MA3101

Analysis III

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Contents

1 Euclidean spaces

1.1 $\mathbb{R}^n$ as a vector space

We are familiar with the vector space $\mathbb{R}^n$, with the standard inner product

$$\langle \boldsymbol{x}, \boldsymbol{y} \rangle = x_1 y_1 + \cdots + x_n y_n.$$

The standard norm is defined as

$$\|\boldsymbol{x} - \boldsymbol{y}\|^2 = \langle \boldsymbol{x} - \boldsymbol{y}, \boldsymbol{x} - \boldsymbol{y} \rangle = \sum_{k=1}^{n} (x_i - y_i)^2.$$

Exercise 1.1. What are all possible inner products on $\mathbb{R}^n$?

Solution. Note that an inner product is a bilinear, symmetric map such that $\langle \boldsymbol{x}, \boldsymbol{x} \rangle \geq 0$, and $\langle \boldsymbol{x}, \boldsymbol{x} \rangle = 0$ if and only if $\boldsymbol{x} = \boldsymbol{0}$. Thus, an product map on $\mathbb{R}^n$ is completely and uniquely determined by the values $\langle \boldsymbol{e}_i, \boldsymbol{e}_j \rangle = a_{ij}$. Let A be the $n \times n$ matrix with entries a_{ij}. Note that A is a real symmetric matrix with positive entries. Now,

$$\langle \boldsymbol{x}, \boldsymbol{e}_j \rangle = x_1 a_{1j} + \cdots + x_n a_{nj} = \boldsymbol{x}^\top \boldsymbol{a}_j,$$

where $\boldsymbol{a}_j$ is the j^{th} column of A. Thus,

$$\langle \boldsymbol{x}, \boldsymbol{y} \rangle = \boldsymbol{x}^\top \boldsymbol{a}_1 y_1 + \cdots + \boldsymbol{x}^\top \boldsymbol{a}_n y_n = \boldsymbol{x}^\top A \boldsymbol{y}.$$

Furthermore, any choice of real symmetric A with positive entries produces an inner product.

Theorem 1.1 (Cauchy-Schwarz)**.** *Given two vectors* $\boldsymbol{v}, \boldsymbol{w} \in \mathbb{R}^n$*, we have*

$$|\langle \boldsymbol{v}, \boldsymbol{w} \rangle| \leq \|\boldsymbol{v}\| \|\boldsymbol{w}\|.$$

Proof. This is trivial when $\boldsymbol{w} = \boldsymbol{0}$. When $\boldsymbol{w} \neq \boldsymbol{0}$, set $\lambda = \langle \boldsymbol{v}, \boldsymbol{w} \rangle / \|\boldsymbol{w}\|^2$. Thus,

$$0 \leq \|\boldsymbol{v} - \lambda \boldsymbol{w}\|^2 = \|\boldsymbol{v}\|^2 - 2\lambda \langle \boldsymbol{v}, \boldsymbol{w} \rangle + \lambda^2 \|\boldsymbol{w}\|^2.$$

Simplifying,

$$0 \leq \|\boldsymbol{v}\|^2 - \frac{|\langle \boldsymbol{v}, \boldsymbol{w} \rangle|^2}{\|\boldsymbol{w}\|^2}.$$

This gives the desired result. Clearly, equality holds if and only if $\boldsymbol{v} = \lambda \boldsymbol{w}$. □

Theorem 1.2 (Triangle inequality)**.** *Given two vectors* $\boldsymbol{v}, \boldsymbol{w} \in \mathbb{R}^n$*, we have*

$$\|\boldsymbol{v} + \boldsymbol{w}\| \leq \|\boldsymbol{v}\| + \|\boldsymbol{w}\|.$$

Proof. Write

$$\|\boldsymbol{v} + \boldsymbol{w}\|^2 = \|\boldsymbol{v}\|^2 + 2\langle \boldsymbol{v}, \boldsymbol{w} \rangle + \|\boldsymbol{w}\|^2 \leq \|\boldsymbol{v}\|^2 + 2|\langle \boldsymbol{v}, \boldsymbol{w} \rangle| + \|\boldsymbol{w}\|^2.$$

Applying Cauchy-Schwarz gives

$$\|\boldsymbol{v} + \boldsymbol{w}\|^2 \leq (\|\boldsymbol{v}\| + \|\boldsymbol{w}\|)^2.$$

Equality holds if and only if $\boldsymbol{v} = \lambda \boldsymbol{w}$ for $\lambda \geq 0$. □

1.2 $\mathbb{R}^n$ as a metric space

Our previous observations allow us to define the standard metric on $\mathbb{R}^n$, seen as a point set.

$$d(\boldsymbol{x}, \boldsymbol{y}) = \|\boldsymbol{x} - \boldsymbol{y}\|.$$

Definition 1.1. For any $\delta > 0$, the set

$$B_\delta(\boldsymbol{x}) = \{\boldsymbol{y} \in \mathbb{R}^n : d(\boldsymbol{x}, \boldsymbol{y}) < \delta\}$$

is called the open ball centred at $\boldsymbol{x} \in \mathbb{R}^n$ with radius δ. This is also called the δ neighbourhood of $\boldsymbol{x}$.

Definition 1.2. A set U is open in $\mathbb{R}^n$ if for every $\boldsymbol{x} \in U$, there exists an open ball $B_\delta(\boldsymbol{x}) \subset U$.

Remark. Every open ball in $\mathbb{R}^n$ is open.

Remark. Both $\emptyset$ and $\mathbb{R}^n$ are open.

Definition 1.3. A set F is closed in $\mathbb{R}^n$ if its complement $\mathbb{R}^n \setminus F$ is open in $\mathbb{R}^n$.

Remark. Both $\emptyset$ and $\mathbb{R}^n$ are closed.

Remark. Finite sets in $\mathbb{R}^n$ are closed.

Theorem 1.3. *Unions and finite intersections of open sets are open.*

Corollary 1.3.1. *Intersections and finite unions of closed sets are closed.*

Definition 1.4. An interior point x of a set $S \subseteq \mathbb{R}^n$ is such that there is a neighbourhood of x contained within S.

Example. Every point in an open set is an interior point by definition. The interior of a set is the largest open set contained within it.

Definition 1.5. An exterior point x of a set $S \subseteq \mathbb{R}^n$ is an interior point of the complement $\mathbb{R}^n \setminus S$.

Definition 1.6. A boundary point of a set is neither an interior point, nor an exterior point.

Example. The boundary of the unit open ball $B_1(0) \subset \mathbb{R}^n$ is the sphere S^{n-1}.

Definition 1.7. A limit point x of a set $S \subseteq \mathbb{R}^n$ is such that every neighbourhood of x contains a point from S other than itself.

Definition 1.8. The closure of a set $S \subseteq \mathbb{R}^n$ is the union of S and its limit points.

Remark. The closure of a set is the smallest closed set containing it.

Lemma 1.4. *Every open set in $\mathbb{R}^n$ is a union of open balls.*

Proof. Let $U \subseteq \mathbb{R}^n$ be open. Thus, for every $\boldsymbol{x} \in \mathbb{R}^n$, we can choose $\delta_x > 0$ such that $B_{\delta_x}(\boldsymbol{x}) \subset U$. The union of all such open balls is precisely the set U. $\square$

1.3 $\mathbb{R}^n$ as a topological space

Definition 1.9. A topology on a set X is a collection τ of subsets of X such that

1. $\emptyset \in \tau$
2. $X \in \tau$
3. Arbitrary union of sets from τ belong to τ.
4. Finite intersections of sets from τ belong to τ.

Sets from τ are called open sets.

Example. The Euclidean metric induces the standard topology on $\mathbb{R}^n$.

Example. The discrete topology on a set X is one where every singleton set is open. This is the topology induced by the discrete metric,

$$d_{\text{discrete}} \colon X \times X \to \mathbb{R}, \qquad (x, y) \mapsto \begin{cases} 0, & \text{if } x = y, \\ 1, & \text{if } x \neq y. \end{cases}$$

Example. Let X be an infinite set. The collection of sets consisting of $\emptyset$ along with all sets A such that $X \setminus A$ is finite is a topology on X. This is called the Zariski topology.

Example. Consider the set of real numbers, and let τ be the collection $\emptyset$, $\mathbb{R}$, and all intervals $(-x, +x)$ for $x > 0$. This constitutes a topology on $\mathbb{R}$, very different from the usual one.

This topology cannot be induced by a metric; it is not metrizable.

Consider the constant sequence of zeros. In this topology $(\mathbb{R}, \tau)$, this sequence converges to *every* point in $\mathbb{R}$. Given any $\ell \in \mathbb{R}$, the open neighbourhoods of ℓ are precisely the sets $\mathbb{R}$ and the open intervals $(-x, +x)$ for $x > |\ell|$. The tail of the constant sequence of zeros is contained within every such neighbourhood of ℓ, hence $0 \to \ell$. Indeed, the element zero belongs to every open set apart from $\emptyset$ in this topology.

Definition 1.10. A topological space is called Hausdorff if for every distinct $x, y \in X$, there exist disjoint neighbourhoods of x and y.

Example. Every metric space is Hausdorff. Given distinct x, y in a metric space (X, d), set $\delta = d(x, y)/3$ and consider the open balls $B_\delta(x)$ and $B_\delta(y)$.

Lemma 1.5. *Every convergent sequence in a Hausdorff space has exactly one limit.*

Proof. Consider a sequence $\{x_n\}_{n \in \mathbb{N}}$, and suppose that it converges to distinct x_1 and x_2. Construct disjoint neighbourhoods U_1 and U_2 around x_1 and x_2. Now, convergence implies that both U_1 and U_2 contain the tail of $\{x_n\}$, which is impossible since they are disjoint and hence contain no elements in common. $\square$

Definition 1.11. Given a topological space (X, τ) and a subset $Y \subseteq X$, the collection of sets $U \cap Y$ where $U \in \tau$ is a topology τ_Y on Y. We call this collection the subspace topology on Y, induced by the topology on X.

1.4 Compact sets in $\mathbb{R}^n$

Definition 1.12. A set $K \subset X$ in a topological space is compact if every open cover of K has a finite sub-cover. That is, for every collection if $\{U_\alpha\}_{\alpha \in A}$ of open sets such that K is contained in their union, there exists a finite sub-collection $U_{\alpha_1}, \dots, U_{\alpha_k}$ such that K is also contained in their union.

Example. All finite sets are compact.

Example. Given a convergent sequence of real numbers $x_n \to x$, the collection $\{x_n\}_{n \in \mathbb{N}} \cup \{x\}$ is compact.

Example. In $\mathbb{R}^n$, compact sets are precisely those sets which are closed and bounded. This is the Heine-Borel Theorem.

Theorem 1.6. *The closed intervals $[a, b] \subset \mathbb{R}$ are compact.*

Remark. This can be extended to show that any k-cell $[a_1, b_1] \times \cdots \times [a_n, b_n] \subset \mathbb{R}^n$ is compact.

Proof. Let $\{U_\alpha\}_{\alpha \in A}$ be an open cover of $[a, b]$, and suppose that $I_1 = [a, b]$ has no finite sub-cover. Then, at least one of the intervals $[a, (a + b)/2]$ and $[(a + b)/2, b]$ must not have a finite sub-cover; pick one and call it I_2. Similarly, one of the halves of I_2 must not have a finite sub-cover; call it I_3. In this process, we generate a sequence of closed intervals $I_1 \supset I_2 \supset \dots$, none of which have a finite sub-cover. The length of each interval is given by

$$|I_n| = 2^{-n+1}\|b - a\| \to 0.$$

Now, pick a sequence of points $\{x_n\}$ where each $x_n \in I_n$. Then, $\{x_n\}$ is a Cauchy sequence. To see this, given any $\epsilon > 0$, we can find sufficiently large n_0 such that $2^{-n_0+1}\|b - a\| < \epsilon$. Thus, $x_n \in I_n \subset I_{n_0}$ for all $n \geq n_0$, which means that for any $m, n \geq n_0$, we have $x_m, x_n \in I_{n_0}$ forcing[1]

$$\|x_m - x_n\| \leq |I_{n_0}| = 2^{-n_0+1}\|b - a\| < \epsilon.$$

From the completeness of $\mathbb{R}$, this sequence must converge in $\mathbb{R}$, specifically in $[a, b]$. Thus, $x_n \to x$ for some $x \in [a, b]$. It can also be seen that the limit $x \in I_n$ for all $n \in \mathbb{N}$; if not, say $x \notin I_{n_0}$, then $x \in [a, b] \setminus I_{n_0}$ which is open, hence there is an open interval such that

[1] If $x_1, x_2 \in [a, b]$ with $x_1 < x_2$, note that $a \leq x_1 < x_2 \leq b$, so

$$|x_2 - x_1| = x_2 - x_1 \leq b - a.$$

$(x-\delta, x+\delta) \cap I_{n_0} = \emptyset$. However, I_{n_0} contains all $x_{n \geq n_0}$, thus this δ-neighbourhood of x would miss out a tail of $\{x_n\}$.

Now, pick the open set $U \in \{U_\alpha\}$ which covers the point x. Thus, $x \in U$ so U contains some non-empty open interval $(x-\delta, x+\delta)$ around x. Choose n_0 such that $2^{-n_0+1}\|b-a\| < \delta$; this immediately gives $I_{n_0} \subseteq (x-\delta, x+\delta) \subset U$. This contradicts that fact that I_{n_0} has no finite sub-cover from $\{U_\alpha\}$, completing the proof. □

Remark. The fact that Cauchy sequences in $\mathbb{R}^n$ converge isn't immediately obvious; it is a consequence of the completeness of $\mathbb{R}^n$. Start by noting that $\mathbb{R}$ has the Least Upper Bound property, from which the Monotone Convergence Theorem follows; every monotonic, bounded sequence of reals converges. It can also be shown that any sequence of reals with contain a monotone subsequence, from which it follows that every bounded sequence contains a convergent subsequence (Bolzano-Weierstrass). Finally, it can be shown that if a subsequence of a Cauchy sequence converges, then the entire sequence also converges to the same limit, giving us the desired result for $\mathbb{R}$. For sequence in $\mathbb{R}^n$, we may apply this coordinate-wise to obtain the result.

Lemma 1.7. *Compact sets in $\mathbb{R}^n$ are closed and bounded.*

Proof. Consider a compact set $K \subset \mathbb{R}^n$. Let $x \in \mathbb{R}^n \setminus K$, and let $y \in K$. Since $x \neq y$, we choose open balls U_y around y and V_y around x such that $U_y \cap V_y = \emptyset$. Repeating this for all $y \in K$, we generate an open cover $\{U_y\}$ of K consisting of open balls. The compactness of K guarantees that this has a finite sub-cover, i.e. there is a finite set Y such that the collection $\{U_y\}_{y \in Y}$ covers X. As a result, the finite intersection of all V_y for $y \in Y$ is contained within $\mathbb{R}^n \setminus K$. Thus, x is in the exterior of K. Since x was chosen arbitrarily from $\mathbb{R}^n \setminus K$, we see that K is closed.

Now, consider the open cover $\{B_1(x)\}_{x \in K}$, and extract a finite sub-cover of unit open balls. The distance between any two points in K is at most the maximum distance between the centres of any two balls in our sub-cover, plus two. □

Lemma 1.8. *The intersection of a closed set and a compact set is compact.*

Proof. Let $F \subseteq \mathbb{R}^n$ be closed and let $K \subseteq \mathbb{R}^n$ be compact. Suppose that the open cover $\{U_\alpha\}$ of $F \cap K$ has no finite sub-cover. Now the complement $U = F^c$ is open in $\mathbb{R}^n$, hence the collection $\{U_\alpha\} \cup \{U\}$ is an open cover of K, and hence must admit a finite sub-cover of K. In particular, this must be a finite sub-cover of $F \cap K$. However, we can remove the set U from this sub-cover since it shares no element with $F \cap K$; as a result, our sub-cover must be a finite sub-collection of sets U_α, contradicting our assumption. This shows that $F \cap K$ is compact. □

Lemma 1.9 (Finite intersection property)**.** *Let $\{K_\alpha\}$ be a collection of compact sets in $\mathbb{R}^n$ which have the property that any finite intersection of them is non-empty. Then,*

$$\bigcap_\alpha K_\alpha \neq \emptyset.$$

Proof. Suppose to the contrary that the intersection of all K_α is empty. Fix an index β, and note that no element of K_β lies in every K_α. Set $J_\alpha = K_\alpha^c$, whence the collection $\{J_\alpha : \alpha \neq \beta\}$

is an open cover of K_β. This must admit a finite sub-cover $\{J_{\alpha_1}, \dots, J_{\alpha_k}\}$ of K_β. Thus, we must have

$$K_\beta^c \cup J_{\alpha_1} \cup \dots \cup J_{\alpha_k} = \mathbb{R}^n.$$

This immediately gives the contradiction

$$K_\beta \cap K_{\alpha_1} \cap \dots \cap K_{\alpha_k} = \emptyset.$$ □

Theorem 1.10 (Heine-Borel)**.** *Compact sets in $\mathbb{R}^n$ are precisely those that are closed and bounded.*

Proof. Given a compact set in $\mathbb{R}^n$, we have already shown that it must be closed and bounded. Next, if $F \subset \mathbb{R}^n$ is closed and bounded, it can be enclosed within a k-cell which we know is compact. Thus, F is the intersection of the closed set F and the compact k-cell, proving that F must be compact. □

1.5 Continuous maps

Definition 1.13. A map $f\colon X \to Y$ is continuous if the pre-image of every open set from Y is open in X.

Lemma 1.11. *A map $f\colon X \to Y$ is continuous if the pre-image of every closed set from Y is closed in X.*

Theorem 1.12. *The projection maps $\pi_i\colon \mathbb{R}^n \to \mathbb{R}$, $\boldsymbol{x} \mapsto x_i$ are continuous.*

Proof. Let $U \subseteq \mathbb{R}$ be open; we claim that $\pi_i^{-1}(U)$ is open. Pick $\boldsymbol{x} \in \pi_i^{-1}(U)$, and note that $\pi_i(\boldsymbol{x}) = x_i \in U$. Thus, there exists $\delta > 0$ such that $(x_i - \delta, x_i + \delta) \subset U$. Now examine $B_\delta(\boldsymbol{x})$; for any point $\boldsymbol{y}$ within this open ball, we have $d(\boldsymbol{x}, \boldsymbol{y}) < \delta$ hence

$$|x_i - y_i|^2 \leq \sum_{k=1}^{n} (x_k - y_k)^2 = d(\boldsymbol{x}, \boldsymbol{y})^2 < \delta^2.$$

In other words, $\pi_i(\boldsymbol{y}) = y_i \in (x_i - \delta, x_i + \delta)$, hence $\pi_i\, B_\delta(\boldsymbol{x}) \subseteq (x_i - \delta, x_i + \delta) \subset U$. Thus, given arbitrary $\boldsymbol{x} \in \pi_i^{-1}(U)$, we have found an open ball $B_\delta(\boldsymbol{x}) \subset \pi_i^{-1}(U)$. □

Lemma 1.13. *Finite sums, products, and compositions of continuous functions are continuous.*

Theorem 1.14. *All polynomial functions of the coordinates in $\mathbb{R}^n$ are continuous.*

Example. The unit sphere $S^{n-1} \subset \mathbb{R}^n$ is closed. It is by definition the pre-image of the singleton closed set $\{1\}$ under the continuous map

$$\boldsymbol{x} \mapsto x_1^2 + \cdots + x_n^2.$$

Theorem 1.15. *The continuous image of a compact set is compact.*

Proof. Let $f\colon X \to Y$ be continuous, where Y is the image of the compact set X, and let $\{U_\alpha\}$ be an open cover of Y. Then, the collection $\{f^{-1}(U_\alpha)\}$ is an open cover of X. Using the compactness of X, extract a finite sub-cover $f^{-1}(U_{\alpha_1}), \ldots, f^{-1}(U_{\alpha_k})$ of X. It follows that the collection $U_{\alpha_1}, \ldots, U_{\alpha_k}$ is a finite sub-cover of Y. □

1.6 Connectedness

Definition 1.14. Let X be a topological space. A separation of X is a pair U, V of non-empty disjoint open subsets such that $X = U \cup V$.

Definition 1.15. A connected topological space is one which cannot be separated.

Lemma 1.16. *A topological space X is connected if and only if the only sets which are both open and closed are $\emptyset$ and X.*

Example. The intervals $(a, b) \subset \mathbb{R}$ are connected. To see this, suppose that U, V is a separation of (a, b). Pick $x \in U$, $y \in V$, and without loss of generality let $x < y$. Define $S = [x, y] \cap U$, and set $c = \sup S$. It can be argued that $c \in (a, b)$, but $c \notin U$, $c \notin V$, using the properties of the supremum.

Theorem 1.17. *The continuous image of a connected set is connected.*

Proof. Let f be a continuous map on the connected set X, and let Y be the image of X. If U, V is a separation of Y, then it can be shown that $f^{-1}(U)$, $f^{-1}(V)$ constitutes a separation of X, which is a contradiction. □

Definition 1.16. A path γ joining two points $x, y \in X$ is a continuous map $\gamma\colon [a, b] \to X$ such that $\gamma(a) = x$, $\gamma(b) = y$.

Definition 1.17. A set in X is path connected if given any two distinct points in X, there exists a path joining them.

Lemma 1.18. *Every path connected set is connected.*

Proof. Let X be path connected, and suppose that U, V is a separation of X. Then, pick $x \in U$, $y \in V$, and choose a path $\gamma\colon [0,1] \to X$ between x and y. The sets $f^{-1}(U)$ and $f^{-1}(V)$ separate the interval $[0,1]$, which is a contradiction. $\square$

Example. All connected sets are not path connected. Consider the topologist's sine curve,

$$\left\{\left(x, \sin\frac{1}{x}\right) : 0 < x \le 1\right\} \cup \{(0,0)\}.$$

Definition 1.18. The ϵ neighbourhood of a set K in a metric space X is defined as

$$\bigcup_{a\in K} B_\epsilon(a) = \bigcup_{a\in K} \{x \in X : d(x,a) < \epsilon\}.$$

Exercise 1.2. Let $K \subseteq \mathbb{R}^n$ be compact, and define $f\colon \mathbb{R}^n \to \mathbb{R}$,

$$f(x) = \operatorname{dist}(x, K) = \inf_{a\in K} d(x,a).$$

Show that f is continuous on $\mathbb{R}^n$, and $f^{-1}(\{0\}) = K$.

Exercise 1.3. If $K \subseteq \mathbb{R}^n$ is compact and $K \cap L = \emptyset$, then

$$\operatorname{dist}(K, L) = \inf_{a\in K} \operatorname{dist}(a, L) > 0.$$

Exercise 1.4. If $K \subseteq \mathbb{R}^n$ is compact and U is an open set containing K, then there exists $\epsilon > 0$ such that U contains the ϵ neighbourhood of K.

Is the compactness of K necessary?