pi} \int_0^{2\pi} f^2(x) dx$$

but this inequality holds for any choice of n , and we can break the series into two as we please, so indeed we have found an upperbound and both of the two series are convergent. ■

Piece-wise smooth functions have exact Fourier Decompositions

Suppose that $f(x)$ is $2 - \pi$ periodic piece-wise smooth, then $\forall x \in [0, 2\pi)$, we have

$$\frac{f(x+) + f(x-)}{2} = a_0 + \sum_{n=1}^N (b_n \cos(nx) + c_n \sin(nx))$$