Exercise Problem Sets 8

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Problem 1. Let (M, d) be a metric space.

1. Show that a closed subset of a compact set is compact.
2. Show that the union of a finite number of sequentially compact subsets of M is compact.
3. Show that the intersection of an arbitrary collection of sequentially compact subsets of M is sequentially compact.

Proof. 1. Let K be a compact set in M, F be a closed subset of K, and $\{x_k\}_{k=1}^{\infty}$ be a sequence in F. Then $\{x_k\}_{k=1}^{\infty}$ is a sequence in K; thus the sequential compactness of K implies that there exists a convergent subsequence $\{x_{k_j}\}_{j=1}^{\infty}$ with limit $x \in K$. Note that $\{x_{k_j}\}_{j=1}^{\infty}$ itself is a convergent sequence in F; thus the limit x of $\{x_{k_j}\}_{j=1}^{\infty}$ belongs to F by the closedness of F.

2. Let $K_1, K_2, \cdots, K_N$ be compact sets, and $K = \bigcup_{\ell=1}^{N} K_\ell$, and $\{x_n\}_{n=1}^{\infty}$ be a sequence in K. Then there exists $1 \leqslant \ell_0 \leqslant N$ such that

$$\#\{n \in \mathbb{N} \,|\, x_n \in K_{\ell_0}\} = \infty .$$

Let $\{x_{n_k}\}_{k=1}^{\infty} \subseteq K_{\ell_0}$. By the compactness of K_{ℓ_0}, there exists a convergent subsequence $\{x_{n_{k_j}}\}_{j=1}^{\infty}$ of $\{x_{n_k}\}_{k=1}^{\infty}$ with limit $x \in K_{\ell_0} \subseteq K$. Since $\{x_{n_{k_j}}\}_{j=1}^{\infty}$ is a subsequence of $\{x_n\}_{n=1}^{\infty}$, we conclude that every sequence in K has a convergent subsequence with limit in K; thus K is compact.

3. Since every compact set is closed, the intersection of an arbitrary collection of compact sets of M is closed. By 1, this intersection is also compact since the intersection is a closed set of any compact set (in the family). □

Problem 2. Given $\{a_k\}_{k=1}^{\infty} \subseteq \mathbb{R}$ a bounded sequence, define

$$A = \Big\{x \in \mathbb{R} \,\Big|\, \text{there exists a subsequence } \{a_{k_j}\}_{j=1}^{\infty} \text{ such that } \lim_{j\to\infty} a_{k_j} = x\Big\} .$$

Show that A is a non-empty sequentially compact set in $\mathbb{R}$. Furthermore , $\limsup_{k\to\infty} a_k = \sup A$ and $\liminf_{k\to\infty} a_k = \inf A$.

Proof. Note that A is the collection of cluster points of bounded sequence $\{a_k\}_{k=1}^{\infty}$; thus Problem 3 of Exercise 7 shows that A is closed. Moreover, A is bounded since $\{a_k\}_{k=1}^{\infty}$ is bounded; thus $\sup A \in A$ and $\inf A \in A$. The desired result then follows from the fact that $\limsup_{k\to\infty} a_k$ is the largest cluster point of $\{a_k\}_{k=1}^{\infty}$ and $\liminf_{k\to\infty} a_k$ is the least cluster point of $\{a_k\}_{k=1}^{\infty}$; thus $\limsup_{k\to\infty} a_k = \sup A \in A$ and $\liminf_{k\to\infty} a_k = \inf A \in A$. □

Problem 3. Complete the following problems that we talked about in class.

1. Let (M, d) be a complete metric space, and A is a totally bounded subset of M. Show that $\text{cl}(A)$ is sequentially compact.

2. Let (M, d) be a metric space. Show that M is complete if and only if every totally bounded sequence has a convergent subsequence.

Proof. Let $r > 0$ be given. Since A is totally bounded, there exist $x_1, x_2, \cdots, x_N \in M$ such that

$$A \subseteq \bigcup_{j=1}^{N} B\big(x_j, \frac{r}{2}\big) . \tag{$\star$}$$

Note that for all $x \in M$, $B\big(x, \frac{r}{2}\big) \subseteq B\big[x, \frac{r}{2}\big]$ which further implies that

$$\text{cl}\big(B\big(x, \frac{r}{2}\big)\big) \subseteq B\big[x, \frac{r}{2}\big] \subseteq B(x, r) \qquad \forall\, x \in M .$$

Therefore, $(\star)$ and 3 of Problem 8 in Exercise 6 imply that

$$\bar{A} \subseteq \text{cl}\Big(\bigcup_{j=1}^{N} B\big(x_j, \frac{r}{2}\big)\Big) = \bigcup_{j=1}^{N} \text{cl}\big(B\big(x_j, \frac{r}{2}\big)\big) \subseteq \bigcup_{j=1}^{N} B(x_j, r) .$$

This shows that $\bar{A}$ is totally bounded. By the fact that (M, d) is complete, $\bar{A}$ is complete; thus $\bar{A}$ is sequentially compact. □

Problem 4. 1. Show the so-called "***Finite Intersection Property***":

> Let (M, d) be a metric space, and K be a subset of M. Then K is compact if and only if for any family of closed subsets $\{F_\alpha\}_{\alpha \in I}$, we have
>
> $$K \cap \bigcap_{\alpha \in I} F_\alpha \neq \varnothing$$
>
> whenever $K \cap \bigcap_{\alpha \in J} F_\alpha \neq \varnothing$ for all $J \subseteq I$ satisfying $\#J < \infty$.

2. Show the so-called "***Nested Set Properpty***":

> Let (M, d) be a metric space, and $\{K_n\}_{n=1}^{\infty}$ be a sequence of non-empty compact sets in M such that $K_j \supseteq K_{j+1}$ for all $j \in \mathbb{N}$. Then there exists at least one point in $\bigcap_{j=1}^{\infty} K_j$; that is,
>
> $$\bigcap_{j=1}^{\infty} K_j \neq \varnothing .$$

Proof. 1. $(\Rightarrow)$ Let K be a compact set, and $\{F_\alpha\}_{\alpha \in I}$ be a collection of closed set such that

$$K \cap \bigcap_{\alpha \in J} F_\alpha \neq \varnothing \qquad \forall\, J \subseteq I\, , \#J < \infty .$$

Suppose the contrary that $K \cap \bigcap_{\alpha\in I} F_\alpha = \varnothing$. Then

$$K \subseteq \Big(\bigcap_{\alpha\in I} F_\alpha\Big)^{\complement} = \bigcup_{\alpha\in I} F_\alpha^{\complement}.$$

This, together with the fact that $F_\alpha^{\complement}$ is open for all $\alpha \in I$, implies that $\{F_\alpha^{\complement}\}_{\alpha\in I}$ is an open cover of K. By the compactness of K, there exists $J \subseteq I$ with $\#J < \infty$ such that $K \subseteq \bigcup\limits_{\alpha\in J} F_\alpha^{\complement}$. Therefore,

$$K \cap \bigcap_{\alpha\in J} F_\alpha = K \cap \Big(\bigcup_{\alpha\in J} F_\alpha\Big)^{\complement} = \varnothing,$$

a contradiction.

($\Leftarrow$) Let $\{U_\alpha\}_{\alpha\in I}$ be an open cover of K. Define $F_\alpha = U_\alpha^{\complement}$. Then $\{F_\alpha\}_{\alpha\in I}$ is a family of closed set satisfying that

$$K \cap \bigcap_{\alpha\in I} F_\alpha = K \cap \bigcap_{\alpha\in I} U_\alpha^{\complement} = K \cap \Big(\bigcup_{\alpha\in I} U_\alpha\Big)^{\complement} = \varnothing.$$

By assumption, there must be $J \subseteq I$ with $\#J < \infty$ such that

$$K \cap \bigcap_{\alpha\in J} F_\alpha = \varnothing.$$

By the fact that $\bigcap\limits_{\alpha\in J} F_\alpha = \Big(\bigcup\limits_{\alpha\in J} U_\alpha\Big)^{\complement}$, we conclude that $K \subseteq \bigcup_{\alpha\in J} U_\alpha$; thus we conclude that every open cover of K has a finite subcover. Therefore, K is compact.

2. Let $K = K_1$, and $F_j = K_j$ for all $j \in \mathbb{N}$. Then for any finite subset J of $\mathbb{N}$,

$$K \cap \bigcap_{j\in J} F_j = K_{\max J} \neq \varnothing;$$

thus 1 implies that $K \cap \bigcap\limits_{j\in\mathbb{N}} F_j \neq \varnothing$. □

Problem 5. 1. Let $\{x_k\}_{k=1}^{\infty} \subseteq \mathbb{R}$ be a sequence in $(\mathbb{R}, |\cdot|)$ that converges to x and let $A_k = \{x_k, x_{k+1}, \cdots\}$. Show that $\{x\} = \bigcap\limits_{k=1}^{\infty} \bar{A}_k$. Is this true in any metric space?

2. Suppose that $\{K_j\}_{j=1}^{\infty}$ is a sequence of non-empty compact sets satisfying the nested set property (that is, $K_j \supseteq K_{j+1}$), and $\operatorname{diam}(K_j) \to 0$ as $j \to \infty$, where

$$\operatorname{diam}(K_j) = \sup\big\{d(x,y) \,\big|\, x, y \in K_j\big\}.$$

Show that there is exactly one point in $\bigcap\limits_{j=1}^{\infty} K_j$.

Proof. 1. By 2, it suffices to show that $\bar{A}_k$ is non-empty compact set for all $k \in \mathbb{N}$ and $\{\bar{A}_k\}_{k=1}^{\infty}$ is a nested set satisfying $\operatorname{diam}(\bar{A}_k) \to 0$ as $k \to \infty$. Note that in class we have shown that the set $\{0\} \cup \big\{1, \frac{1}{2}, \frac{1}{3}, \cdots, \frac{1}{n} \cdots\big\}$ is compact, and similar proof shows that $A_k \cup \{x\}$ is compact; thus $\bar{A}_k = A_k \cup \{x\}$. Therefore, $\{\bar{A}_k\}_{k=1}^{\infty}$ is a nested set.

Let $\varepsilon > 0$ be given. Since $\{x_k\}_{k=1}^{\infty}$ converges to x, there exists $N > 0$ such that $d(x_k, x) < \dfrac{\varepsilon}{3}$ whenever $k \geqslant N$. Then

$$d(y,z) < \frac{2\varepsilon}{3} \qquad \forall\, y,z \in A_N\,;$$

thus for $j \geqslant N$,

$$\operatorname{diam}(K_j) \leqslant \frac{2\varepsilon}{3} < \varepsilon$$

which implies that $\operatorname{diam}(K_j) \to 0$ as $j \to \infty$.

2. First, by the nested set property, $\bigcap\limits_{j=1}^{\infty} K_j \neq \varnothing$. Assume that $x, y \in \bigcap\limits_{j=1}^{\infty} K_j$. Then $x, y \in K_j$ for all $j \in \mathbb{N}$; thus

$$0 \leqslant d(x,y) \leqslant \operatorname{diam}(K_j) \qquad \forall\, j \in \mathbb{N}\,.$$

By the assumption that $\operatorname{diam}(K_j) \to 0$ as $j \to \infty$, we conclude that $d(x,y) = 0$; thus by the property of the metric, $x = y$. □

Problem 6. Let ℓ^2 be the collection of all sequences $\{x_k\}_{k=1}^{\infty} \subseteq \mathbb{R}$ such that $\sum\limits_{k=1}^{\infty} |x_k|^2 < \infty$. In other words,

$$\ell^2 = \Big\{ \{x_k\}_{k=1}^{\infty} \,\Big|\, x_k \in \mathbb{R} \text{ for all } k \in \mathbb{N},\ \sum_{k=1}^{\infty} |x_k|^2 < \infty \Big\}\,.$$

Define $\|\cdot\|_2 : \ell^2 \to \mathbb{R}$ by

$$\big\|\{x_k\}_{k=1}^{\infty}\big\|_2 = \Big(\sum_{k=1}^{\infty} |x_k|^2 \Big)^{\frac{1}{2}}\,.$$

1. Show that $\|\cdot\|_2$ is a norm on ℓ^2. The normed space $(\ell^2, \|\cdot\|)$ usually is denoted by ℓ^2.

2. Show that $\|\cdot\|_2$ is induced by an inner product.

3. Show that $(\ell^2, \|\cdot\|_2)$ is complete.

4. Let $A = \big\{ \boldsymbol{x} \in \ell^2 \,\big|\, \|\boldsymbol{x}\|_2 \leqslant 1 \big\}$. Is A sequentially compact or not?

Problem 7. Let A, B be two non-empty subsets in $\mathbb{R}^n$. Define

$$d(A,B) = \inf\big\{ \|x - y\|_2 \,\big|\, x \in A, y \in B \big\}$$

to be the distance between A and B. When $A = \{x\}$ is a point, we write $d(A,B)$ as $d(x,B)$.

(1) Prove that $d(A,B) = \inf\big\{ d(x,B) \,\big|\, x \in A \big\}$.

(2) Show that $\big|d(x_1,B) - d(x_2,B)\big| \leqslant \|x_1 - x_2\|_2$ for all $x_1, x_2 \in \mathbb{R}^n$.

(3) Define $B_\varepsilon = \big\{ x \in \mathbb{R}^n \,\big|\, d(x,B) < \varepsilon \big\}$ be the collection of all points whose distance from B is less than ε. Show that B_ε is open and $\bigcap\limits_{\varepsilon > 0} B_\varepsilon = \operatorname{cl}(B)$.

(4) If A is sequentially compact, show that there exists $x \in A$ such that $d(A,B) = d(x,B)$.

(5) If A is closed and B is sequentially compact, show that there exists $x \in A$ and $y \in B$ such that $d(A, B) = d(x, y)$.

(6) If A and B are both closed, does the conclusion of (5) hold?

Proof. The proof of (1)-(4) does not rely on the structure of $(\mathbb{R}^n, \|\cdot\|_2)$, so in the proofs of (1)-(4) we write $d(\boldsymbol{x}, \boldsymbol{y})$ instead of $\|\boldsymbol{x} - \boldsymbol{y}\|$.

(1) Define $f : A \times B \to \mathbb{R}$ by $f(\boldsymbol{a}, \boldsymbol{b}) = d(\boldsymbol{a}, \boldsymbol{b})$. We note that similar proof for Problem 4 of Exercise 2 also shows that if $f : A \times B \to \mathbb{R}$, then

$$\inf_{(\boldsymbol{a},\boldsymbol{b}) \in A \times B} f(\boldsymbol{a}, \boldsymbol{b}) = \inf_{\boldsymbol{a} \in A} \Big(\inf_{\boldsymbol{b} \in B} f(\boldsymbol{a}, \boldsymbol{b}) \Big) = \inf_{\boldsymbol{b} \in B} \Big(\inf_{\boldsymbol{a} \in A} f(\boldsymbol{a}, \boldsymbol{b}) \Big).$$

Since $\inf\limits_{\boldsymbol{b} \in B} f(\boldsymbol{a}, \boldsymbol{b}) = d(\boldsymbol{a}, B)$, we conclude that

$$d(A, B) = \inf_{(\boldsymbol{a},\boldsymbol{b}) \in A \times B} f(\boldsymbol{a}, \boldsymbol{b}) = \inf_{\boldsymbol{a} \in A} d(\boldsymbol{a}, B).$$

(2) Let $\boldsymbol{x}, \boldsymbol{y} \in \mathbb{R}^n$ and $\varepsilon > 0$ be given. By the definition of infimum, there exists $\boldsymbol{z} \in B$ such that

$$d(\boldsymbol{x}, B) \leqslant d(\boldsymbol{x}, \boldsymbol{z}) < d(\boldsymbol{x}, B) + \varepsilon.$$

By the definition of $d(\boldsymbol{y}, B)$ and the triangle inequality,

$$d(\boldsymbol{y}, B) \leqslant d(\boldsymbol{y}, \boldsymbol{z}) \leqslant d(\boldsymbol{y}, \boldsymbol{x}) + d(\boldsymbol{x}, \boldsymbol{z}) < d(\boldsymbol{x}, \boldsymbol{y}) + d(\boldsymbol{x}, B) + \varepsilon;$$

thus

$$d(\boldsymbol{y}, B) - d(\boldsymbol{x}, B) < d(\boldsymbol{x}, \boldsymbol{y}) + \varepsilon.$$

A symmetric argument (switching $\boldsymbol{x}$ and $\boldsymbol{y}$) also shows that $d(\boldsymbol{x}, B) - d(\boldsymbol{y}, B) < d(\boldsymbol{x}, \boldsymbol{y}) + \varepsilon$. Therefore,

$$\big| d(\boldsymbol{x}, B) - d(\boldsymbol{y}, B) \big| < d(\boldsymbol{x}, \boldsymbol{y}) + \varepsilon.$$

Since $\varepsilon > 0$ is given arbitrarily, we conclude that

$$\big| d(\boldsymbol{x}, B) - d(\boldsymbol{y}, B) \big| \leqslant d(\boldsymbol{x}, \boldsymbol{y}).$$

(3) Let $\boldsymbol{x} \in B_\varepsilon$. Define $r = \varepsilon - d(\boldsymbol{x}, B)$. Then $r > 0$; thus there exists $\boldsymbol{z} \in B$ such that

$$d(\boldsymbol{x}, B) \leqslant d(\boldsymbol{x}, \boldsymbol{z}) < d(\boldsymbol{x}, B) + \frac{r}{2} = \varepsilon.$$

Therefore, if $\boldsymbol{y} \in B\big(\boldsymbol{x}, \frac{r}{2}\big)$, then

$$d(\boldsymbol{y}, \boldsymbol{z}) \leqslant d(\boldsymbol{y}, \boldsymbol{x}) + d(\boldsymbol{x}, \boldsymbol{z}) < \frac{r}{2} + d(\boldsymbol{x}, B) + \frac{r}{2} = d(\boldsymbol{x}, B) + r = \varepsilon$$

which shows that $B\big(\boldsymbol{x}, \frac{r}{2}\big) \subseteq B_\varepsilon$. Therefore, B_ε is open.

Next, we note that

$$d(\boldsymbol{x}, B) = 0 \quad \Leftrightarrow \quad (\forall\, \varepsilon > 0)(d(\boldsymbol{x}, B) < \varepsilon) \quad \Leftrightarrow \quad (\forall\, \varepsilon > 0)(\boldsymbol{x} \in B_\varepsilon) \quad \Leftrightarrow \quad \boldsymbol{x} \in \bigcap_{\varepsilon > 0} B_\varepsilon;$$

thus $\boldsymbol{x} \in \bigcap\limits_{\varepsilon > 0} B_\varepsilon$ if and only if $d(\boldsymbol{x}, B) = 0$. Since $\boldsymbol{x} \in \bar{B}$ if and only if $d(\boldsymbol{x}, B) = 0$, we conclude that $\bigcap\limits_{\varepsilon > 0} B_\varepsilon = \bar{B}$.

(4) By the definition of infimum, for each $n \in \mathbb{N}$ there exists $\boldsymbol{a}_n \in A$ such that

$$d(A, B) \leqslant d(\boldsymbol{a}_n, B) < d(A, B) + \frac{1}{n}.$$

Since A is compact, there exists a convergent subsequence $\{\boldsymbol{a}_{n_j}\}_{j=1}^{\infty}$ of $\{\boldsymbol{a}_n\}_{n=1}^{\infty}$ with limit $\boldsymbol{a} \in A$. By the Sandwich Lemma,

$$d(\boldsymbol{a}_{n_j}, B) \to d(A, B) \quad \text{as} \quad j \to \infty.$$

On the other hand, (2) implies that

$$\big|d(\boldsymbol{a}_{n_j}, B) - d(\boldsymbol{a}, B)\big| \leqslant d(\boldsymbol{a}_{n_j}, \boldsymbol{a}) \to 0 \quad \text{as} \quad j \to \infty.$$

Therefore,

$$\big|d(\boldsymbol{a}, B) - d(A, B)\big| \leqslant \big|d(\boldsymbol{a}, B) - d(\boldsymbol{a}_{n_j}, B)\big| + \big|d(\boldsymbol{a}_{n_j}, B) - d(A, B)\big| \to 0 \quad \text{as} \quad j \to \infty$$

which establishes the existence of $\boldsymbol{a} \in A$ such that $d(\boldsymbol{a}, B) = d(A, B)$ if A is compact.

(5) By (4), there exists $\boldsymbol{b} \in B$ such that $d(A, B) = d(\boldsymbol{b}, A)$. Let $C = B[\boldsymbol{b}, d(A, B) + 1] \cap A$. Then

$$d(\boldsymbol{b}, A) = d(\boldsymbol{b}, C)$$

since every point $\boldsymbol{x} \in A \backslash C$ satisfies that $d(\boldsymbol{b}, \boldsymbol{x}) > d(A, B) + 1$. On the other hand, the Heine-Borel Theorem implies that C is compact; thus (4) implies that there exists $\boldsymbol{c} \in C$ such that $d(\boldsymbol{b}, C) = d(\boldsymbol{b}, \boldsymbol{c}) = \|\boldsymbol{b} - \boldsymbol{c}\|$. The desired result then follows from the fact that C is a subset of A (so that $\boldsymbol{c} \in A$).

(6) Let $A = \big\{(x, y) \in \mathbb{R}^2 \,\big|\, xy \geqslant 1, x > 0\big\}$ and $B = \big\{(x, y) \in \mathbb{R}^2 \,\big|\, xy \leqslant -1, x < 0\big\}$. Then A and B are closed set since they contain their boundaries. However, since $\boldsymbol{a} = \big(\frac{1}{n}, n\big) \in A$ and $\boldsymbol{b} = \big(-\frac{1}{n}, n\big) \in B$ for all $n \in \mathbb{N}$, $d(A, B) \leqslant d(\boldsymbol{a}, \boldsymbol{b}) = \frac{2}{n}$ for all $n \in \mathbb{N}$ which shows that $d(A, B) = 0$. However, the fact that $A \cap B = \varnothing$ implies that $d(\boldsymbol{a}, \boldsymbol{b}) > 0$ for all $\boldsymbol{a} \in A$ and $\boldsymbol{b} \in B$. Therefore, in this case there are not $\boldsymbol{a} \in A$ and $\boldsymbol{b} \in B$ such that $d(A, B) = d(\boldsymbol{a}, \boldsymbol{b})$. □

Problem 8. Let (M, d) be a metric space, and $A \subseteq M$. Show that A is disconnected (not connected) if and only if there exist non-empty closed set F_1 and F_2 such that

1. $A \cap F_1 \cap F_2 = \varnothing$; 2. $A \cap F_1 \neq \varnothing$; 3. $A \cap F_2 \neq \varnothing$; 4. $A \subseteq F_1 \cup F_2$.

Proof. By definition, A is disconnected if (and only if) there exist non-empty open set U_1 and U_2 such that

(a) $A \cap U_1 \cap U_2 = \varnothing$, (b) $A \cap U_1 \neq \varnothing$, (c) $A \cap U_2 \neq \varnothing$, (d) $A \subseteq U_1 \cup U_2$.

Therefore, A is disconnected if and only if there exist non-empty closed set $F_1 \equiv U_1^{\complement}$ and $F_2 \equiv U_2^{\complement}$ such that

(i) $A \cap F_1^{\complement} \cap F_2^{\complement} = \varnothing$, (ii) $A \cap F_1^{\complement} \neq \varnothing$, (iii) $A \cap F_2^{\complement} \neq \varnothing$, (iv) $A \subseteq F_1^{\complement} \cup F_2^{\complement}$.

Note that (i) above is equivalent to that $A \subseteq F_1 \cup F_2$, while (iv) above is equivalent to that $A \cap F_1 \cap F_2 = \varnothing$. Moreover, note that if A, B, C are sets satisfying $A \cap B \cap C = \varnothing$, $A \cap B \neq \varnothing$ and $A \cap C \neq \varnothing$, then

$$\varnothing \neq A \cap B \subseteq A \cap C^{\complement} \quad \text{and} \quad \varnothing \neq A \cap C \subseteq A \cap B^{\complement}.$$

Therefore, (a), (b) and (c) above imply 2 and 3 above, while (i) together with 2 and 3 above implies that (b) and (c); thus we establish that A is disconnected if and only if there exist non-empty closed sets F_1 and F_2 such that

1. $A \cap F_1 \cap F_2 = \varnothing$; 2. $A \cap F_1 \neq \varnothing$; 3. $A \cap F_2 \neq \varnothing$; 4. $A \subseteq F_1 \cup F_2$. □

Problem 9. Prove that if A is connected in a metric space (M, d) and $A \subseteq B \subseteq \bar{A}$, then B is connected.

Proof. Suppose the contrary that B is disconnected. Then Problem 8 implies that there exist two closed set F_1 and F_2 such that

1. $B \cap F_1 \cap F_2 = \varnothing$; 2. $B \cap F_1 \neq \varnothing$; 3. $B \cap F_2 \neq \varnothing$; 4. $B \subseteq F_1 \cup F_2$.

Define $A_1 = F_1 \cap A$ and $A_2 = F_2 \cap A$. Then $A = A_1 \cup A_2$. If $A_1 = \varnothing$, then $A_2 = A$ which, together with 3 of Problem 8 in Exercise 6, implies that

$$B \subseteq \bar{A} = \bar{A}_2 \subseteq \bar{A} \cap \bar{F}_2 = \bar{A} \cap F_2$$

which implies that $B = B \cap F_2$. The fact that $B \cap F_1 \cap F_2 = \varnothing$ then implies that $B \cap F_1 \subseteq (B \cap F_2)^{\complement} = B^{\complement}$; thus $B \cap F_1 = \varnothing$, a contradiction. Therefore, $A_1 \neq \varnothing$. Similarly, $A_2 \neq \varnothing$. However, 3 of Problem 8 in Exercise 6 implies that

$$A_1 \cap \bar{A}_2 = A_1 \cap \text{cl}(F_2 \cap A) \subseteq A_1 \cap \bar{F}_2 \cap \bar{A} = A_1 \cap F_2 \subseteq B \cap F_1 \cap F_2 = \varnothing$$

and

$$A_2 \cap \bar{A}_1 = A_2 \cap \text{cl}(F_1 \cap A) \subseteq A_2 \cap \bar{F}_1 \cap \bar{A} = A_2 \cap F_1 \subseteq B \cap F_2 \cap F_1 = \varnothing,$$

a contradiction to the assumption that A is connected. □

Problem 10. Let (M, d) be a metric space, and $A \subseteq M$ be a subset. Suppose that A is connected and contain more than one point. Show that $A \subseteq A'$, where A' is the collection of accumulation points of A defined in Exercise 6.

Proof. Suppose the contrary that there exists $x \in A \backslash A'$. Since $A \backslash A'$ is the collection of isolated point of A, there exists $r > 0$ such that $B(x, r) \cap A = \{x\}$. Let $U = B(x, r)$ and $V = B\big[x, \frac{r}{2}\big]^{\complement}$. Then

1. $A \cap U \cap V = \varnothing$.

2. $A \cap U = \{x\} \neq \varnothing$.

3. $A \cap V \supseteq A\backslash\{x\} \neq \varnothing$ since A contains more than one point.

4. $A \subseteq M = U \cup V$.

Therefore, A is disconnected, a contradiction. ▫

Problem 11. Let (M, d) be a metric space. A subset A of M is said to be totally disconnected if for all $x, y \in A$ and $x \neq y$, there exist opens sets U and V separating A as well as $x \in U$ and $y \in V$. Show that the Cantor set C defined in Problem 9 of Exercise 7 is totally disconnected.

Proof. It suffices to show that for every $x, y \in C$, $x < y$, there exists $z \in C^{\complement}$ and $x < z < y$. Note that there exists $N > 0$ such that $|x - y| < \dfrac{1}{3^n}$ for all $n \geqslant N$. If $C = \bigcap_{n=1}^{\infty} E_n$, where E_n is given is Problem 9 of Exercise 7. Then the length of each interval in E_n has length $\dfrac{1}{3^n}$; thus if $n \geqslant N$, the interval $[x, y]$ is not contained in any interval of E_n. In other words, there must be $z \in (x, y)$ such that $z \in E_n^{\complement}$. Since $E_n^{\complement} \subseteq C^{\complement}$, we establish the existence of $x < z < y$ such that $z \in C^{\complement}$. ▫

Problem 12. Let F_k be a nest of connected compact sets (that is, $F_{k+1} \subseteq F_k$ and F_k is connected for all $k \in \mathbb{N}$). Show that $\bigcap_{k=1}^{\infty} F_k$ is connected. Give an example to show that compactness is an essential condition and we cannot just assume that F_k is a nest of closed connected sets.

Proof. Let $K = \bigcap_{k=1}^{\infty} F_k$. Then the nested set property implies that $K \neq \varnothing$. Suppose the contrary that there exist open sets U and V such that

1. $K \cap U \cap V = \varnothing$, 2. $K \cap U \neq \varnothing$, 3. $K \cap V \neq \varnothing$, 4. $K \subseteq U \cup V$.

Define $K_1 = K \cap U^{\complement}$ and $K_2 = K \cap V^{\complement}$. Then K_1, K_2 are non-empty closed sets (**Check!!!**) of K such that

$$K = K_1 \cup K_2 \quad \text{and} \quad K_1 \cap K_2 = \varnothing\,.$$

In other words, K is the disjoint union of two compact subsets K_1 and K_2. By (5) of Problem 7, there exists $x_1 \in K_1$ and $x_2 \in K_2$ such that $d(x_1, x_2) = d(K_1, K_2)$. Since $K_1 \cap K_2 = \varnothing$, $\varepsilon_0 \equiv d(x_1, x_2) > 0$; thus the definition of the distance of sets implies that

$$\varepsilon_0 \leqslant d(x, y) \qquad \forall\, x \in K_1, y \in K_2\,.$$

Define $O_1 = \bigcup_{x \in K_1} B\big(x, \frac{\varepsilon_0}{3}\big)$ and $O_2 = \bigcup_{y \in K_2} B\big(y, \frac{\varepsilon_0}{3}\big)$. Note that

$$K_1 \subseteq O_1\,, \quad K_2 \subseteq O_2 \quad \text{and} \quad O_1 \cap O_2 = \varnothing\,.$$

Claim: There exists $n \in \mathbb{N}$ such that $F_n \subseteq O_1 \cup O_2$.

Proof. Suppose the contrary that for each $n_0 \in \mathbb{N}$, $F_{n_0} \nsubseteq O_1 \cup O_2$. Then

$$F_n \cap O_1^{\complement} \cap O_2^{\complement} = F_n \cap (O_1 \cup O_2)^{\complement} \neq \varnothing \qquad \forall\, n \in \mathbb{N}\,.$$

Since O_1 and O_2 are open, $F_n \cap O_1^\complement \cap O_2^\complement$ is a nest of non-empty compact sets; thus the nested set property shows that

$$K \cap O_1^\complement \cap O_2^\complement = \bigcap_{n=1}^{\infty} (F_n \cap O_1^\complement \cap O_2^\complement) \neq \varnothing\,;$$

thus $K \nsubseteq O_1 \cup O_2$, a contradiction. □

Having established the claim, by the fact that $K_1 \subseteq F_{n_0} \cap O_1$ and $K_2 \subseteq F_{n_0} \cap O_2$, we find that

$$F_{n_0} \cap O_1 \neq \varnothing \qquad \text{and} \qquad F_{n_0} \cap O_2 \neq \varnothing\,.$$

Together with the fact that $F_{n_0} \cap O_1 \cap O_2 = \varnothing$ and $F_{n_0} \subseteq O_1 \cup O_2$, we conclude that F_{n_0} is disconnected, a contradiction.

The compactness of F_n is crucial to obtain the result or we will have counter-examples. For example, let $F_k = \mathbb{R}^2 \backslash (-k,k) \times (-1,1)$. Then clearly F_k is closed but not bounded (hence F_k is not compact). Moreover, $F_k \supseteq F_{k+1}$ for all $k \in \mathbb{N}$; thus $\{F_k\}_{k=1}^{\infty}$ is a nest of sets. However, $\bigcap\limits_{k=1}^{\infty} F_k = \mathbb{R}^2 \backslash \mathbb{R} \times (-1,1)$ which is disconnected and is the union of two disjoint closed set $\mathbb{R} \times [1,\infty)$ and $\mathbb{R} \times (-\infty,-1]$. Therefore, if $\{F_k\}_{k=1}^{\infty}$ is a nest of closed connected sets, it is possible that $\bigcap\limits_{k=1}^{\infty} F_k$ is disconnected. □

Problem 13. Let $\{A_k\}_{k=1}^{\infty}$ be a family of connected subsets of M, and suppose that A is a connected subset of M such that $A_k \cap A \neq \varnothing$ for all $k \in \mathbb{N}$. Show that the union $\big(\bigcup\limits_{k \in \mathbb{N}} A_k\big) \cup A$ is also connected.

Proof. By the induction argument, it suffices to show that if A and B are connected sets and $A \cap B \neq \varnothing$, then $A \cup B$ is connected. Suppose the contrary that there exist open sets U and V such that

1. $(A \cup B) \cap U \cap V = \varnothing\,,$
2. $(A \cup B) \cap U \neq \varnothing\,,$
3. $(A \cup B) \cap V \neq \varnothing\,,$
4. $(A \cup B) \subseteq U \cup V.$

Note that 1 and 4 implies that $A \cap U \cap V = \varnothing$ and $A \subseteq U \cup V$; thus by the connectedness of A, either $A \cap U = \varnothing$ or $A \cap V = \varnothing$. W.L.O.G., we assume that $A \cap U = \varnothing$ so that $A \subseteq V$. Then 1 implies that $B \cap U \cap V = \varnothing$, 2 implies that $B \cap U \neq \varnothing$, and 4 implies that $B \subseteq U \cup V$. Next we show that $B \cap V \neq \varnothing$ to reach a contradiction (to that B is connected). Suppose the contrary that $B \cap V = \varnothing$. Then 3 implies that $A \cap B \subseteq A = A \cap V \neq \varnothing$ so that $B \cap V \supseteq A \cap B \neq \varnothing$, a contradiction.

For an alternative proof, see the proof of 1 of Problem 15. □

Problem 14. Let $A, B \subseteq M$ and A is connected. Suppose that $A \cap B \neq \varnothing$ and $A \cap B^\complement \neq \varnothing$. Show that $A \cap \partial B \neq \varnothing$.

Proof. Suppose the contrary that $A \cap \partial B = \varnothing$. Let $U = \text{int}(B)$ and $V = \text{int}(B^{\complement})$. If $\mathring{B} = \varnothing$, then $\partial B = \bar{B} \supseteq B$; thus the assumption that $A \cap B \neq \varnothing$ implies that $A \cap \partial B \neq \varnothing$. Similarly, if $\text{int}(B^{\complement}) = \varnothing$, then $A \cap \partial B \neq \varnothing$.

Now suppose that U and V are non-empty open sets. If $x \notin U \cup V$, then $x \in \partial B$; thus $(U \cup V)^{\complement} \subseteq \partial B$ and the assumption that $A \cap \partial B = \varnothing$ further implies that $A \subseteq U \cup V$. Moreover, $U \cap V = \varnothing$; thus $A \cap U \cap V = \varnothing$. Now we prove that $A \cap U \neq \varnothing$ and $A \cap V \neq \varnothing$ to reach a contradiction.

Suppose the contrary that $A \cap U = \varnothing$. Then $A \cap B \subseteq A \cap \bar{B} = A \cap (U \cup \partial B) = \varnothing$, a contradiction. Therefore, $A \cap U = \varnothing$. Similarly, if $A \cap V = \varnothing$, $A \cap B^{\complement} \subseteq A \cap \overline{B^{\complement}} = A \cap (V \cup \partial B^{\complement}) = A \cap (V \cup \partial B) = \varnothing$, a contradiction. □

Problem 15. Let (M, d) be a metric space and A be a non-empty subset of M. A maximal connected subset of A is called a ***connected component*** of A.

1. Let $a \in A$. Show that there is a unique connected components of A containing a.
2. Show that any two distinct connected components of A are disjoint. Therefore, A is the disjoint union of its connected components.
3. Show that every connected component of A is a closed subset of A.
4. If A is open, prove that every connected component of A is also open. Therefore, when $M = \mathbb{R}^n$, show that A has at most countable infinite connected components.
5. Find the connected components of the set of rational numbers or the set of irrational numbers in $\mathbb{R}$.

Proof. 1. Let $\mathscr{F}$ be the family $\mathscr{F} = \{C \subseteq A \,|\, x \in C \text{ and } C \text{ is connected}\}$. We note that $\mathscr{F}$ is not empty since $\{x\} \in \mathscr{F}$. Let $B = \bigcup_{C \in \mathscr{F}} C$. It then suffices to show that B is connected (since if so, then it is the maximal connected subset of A containing x).

Claim: A subset $A \subseteq M$ is connected if and only if every continuous function defined on A whose range is a subset of $\{0, 1\}$ is constant.

Proof. "$\Rightarrow$" Assume that A is connected and $f : A \to \{0, 1\}$ is a continuous function, and $\delta = 1/2$. Suppose the contrary that $f^{-1}(\{0\}) \neq \varnothing$ and $f^{-1}(\{1\}) \neq \varnothing$. Then $A = f^{-1}((-\delta, \delta))$ and $B = f^{-1}((1-\delta, 1+\delta))$ are non-empty set. Moreover, the continuity of f implies that A and B are open relative to A; thus there exist open sets U and V such that

$$f^{-1}((-\delta, \delta)) = U \cap A \qquad \text{and} \qquad f^{-1}((1-\delta, 1+\delta)) = V \cap A\,.$$

Then

(1) $A \cap U \cap V = f^{-1}((-\delta, \delta)) \cap f^{-1}((1-\delta, 1+\delta)) = \varnothing\,,$

(2) $A \cap U \neq \varnothing$ and $A \cap V \neq \varnothing\,,$

(3) $A \subseteq U \cup V$ since the range of f is a subset of $\{0, 1\}\,;$

thus A is disconnect, a contradiction.

"$\Leftarrow$" Suppose the contrary that A is disconnected so that there exist open sets U and V such that

(1) $A \cap U \cap V = \varnothing$, (2) $A \cap U \neq \varnothing$, (3) $A \cap V \neq \varnothing$, (4) $A \subseteq U \cup V$.

Let $f : A \to \mathbb{R}$ be defined by

$$f(x) = \begin{cases} 0 & \text{if } x \in A \cap U\,, \\ 1 & \text{if } x \in A \cap V\,. \end{cases}$$

We first prove that f is continuous on A. Let $a \in A$. Then $a \in A \cap U$ or $a \in A \cap V$. Suppose that $a \in A \cap U$. In particular $a \in U$; thus the openness of U provides $r > 0$ such that $B(a, r) \subseteq U$. Note that if $x \in B(a, r) \cap A$, then $x \in A \subseteq U$; thus

$$\big|f(x) - f(a)\big| = 0 \qquad \forall\, x \in B(a, r) \cap A$$

which shows the continuity of f at a. Similar argument can be applied to show that f is continuous at $a \in A \cap V$. □

Now let $f : B \to \{0, 1\}$ be a continuous function. Let $y \in B$. Then $y \in C$ for some $C \in \mathscr{F}$. Since C is a connected set, $f : C \to \{0, 1\}$ is a constant; thus by the fact that $x \in C$, we must have $f(x) = f(y)$. Therefore, $f(y) = f(x)$ for all $y \in B$; thus $f : B \to \{0, 1\}$ is a constant. The claim then shows that B is connected.

2. By Problem 13, the union of two overlapping connected sets is connected; thus distinct connected components of A are disjoint.

3. Let C be a connected component of A.

Claim: $\bar{C} \cap A$ is connected.

Proof. Suppose the contrary that there exist open sets U and V such that

(1) $\bar{C} \cap A \cap U \cap V = \varnothing$, (2) $\bar{C} \cap A \cap U \neq \varnothing$, (3) $\bar{C} \cap A \cap V \neq \varnothing$, (4) $\bar{C} \cap A \subseteq U \cup V$.

Note that (1) and (4) implies that $C \cap U \cap V = \varnothing$ and $C \subseteq U \cup V$ since $C \subseteq \bar{C} \cap A$. If $C \cap U = \varnothing$, then $C \subseteq U^{\complement}$; thus the closedness of $U^{\complement}$ implies that $\bar{C} \subseteq U^{\complement}$ which shows that $\bar{C} \cap A \cap U = \varnothing$, a contradiction. Therefore, $C \cap U \neq \varnothing$. Similarly, $C \cap V \neq \varnothing$, so we establish that C is disconnected, a contradiction. □

Having established that $\bar{C} \cap A$ is connected, we immediately conclude that $C = \bar{C} \cap A$ since $C \subseteq \bar{C} \cap A$ and C is the largest connected component of A containing points in C.

4. Suppose that A is open and C is a connected component of A. Let $x \in C$. Then $x \in A$; thus there exists $r > 0$ such that $B(x, r) \subseteq A$. Note that $B(x, r)$ is a connected set and $B(x, r) \cap C \supseteq \{x\} \neq \varnothing$. Therefore, Problem 13 implies that $B(x, r) \cup C$ is a connected subset of A containing x. Since C is the largest connected subset of A containing x, we must have $B(x, r) \cup C = C$; thus $B(x, r) \subseteq C$.

   If $M = \mathbb{R}^n$, then each connected component contains a point whose components are all rational. Since $\mathbb{Q}^n$ is countable, we find that an open set in $\mathbb{R}^n$ has countable connected components.

5. In $(\mathbb{R}, |\cdot|)$ every connected set is an interval or a set of a single point. Since $\mathbb{Q}$ and $\mathbb{Q}^\complement$ do not contain any intervals, the connected component of $\mathbb{Q}$ and $\mathbb{Q}^\complement$ are points. $\square$