Theorems, Lemmas, Properties: Real Analysis and Measure Theory

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Ref: Real Analysis 3: Stein-Shakarachi

Chapter 1

MEASURE THEORY

1.1 Basic Definitions

Definition 1 (Open Ball)**.** *The open ball in $\mathbb{R}^d$ centered at x and of radius r is defined by*

$$B_r(x) = \left\{y \in \mathbb{R}^d : |y - x| < r\right\}$$

Definition 2 (Open Set and Closed Set)**.** *A subset $E \subset \mathbb{R}^d$ is open if for every $x \in E$ there exists $r > 0$ with $B_r(x) \subset E$. By definition, a set is closed if its complement is open.*

- *Any (not necessarily countable) union of open sets is open*
- *The intersection of finitely many open sets is open*
- *Any (not necessarily countable) intersection of close sets is closed*
- *The union of finitely many close sets is close*

Definition 3 (Bounded Set and Compact Set)**.** *A set E is bounded if it is contained in some ball of finite radius. A bounded set is compact if it is also closed.*

Property 1 (Heine-Borel covering property)**.** *Any covering of a compact set by a collection of open sets contains a finite subcovering.*

Definition 4 (Limit Point)**.** *A point $x \in \mathbb{R}^d$ is a limit point of the set E if for every $r > 0$, the ball $B_r(x)$ contains points of E.*

Definition 5 (Isolated Point)**.** *An isolated point of E is a point $x \in E$ such that there exists an $r > 0$ where $B_r(x)\backslash E$ is equal to x.*

Definition 6 (Interior)**.** *A point $x \in E$ is an interior point of E if there exists $r > 0$ such that $B_r(x) \subset E$. The set of all interior points of E is called the interior of E.*

Definition 7 (Closure)**.** *The closure $\bar{E}$ of the E consists of the union of E and all its limit points.*

Definition 8 (Boundary)**.** *The boundary of a set E, denoted by δE, is the set of points which are in the closure of E but not in the interior of E.*

Property 2.

- *The closure of a set is a closed set.*
- *Every point in E is a limit point of E.*
- *A set is closed if and only if it contains all its limit points.*

Definition 9 (Perfect Set)**.** *A closed set E is perfect if E does not have any isolated points.*

Definition 10 (Rectangle)**.** *A (closed) rectangle R in $\mathbb{R}^d$ is given by the product of d one-dimensional closed and bounded intervals,*

$$R = [a_1, b_1] \times [a_2, b_2] \times \cdots \times [a_d, b_d]$$

where a_j, b_j are real numbers, $j = 1, 2, \ldots, d$. If all intervals are equal then it is a cube.

Lemma 1. *If a rectangle is the almost disjoint (interior disjoint) union of finitely many other rectangles, say* $R = \bigcup_{k=1}^{N} R_k$ *then* $|R| = \sum_{k=1}^{N} |R_k|$.

Lemma 2. *If* $R, R_1, \ldots, R_N$ *are rectangles, and* $R \subset \bigcup_{k=1}^{N} R_k$ *then*$|R| \leq \sum_{k=1}^{N} |R_k|$.

Theorem 1. *Every open subset* O *of* $\mathbb{R}$ *can be written uniquely as a countable union of disjoint open intervals. In general, this is not true for* $\mathbb{R}^d, d > 1$.

Theorem 2. *Every open subset* O *of* $\mathbb{R}^d, d \geq 1$*, can be written as a countable union of almost disjoint closed rectangles (cubes).*

Need to add more

1.2 Measurable Sets and Lebesgue Measure

Definition 11 (σ-algebra)**.** *A* σ*-algebra of sets is a collection of subsets of* $\mathbb{R}^d$ *that is closed under countable unions, countable intersections, and complements. Example: Collection of all subsets of* $\mathbb{R}^d$*, collection of all measurable sets of* $\mathbb{R}^d$

Definition 12 (Borel σ-algebra and Borel sets)**.** *A set* $E \subseteq \mathbb{R}^d$ *is an* F_σ *set provided that it is the countable union of closed sets and is a* G_δ *set if it is the countable intersection of open sets.The smallest* σ*-algebra that contains all open sets. Elements of this* σ*-algebra are called Borel sets.*

1.3 Measurable Functions

Definition 13 (Characteristic Function)**.** *A characteristic function of a set* E *is defined by*

$$\chi_E(x) = \begin{cases} 1, & if\ x \in E \\ 0, & if\ x \notin E. \end{cases}$$

Definition 14 (Step Function)**.** *Step functions are defined as finite sum,* $f = \sum_{k=1}^{N} a_k \chi_{R_k}$*, where each* R_k *is a rectangle and each* a_k *is a constant. These are used in Reimann integral.*

Definition 15 (Simple Function)**.** *A simple function is a finite sum,* $f = \sum_{k=1}^{N} a_k \chi_{E_k}$*, where each* E_k *is a measurable set of finite measure, and the* a_k *are constants. These are used in Lebesgue integral.*

Definition 16 (Measurable Function)**.** *A function* f *defined on a measurable subset* E *of* $\mathbb{R}^d$ *is measurable, if for all* $a \in \mathbb{R}$*, the set*

$$f^{-1}\big([-\infty, a)\big) = \big\{x \in E : f(x) < a\big\} = \big\{f < a\big\}$$

is measurable. Equivalently, $\{f \leq a\}, \{f > a\}, \{f \geq a\}$ *are measurable. If* f *is finite valued then* $\{a < f < b\}$ *is measurable (with any combinations of* $\leq, \geq$*).*

Property 3. *The finite-valued function* f *is measurable if and only if* $f^{-1}(O)$ *is measurable for every open set* O*, and if and only if* $f^{-1}(F)$ *is measurable for every closed set* F.

Property 4. *If* f *is continuous on* $\mathbb{R}^d$*, then* f *is measurable. If* f *is measurable and finite-valued, and* ϕ *is continuous, then* $\phi \circ f$ *is measurable. But* $f \circ \phi$ *may not.*

Property 5. *Suppose* $\{f_n\}_{n=1}^{\infty}$ *is a sequence of measurable functions. Then*

$$\sup_n f_n(x), \inf_n f_n(x), \limsup_{n\to\infty} f_n(x), \liminf_{n\to\infty} f_n(x)$$

are measurable.

Property 6. *Suppose* $\{f_n\}_{n=1}^{\infty}$ *is a sequence of measurable functions. Then*

$$\lim_{n\to\infty} f_n(x) = f(x)$$

then f *is measurable.*

Property 7. *If f and g are measurable, then,*

- *The integer powers $f^k, k \geq 1$ are measurable.*
- *$f+g$ and fg are measurable if both f and g are finite-valued.*

Definition 17 (Almost Everywhere)**.** *We shall say that two functions f and g defined on a set E are equal almost everywhere, and write,*

$$f(x) = g(x) \text{ a.e. } x \in E,$$

if the set $\{x \in E : f(x) \neq g(x)\}$ has measure zero. All the properties above can be relaxed to conditions holding almost everywhere.

Property 8. *Suppose f is measurable, and $f(x) = g(x)$ for a.e. x. Then g is measurable.*

Theorem 3. *Suppose f is a non-negative measurable function on $\mathbb{R}^d$. Then there exists an increasing sequence of non-negative simple functions $\{\phi\}_{k=1}^{\infty}$ that converges pointwise to f, namely,*

$$\phi_k(x) \leq \phi_{k+1}(x) \text{ and } \lim_{k\to\infty} = f(x) \ \forall \ x.$$

Theorem 4. *Suppose f is a measurable function on $\mathbb{R}^d$. Then there exists a sequence of simple functions $\{\phi\}_{k=1}^{\infty}$ that satisfies,*

$$|\phi_k(x)| \leq |\phi_{k+1}(x)| \text{ and } \lim_{k\to\infty} = f(x) \ \forall \ x.$$

Theorem 5. *Suppose f is measurable on $\mathbb{R}^d$. Then there exists a sequence of step functions $\{\psi\}_{k=0}^{\infty}$ that converges pointwise to $f(x)$ for almost every x.*

Theorem 6 (Egorov)**.** *Suppose $\{f_k\}_{k=1}^{\infty}$ is a sequence of measurable functions defined on a measurable set E with $m(E) < \infty$, and assume that $f_k \to f$ a.e on E. Given $\epsilon > 0$, we can find a closed set $A_\epsilon \subset E$ such that $m(E - A_\epsilon) \leq \epsilon$ and $f_k \to f$ uniformly on A_ϵ.*

Theorem 7 (Lusin)**.** *Suppose f is measurable and finite valued on E with E of finite measure. Then for every $\epsilon > 0$ there exists a closed set F_ϵ, with*

$$F_\epsilon \subset E \text{ and } m(E - F_\epsilon) \leq \epsilon$$

and such that $f|_{F_\epsilon}$ is continuous.

Chapter 2

INTEGRATION THEORY

Definition 18 (Canonical Form of Simple Function). *The canonical form of a simple function ϕ is the unique decomposition as below,*

$$\phi = \sum_{k=1}^{M} c_k \chi_{F_k}$$

where the numbers c_k are distinct and non-zero, and the sets F_k are disjoint.

Property 9. *If ϕ is a simple function with canonical form $\phi = \sum_{k=1}^{M} c_k \chi_{F_k}$, then we define the Lebesgue integral of ϕ by $\int_{\mathbb{R}^d} \phi(x)dx = \sum_{k=1}^{M} c_k m(Fk)$.*