

UofT-MAT257-2014 Note

hysw, etc(will add later)...

January 18, 2015

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1 KW

Euclidean n-space \mathbb{R}^n , norm, inner product, usual basis, distance, closed rectangle, open rectangle, open, closed, interior, exterior, boundary, open cover, compact(etc...), Heine-Borel Theorem, function, composition, component function, projection function π^i , continuous function, continuous & compact, oscillation, Jacobian matrix, chain rule, partial derivative, continuously differentiable, inverse functions, implicit functions,

2 TODO

Munkers 11.3, 13.*, 14.3, 14.4, 15.*

3 Basic knowledge

Note, this section is for something that does not fit anywhere

3.1 Abbreviations

cts Continuous

msr Measure

3.2 Multi-index Notation

- $\alpha = (\alpha_1, \dots, \alpha_n)$
- $|\alpha| = \alpha_1 + \dots + \alpha_n$
- $\alpha! = \alpha_1! \dots \alpha_n!$
- $x^\alpha = x_1^{\alpha_1} \dots x_n^{\alpha_n}$
- $\partial^\alpha f = \partial_1^{\alpha_1} \partial_2^{\alpha_2} \dots \partial_n^{\alpha_n} f = \frac{\partial^{|\alpha|} f}{\partial x_1^{\alpha_1} \partial x_2^{\alpha_2} \dots \partial x_n^{\alpha_n}}$

4 Linear Algebra

4.1 Definitions

norm A function $p : V \rightarrow \mathbb{R}$ such that

For all $a \in F$ and all $u, v \in V$

- $p(v) \geq 0 \wedge [p(v) = 0 \iff v = 0]$ (separates points)
- $p(av) = |a|p(v)$ (absolute homogeneity)
- $p(u + v) \leq p(u) + p(v)$ (triangle inequality)

inner product A function $\langle x, y \rangle : V \times V \rightarrow \mathbb{R}$ such that

For all $x, y, z \in V$ and $c \in \mathbb{F}$.

- $\langle x, y \rangle = \langle y, x \rangle$
- $\langle x + y, z \rangle = \langle x, z \rangle + \langle y, z \rangle$
- $\langle cx, y \rangle = c\langle x, y \rangle = \langle x, cy \rangle$
- $\langle x, x \rangle > 0$ if $x \neq 0$

5 Topology

5.1 Definitions

metric A function $d : X \times X \rightarrow \mathbb{R}$ such that

For all $x, y, z \in X$

- $d(x, y) \geq 0$
- $d(x, y) = 0 \iff x = y$
- $d(x, y) = d(y, x)$
- $d(x, z) \leq d(x, y) + d(y, z)$

ϵ -neighborhood $U(x; \epsilon) = \{y | d(x, y) < \epsilon\}$

open set in metric space A set $U \subseteq X$ is said to be open in X if $\forall x \in U \exists \epsilon > 0 [U(x; \epsilon) \subseteq U]$ note that finite intersections and arbitrary unions of open set are open set

closed set in metric space A set contains all its limit point.
note that closed set is complement of open set in topology

5.2 Partition of unity

TODO

6 Measure Theory

6.1 Measure zero

Let $A \subseteq \mathbb{R}^n$. We say A has measure zero in \mathbb{R}^n if for every $\epsilon > 0$, there is a covering Q_1, Q_2, \dots of A by countably many rectangles such that $\sum_{i=1}^{\infty} v(Q_i) < \epsilon$. If this inequality holds, we often say that the total volume of the rectangles Q_1, Q_2, \dots is less than ϵ .

6.2 Theorems

{Munkers-11.1}

1. If $B \subseteq A$ and A has measure zero in \mathbb{R}^n , then so does B .
2. Let A be the union of the collection of sets A_1, A_2, \dots . If each A_i has measure zero, so does A .
3. A set A has measure zero in \mathbb{R}^n if and only if

7 General Calculus

7.1 Definitions

oscillation

Given $a \in Q$ define $A_\delta = \{f(x) | x \in Q \wedge |x - a| < \delta\}$. Let $M_\delta(f) = \sup A_\delta$, and let $m_\delta(f) = \inf A_\delta$, define oscillation at f by $\text{osc}(f; a) = \inf_{\delta > 0} [M_\delta(f) - m_\delta(f)]$. f is cts at a iff $\text{osc}(f; a) = 0$

7.2 Extreme Value Theorem

Suppose $f : X \rightarrow \mathbb{R}$ is continuous and X is compact, then $\exists x_0 \in X$ such that $\forall x \in X. f(x) \leq f(x_0)$.

7.3 Intermediate Value Theorem

Suppose $E \in \mathbb{R}$ is connected and $f : E \rightarrow \mathbb{R}$ is continuous.

Suppose $f(x) = a$ and $f(y) = b$ for some $x, y \in E$ and $a < b$.

Then $\forall a < c < b \exists$ some $z \in E$ such that $f(z) = c$.

7.4 Mean Value Theorem

Suppose $\phi : [a, b] \rightarrow \mathbb{R}$ is

- continuous at each point of **closed** interval $[a, b]$
- differentiable at each point of **open** interval (a, b)

Then there exists a point $c \in (a, b)$ such that $\phi(b) - \phi(a) = \phi'(c)(b - a)$.

8 Differential Calculus

8.1 Definitions

differentiable f is differentiable at a if there is an n by m matrix B such that

$$\frac{f(a+h) - f(a) - B \cdot h}{|h|} \rightarrow 0 \quad \text{as } h \rightarrow 0$$

The matrix B is unique.

Directional derivative Given $u \in \mathbb{R}^m$ which $u \neq 0$ define

$$f'(a; u) = \lim_{t \rightarrow 0} \frac{f(a + tu) - f(a)}{t}$$

Provide the limit exists.

Partial derivative Define the j^{th} partial derivative of f at a to be the directional derivative of f at a with respect to the vector e_j , provide derivative exists.

$$D_j f(a) = \lim_{t \rightarrow 0} \frac{f(a + te_j) - f(a)}{t}$$

8.2 Notations

$Df(a)$: derivative of f at a

$f'(a; u)$: directional derivative of f at a respect to vector u .

$D_j f(a)$: j^{th} partial derivative of f at a .

f_i : i^{th} component function of f .

∇g : gradient of g , $\nabla g = \mathbf{grad} g = \sum_i (D_i g) e_i$

Jf : Jacobian matrix, $J_{ij} = D_j f_i(a)$

8.3 Differentiability Theorems

Theorems Munkers.5.1

If f is differentiable at a then all directional derivative of f at a exist and $f'(a; u) = Df(a) \cdot u$

Theorems Munkers.5.2

If f is differentiable at a then f is continuous at a .

Theorems Munkers.5.3

If f is differentiable at a then $Df(a) = [D_1 f(a) \ D_2 f(a) \ \cdots \ D_m f(a)]$.

Theorems Munkers.5.4

a. $[f \text{ is differentiable at } a] \Leftrightarrow \forall i [f_i \text{ is differentiable at } a]$.

b. If f is differentiable at a , then its derivative is the n by m matrix whose i^{th} row is the derivative of the function f_i . $(Df(a))_i = Df_i(a)$

8.4 Continuously Differentiable Functions

A function is C^1 if all of its partial derivatives are continuous. A function is C^r if all of its partial derivatives are C^{r-1} .

Munkers 6.1

If $f : [a, b] \rightarrow \mathbb{R}$ is continuous on $[a, b]$ and differentiable on (a, b) , then there exists $c \in (a, b)$ such that $f(b) - f(a) = f'(c)(b - a)$.

Munkers 7.3

Let A be open in \mathbb{R}^m ; let $f : A \rightarrow \mathbb{R}$ be differentiable on A . If A contains the line segment with end points a and $a + h$, then there is a point $c = a + th$ with $0 < t < 1$ of this line segment such that $f(a + h) - f(a) = (Df(c))h$.

Munkers 6.2

Let A be open in \mathbb{R}^m . Suppose that the partial derivative $D_i f_i(x)$ of the component function of f exists at each point x of A and are continuous on A . Then f is differentiable at each point of A .

Munkers 6.3

Let A be open in \mathbb{R}^m , let $f : A \rightarrow \mathbb{R}$ be a function of class C^2 . Then for each $a \in A$: $D_k D_j f(a) = D_j D_k f(a)$.

8.5 Chain Rule

Let $A \subset \mathbb{R}^m$. Let $B \subset \mathbb{R}^n$. Let $f : A \rightarrow \mathbb{R}^n$ and $g : B \rightarrow \mathbb{R}^p$, with $f(A) \subset B$. Suppose $f(a) = b$. If f is differentiable at a and g is differentiable at b , then the composite function $g \circ f$ is differentiable at a . Furthermore,

$$D(g \circ f)(a) = Dg(b) \cdot Df(a)$$

8.6 Inverse Function Theorem

Let A be open in \mathbb{R}^n . Let $f : A \rightarrow \mathbb{R}^n$ be of class C^r .

IF $Df(x)$ is invertible at $a \in A$.

THEN There exists a neighborhood of a such that

- $f|_U$ is injective AND $f(U) = V$ open in \mathbb{R}^n
- the inverse function is of class C^r
- $f^{-1}(y) = [f'(f^{-1}(y))]^{-1}$

8.7 Implicit Function Theorem

Suppose $f : A \rightarrow \mathbb{R}^n$ be of class C^r .

Write f in the form $f(x, y)$, for $x \in \mathbb{R}^k$ and $y \in \mathbb{R}^n$.

IF $(a, b) \in A$ AND $f(a, b) = 0$ AND $\det \frac{\partial f}{\partial y}(a, b) \neq 0$

THEN There exists $B \in \mathbb{R}^k, a \in B$ and a unique $g : B \rightarrow \mathbb{R}^n$ such that $g(a) = b$ AND $\forall x \in B. f(x, g(x)) = 0$ AND g is C^r

Munkers 9.1

Let A be open in \mathbb{R}^{k+n} , B be open in \mathbb{R}^k .

Let $f : A \rightarrow \mathbb{R}^n, g : B \rightarrow \mathbb{R}^n$ be differentiable.

Write f in the form $f(x, y)$, for $x \in \mathbb{R}^k$ and $y \in \mathbb{R}^n$.

IF $f(x, g(x)) = 0$ AND $\frac{\partial f}{\partial y}$ is invertible

THEN $Dg(x) = - \left[\frac{\partial f}{\partial y}(x, g(x)) \right]^{-1} \cdot \frac{\partial f}{\partial x}(x, g(x))$

8.8 Taylor's theorem

Suppose $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is of class C^k on an open convex set S . If $a \in S$ and $a + h \in S$, then

$$f(a + h) = \sum_{|\alpha| \leq k} \frac{\partial^\alpha f(a)}{\alpha!} h^\alpha + R_{a,k}(h),$$

If f is of class C^{k+1} on S , for some $c \in (0, 1)$ we have

$$R_{a,k}(h) = \sum_{|\alpha|=k+1} \frac{\partial^\alpha f(a + ch)}{\alpha!} h^\alpha$$

9 Integral Calculus

Note, Riemann Integral was taught in this class.

9.1 Definitions

rectangle (in \mathbb{R}^n) $Q = [a_1, b_1] \times [a_2, b_2] \times \dots \times [a_n, b_n]$

component interval of Q $[a_i, b_i]$

volume of Q $v(Q) = (b_1 - a_1)(b_2 - a_2) \cdots (b_n - a_n)$

partition *TODO*

subinterval(determined by P) *OMIT*

subrectangle(determined by P) *OMIT*

mech of P *OMIT*

refinement *OMIT*

common refinement *OMIT*

?- $m_R(f) = \inf\{f(x) | x \in R\}$

?- $M_R(f) = \sup\{f(x) | x \in R\}$

lower sum $L(f, P) = \sum_R m_R(f) \cdot v(R)$

upper sum $U(f, P) = \sum_R M_R(f) \cdot v(R)$

lower integral $\int_Q f = \sup_P \{L(f, P)\}$

upper integral $\overline{\int_Q f} = \inf_P \{U(f, P)\}$

oscillation *TODO*

rectifiable set A bounded set $S \in \mathbb{R}^n$ is rectifiable if the constant function 1 is integrable over S . S is rectifiable iff S is bounded and $\text{Bd}S$ has measure zero

volume of a rectifiable set $v(S) = \int_S 1$

9.2 Riemann condition

Given: Q a rectangle, $f : Q \rightarrow \mathbb{R}$ a bounded function.

$$\boxed{\int_Q f = \overline{\int_Q f} \text{ iff } \forall \epsilon > 0 \exists P [U(f, P) - L(f, P) \leq \epsilon]}$$

P is a partition of Q

Corollary/Theorem: every constant function is integrable.

9.3 Riemann-Lebesgue theorem

A function on a compact interval $[a, b]$ is Riemann integrable if and only if it is bounded and continuous almost everywhere (the set of its points of discontinuity has measure zero, in the sense of Lebesgue measure). [\[wiki\]](#) [\[11.2\]](#)

9.4 Fundamental theorem of Calculus

- If f is continuous on $[a, b]$, and if $F(x) = \int_a^x f$ for $x \in [a, b]$, then $F'(x)$ exists and equals $f(x)$.
- If f is continuous on $[a, b]$, and if g is a function such that $g'(x) = f(x)$ for $x \in [a, b]$ then $\int_a^b f = g(b) - g(a)$

9.5 Fubini's theorem

Let $Q = A \times B$, where A is a rectangle in \mathbb{R}^k and B is a rectangle in \mathbb{R}^n . If f is a bounded function and integrable over Q , then $\int_{y \in B} f(x, y)$ and $\overline{\int_{y \in B} f(x, y)}$ are integrable over A and

$$\int_Q f = \int_{x \in A} \int_{y \in B} f(x, y) = \int_{x \in A} \overline{\int_{y \in B} f(x, y)}$$

9.6 Properties of integral

TODO

9.7 Properties of rectifiable set

TODO

10 Change of Variables

Diffeomorphism [\[wiki\]](#)

$f : A \rightarrow B$ is a diffeomorphism if f is a bijection AND f and f^{-1} are of class C^r .

Moreover f is called C^r -diffeomorphism

Change of Variables Theorem [\[17.2\]](#)

LET opensets $U, V \subseteq \mathbb{R}$

$g : U \rightarrow V$ a diffeomorphism

$f : V \rightarrow \mathbb{R}$ be a continuous function

THEN f is intergrable over B

IFF $(f \circ g)|\det Dg|$ is integrable over A

NOTE $\int_B f = \int_A (f \circ g)|\det Dg|$

Substitution rule [\[17.1\]](#)

LET $I = [a, b], J = [c, d] \subseteq \mathbb{R}$

$g : I \rightarrow J$ of class C^1

$f : J \rightarrow \mathbb{R}$ is continuous

IF $\forall x \in (a, b) [g'(x) \neq 0]$

THEN $\int_{g(a)}^{g(b)} f = \int_a^b (f \circ g)g'$

equivalently $\int_J f = \int_I (f \circ g)|g'|$

11 Manifolds

12 Lecture Notes

12.1 2015-01-05 Monday

12.1.1 Review

THM : rectifiable

LET : $S \subset \mathbb{R}^n$ be bounded

THEN : S is rectifiable

IFF ∂S has measure zero, equivalently χ_S is integrable

IDEA : rectifiable is a property of the boundary of a set. If the boundary has measure zero then the set is rectifiable.

DEFN : volume

LET : $S \subset \mathbb{R}^n$ be bounded and *rectifiable*

THEN : define the volume of S as:

$$V(S) := \int_S 1 := \int_Q \chi_S$$

THM : partition of unity

LET : $A \subset \mathbb{R}^n$, $\{U_\alpha\}_{\alpha \in \mathcal{A}}$ be an open cover of A

THEN : \exists a collection of C^∞ functions $\{\psi_\beta\}_{\beta \in \mathcal{B}}$ s.t

- i $\forall x \in A \quad 0 < \psi_\beta \leq 1 \quad \forall \beta \in \mathcal{B}$
- ii $\forall x \in A \quad \exists$ open neighbourhood V of x such that:
all but finitely many ψ_β vanish on V (*locally finite*)
- iii $\forall x \in A \quad \sum_{\beta \in \mathcal{B}} \psi_\beta(x) \equiv 1$
- iv $\forall x \in A \quad \exists \alpha$ such that
 $\text{supp}(\psi_\beta) \subset U_\alpha$, ie $\{x | \psi_\beta(x) \neq 0\} \subset U_\alpha$

A collection of functions satisfying i, ii, iii is called a *partition of unity*

It is *subordinate* to the open cover $\{U_\alpha\}_{\alpha \in \mathcal{A}}$ if it satisfies condition iv

12.1.2 Open Sets

DEFN : extended integral

LET : $U^{open} \subset \mathbb{R}^n$, $f : U \rightarrow \mathbb{R}$ is continuous

IF $f \geq 0$

THEN : define then *extended integral* of f over U as:

$$\int_U f := \sup \left\{ \int_D f \mid D \subset U \text{ where } D \text{ is compact, rectifiable} \right\}$$

IF f is arbitrary and $\int_U f_+$, $\int_U f_-$ exist

THEN : define then *extended integral* of f over U as:

$$\int_U f := \int_U f_+ - \int_U f_- \text{ where } f_+(x) = \max\{f(x), 0\} \text{ and } f_-(x) = \min\{-f(x), 0\}$$

THM : mnk 15.2

LET : $U^{open} \subset \mathbb{R}^n$, $f : U \rightarrow \mathbb{R}$ is continuous

Choose an *exhaustion* of U by compact K_i such that

$$K_1 \subset K_2^\circ \subset K_2 \subset K_3^\circ \dots \text{ and } U = \bigcup_{i=1}^\infty K_i$$

f has an *extended integral*

IFF the sequence $\int_{K_i} |f_i|$ is bounded

THEN : $\int_U f = \lim_{i \rightarrow \infty} \int_{K_i} f$

RMK : If $U^{open} \subset \mathbb{R}^n$, then $\int_U f$ refers to the *extended integral*

THM : mnk 15.4

LET : U^{open} is bounded, $f : U \rightarrow \mathbb{R}^n$ is bounded and continuous

THEN :

- i the extended integral exists
- ii if the ordinary integral exists, then they are equal

THM : mnk 16.5

LET : $U^{open} \subset \mathbb{R}^n$, $f : U \rightarrow \mathbb{R}$ is continuous, $\{\psi_i\}$ be a partition of unity with compact support

THEN : $\int_U f$ exists

IFF $\sum_{i=1}^\infty \int_U \psi_i |f|$ converges to a finite number

$$\text{In this case } \int_U f = \sum_{i=1}^\infty \left(\int_U \psi_i f \right)$$

12.2 2015-01-07 Wednesday

Note: this is not finished --.

- Diffeomorphism
- Change of Variables
- Substitution Rule

12.3 2015-01-09 Friday

Change of Variables Theorem ^[17.2]

LET opensets $U, V \subseteq \mathbb{R}$

$g : U \rightarrow V$ a diffeomorphism

$f : V \rightarrow \mathbb{R}$ be a continuous function

THEN f is intergrable over B

IFF $(f \circ g)|\det Dg|$ is integrable over A

NOTE $\int_B f = \int_A (f \circ g)|\det Dg|$

IDEA : The theorem is proved in 5 steps.

- i Let $g : U \rightarrow V$ and $h : V \rightarrow W$ be diffeomorphisms of open sets in \mathbb{R}^n . Show that if the theorem holds for g and h , then it holds for $g \circ h$. The idea is to show that $\int_W f = \int_V (f \circ h) |\det Dh| = \int_U (f \circ h \circ g) |(\det Dh) \circ g| |\det Dg| = \int_U (f \circ h \circ g) |\det(h \circ g)|$
- ii Suppose that for each $x \in A$, there is a neighborhood U of x contained in A such that the theorem holds for the diffeomorphism $g : U \rightarrow V$ where $V = g(U)$ and all continuous functions $f : V \rightarrow \mathbb{R}$ whose supports are compact subsets of V . Then show that the theorem holds for g . This basically means: show that if the theorem holds locally for g and functions f having compact support, then it holds for all g and all f . The idea is to find a partition of unity $\{\phi_i\}$ of B with compact support and show that the collection $\{\phi_i \circ g\}$ is a partition of unity on A having compact support. Then use the fact that $\int_B f = \sum_{i=1}^{\infty} \int_B (\phi_i)(f)$.
- iii Show the the theorem holds for $n = 1$. This can be done by showing that the theorem holds for the interiors of all closed intervals contained in A then applying step 2.
- iv We only need to prove the theorem for primitive diffeomorphisms. This is because, when restricted to a small enough neighbourhood, all diffeomorphisms are a composition of primitive diffeomorphisms. Step 1 shows that the validity of the theorem is preserved by composition. Step 2 shows that if the theorem holds on all the small neighbourhoods in A then it holds for all of A .
- v Show that if the theorem holds in dimension $n - 1$, it holds in dimension n . Due to step 4, we only need to prove this for primitive diffeomorphisms. Assume without loss of generality that the primitive diffeomorphism preserves the last component. We can use Fubini's theorem to reduce this to the $n - 1$ dimensional case.

12.4 2015-01-12 Monday

12.4.1 Torus

Problem: Find the volume of the solid torus given by

$$\{(x, y, z) | (\sqrt{x^2 + y^2} - b)^2 + z^2 \leq a^2\}$$

When $y = 0$, $(x - b)^2 + z^2 \leq a^2$ is the circle centered at $(b, 0, 0)$ in the (x, z) plane with radius a .

For angle $0 < \varphi < 2\pi$, parametrize the circle by

- $x = b + a \cos \varphi$

- $z = a \sin \varphi$

and for $0 < \rho < a$ and parametrize the disc by

- $x = b + \rho \cos \varphi$

- $z = \rho \sin \varphi$

This defines a diffeomorphism from $(0, a) \times (0, 2\pi) \rightarrow$ disc with slit removed. Now rotate around z axis. For $0 < \theta < 2\pi$:

- $x = (b + \rho \cos \varphi) \cos \theta$

- $y = (b + \rho \cos \varphi) \sin \theta$

- $z = \rho \sin \varphi$

We want $G(\rho, \varphi, \theta) := (x, y, z)$, so $G(\rho, \varphi, \theta) \rightarrow \{(\sqrt{x^2 + y^2} - b)^2 + z^2 < a^2\} \setminus (T \cap \{x > 0, y = 0\}) \cup (T \cap \{z = 0 \cap x^2 + y^2 \geq b^2\})$ is a diffeomorphism.

Notice that the set we have removed has measure 0 (First part $\subset \{y = 0\}$ which has measure 0 and second part $\subset \{z = 0\}$ which has measure 0).

Thus, $\text{Vol}(T) = \text{volume of the image of } G$ (they differ by a set of measure 0).

So $\chi_T \equiv \chi_{G(R)}$ except on a set of measure 0.

Apply change of variables!

First check if G is a diffeomorphism:

G is a bijection by construction.

$$DG = \begin{bmatrix} \cos \varphi \cos \theta & -\rho \sin \varphi \cos \theta & (b + \rho \cos \varphi) \cos \theta \\ \cos \varphi \sin \theta & -\rho \sin \varphi \sin \theta & (b + \rho \cos \varphi) \sin \theta \\ \sin \varphi & \rho \cos \varphi & 0 \end{bmatrix}$$

$$\begin{aligned} |DG| &= -(b + \rho \cos \varphi) \sin \theta (\rho \cos^2 \varphi \sin \theta + \rho \sin^2 \varphi) \cos \theta \\ &\quad - (b + \rho \cos \varphi) \cos \theta (\rho \cos^2 \varphi \cos \theta + \rho \sin^2 \varphi) \cos \theta \\ &= -(b + \rho \cos \varphi) \rho \\ &\neq 0 \end{aligned}$$

Thus G is a diffeomorphism of open sets.

Then by change of variables,

$$\int_{G(R)} 1 = \int_R 1 |DG| = \int_{(0,a) \times (0,2\pi) \times (0,2\pi)} \rho (b + \rho \cos \theta)$$

Then by Fubini's theorem:

$$\int_{\rho=0}^a \int_0^{2\pi} \int_0^{2\pi} \rho (b + \rho \cos \varphi) = 4\pi^2 \int_0^a \rho b = 2\pi^2 a^2 b$$

That's the torus!

12.5 2015-01-14 Wednesday

Second test review

12.5.1 Existence of the Integral

DEFN : integral

LET : Q be a rectangle, $f : Q \rightarrow \mathbb{R}$ be a bounded function, define:

$\overline{\int}_Q f := \inf\{L(f, P)\}$ as the upper integral

$\underline{\int}_Q f := \sup\{L(f, P)\}$ as the lower integral

IF then the upper and lower sums agree

THEN : f is *integrable* over Q

THM : Riemann Condition

LET : Q be a rectangle, $f : Q \rightarrow \mathbb{R}$ be a bbd fn

THEN : upper and lower integral agree

IFF given $\epsilon > 0$ there is a partition P such that:

$$U(f, P) - L(f, P) \leq \epsilon$$

IDEA : necessary condition for the existence

THM : mnk 11.2

LET : $Q \subset \mathbb{R}^n$, $f : Q \rightarrow \mathbb{R}$ be a bounded function.

Define D to be the set of points for which f fails to be continuous

THEN : $\int_Q f$ exists

IFF D has measure zero (f is *almost continuous everywhere*)

THM : mnk 11.3

LET : $Q \subset \mathbb{R}^n$, $f : Q \rightarrow \mathbb{R}$. Assume f is *integrable*

IF f vanishes except on a set of measure zero

THEN : $\int_Q f = 0$

IF f is non-negative and $\int_Q f = 0$

THEN : $f = 0$ almost everywhere

12.5.2 Evaluation of the Integral

THM : Fundamental Theory of Calculus

LET : $f : [a, b] \rightarrow \mathbb{R}$ be continuous

IF $F(x) = \int_a^x f(x)$ for $x \in [a, b]$

THEN : $D \int_a^x f = f(x)$

IF g is a function such that $g'(x) = f(x) \forall x$

THEN : $\int_a^x Dg = g(x) - g(a)$

THM : Fubini's Theorem

LET : $Q = A \times B$, where $A \subset \mathbb{R}^k$ and $B \subset \mathbb{R}^n$.

$f : Q \rightarrow \mathbb{R}$ be bdd, write $f(x, y)$ for $x \in A$ and $y \in B$.

For each $x \in A$ consider upper and lower integrals

$$\underline{\int}_{y \in B} f(x, y) \text{ and } \overline{\int}_{y \in B} f(x, y)$$

IF f is integrable over Q

THEN : these two functions are integrable over Q and

$$\int_Q f = \int_{x \in A} \underline{\int}_{y \in B} f(x, y) = \int_{x \in A} \overline{\int}_{y \in B} f(x, y)$$

12.5.3 Integral Over a Bounded Set

THM : mnk 13.5

LET : $S \subset \mathbb{R}^n$ be bounded, $f : S \rightarrow \mathbb{R}$ be bounded and continuous function. Define E to be the set of all points $x_0 \in \partial S$ for which the condition $\lim_{x \rightarrow x_0} f(x) = 0$ fails

IF E has measure zero

THEN : f is integrable over S

Converse also holds

THM : mnk 13.6

LET : $S \subset \mathbb{R}^n$ be bounded, $f : S \rightarrow \mathbb{R}$ be bounded and continuous function, and $A = S^\circ$.

IF f is integrable over S

THEN : f is integrable over A and

$$\int_S f = \int_A f$$

12.5.4 Rectifiable Sets

THM : mnk 14.1

LET : $S \subset \mathbb{R}^n$ **THEN** : S is *rectifiable*

IFF S bounded and ∂S has measure zero

THM : mnk 14.2

Properties of rectifiable sets

- i (Positivity). If S is rectifiable, $v(S) \geq 0$
- ii (Monotonicity). If S_1 and S_2 are rectifiable with $S_1 \subset S_2$ then $v(S_1) \leq v(S_2)$
- iii (Additivity). If S_1 and S_2 are rectifiable so are, $S_1 \cup S_2$ and $S_1 \cap S_2$
- iv Suppose S is rectifiable. Then $v(S) = 0$ iff S has measure zero
- v If S is rectifiable, so is S° and $v(S) = v(S^\circ)$
- vi If S is rectifiable, and $f : S \rightarrow \mathbb{R}$ is bounded continuous, then f is integrable over S .

DEFN : simple region

LET : C be a compact and rectifiable set in \mathbb{R}^{n-1} , $\phi, \psi : C \rightarrow \mathbb{R}$ be continuous functions such that

$\phi(x) \leq \psi(x) \forall x \in C$.

THEN : $S \subset \mathbb{R}^n$ defined as

$S := \{(x, t) | x \in C \text{ and } \phi(x) \leq t \leq \psi(x)\}$

is a simple region.

THM : Fubini's Theorem for Simple Regions

LET : $S = \{(x, t) | x \in C \text{ and } \phi(x) \leq t \leq \psi(x)\}$ be a simple region in \mathbb{R}^n and let $f : S \rightarrow \mathbb{R}$ be a continuous function

THEN : f is integrable over S and

$$\int_S f = \int_{x \in C} \int_{t=\phi(x)}^{t=\psi(x)} f(x, t)$$

12.5.5 Extended Integrals

Three definitions of the extended integral:

- i [Extended Integral 1](#)
- ii [Extended Integral 2](#)
- iii [Extended Integral 3](#)

THM : mnk 15.4

LET : U^{open} is bounded, $f : U \rightarrow \mathbb{R}^n$ is bounded and continuous

THEN :

- i the extended integral exists
- ii if the ordinary integral exists, then they are equal

12.5.6 Change of Variables

DEFN : diffeomorphism

$f : A \rightarrow B$ is a diffeomorphism if f is a bijection AND f and f^{-1} are of class C^r .

THM : Change of Variables

LET : opensets $U, V \subseteq \mathbb{R}$

$g : U \rightarrow V$ a diffeomorphism

$f : V \rightarrow \mathbb{R}$ be a continuous function

THEN : f is integrable over B

IFF $(f \circ g) |\det Dg|$ is integrable over A

RMK : $\int_B f = \int_A (f \circ g) |\det Dg|$

THM : Substitution Rule

LET : $I = [a, b], J = [c, d] \subseteq \mathbb{R}$

$g : I \rightarrow J$ of class C^1

$f : J \rightarrow \mathbb{R}$ is continuous

IF $\forall x \in (a, b) [g'(x) \neq 0]$

THEN : $\int_{g(a)}^{g(b)} f = \int_a^b (f \circ g) g'$

equivalently $\int_J f = \int_I (f \circ g) |g'|$