

Chapter 2: 5.4, 5.5, 6.4

Chapter 3: 1.7, 2.3, 2.4, 2.6, 2.8, 2.11, 2.12, 2.16, 2.20

Exercise 5.4. Let a and b be real numbers. Show that the following three equalities hold:

$$\bigcap_{x>b} (a, x) = (a, b], \quad \bigcup_{n=1}^{\infty} [a + \frac{1}{n}, b - \frac{1}{n}) = (a, b), \quad \bigcap_{n=1}^{\infty} (a + n, +\infty) = \emptyset.$$

1. $\bigcap_{x>b} (a, x) = \{y \in \mathbb{R} : y \in (a, x) \forall x > b\}$. \mathbb{R} has a least upper bound so call this bound, d so $y \leq d \forall y \in \bigcap_{x>b} (a, x)$. Assume $d < b$, then $a < y \leq d < b < x \exists p \in \bigcap_{x>b} (a, x)$ s.t. $a < b < p < x$. So, d is not the least upper bound. So, $b \leq d$ and $a < y \leq b \leq d \forall \bigcap_{x>b} (a, x)$. $\bigcap_{x>b} (a, x) = \{y \in \mathbb{R} : a < y \leq b\} = (a, b]$.
2. $\bigcup_{n=1}^{\infty} [a + \frac{1}{n-1}, b - \frac{1}{n-1}) \cup [a + \frac{1}{n}, b - \frac{1}{n}) = \{y \in \mathbb{R} : a + \frac{1}{n} \leq y \leq b - \frac{1}{n}\} = B$.
 - $a - \frac{1}{2}$ is a lower bound since $\nexists y \in B$ s.t. $y < a + \frac{1}{n}$. Assume \exists a lower bound called β s.t. $\beta > a + \frac{1}{n}$. If so then, $B = \{a + \frac{1}{n} < y < b - \frac{1}{n}\}$. But, $\exists y \in B$ s.t. $y = a + \frac{1}{n}$. So, \nexists any β so $\inf B = a + \frac{1}{n}$ and $a < a + \frac{1}{n} = \inf B$.
 - $b - \frac{1}{n}$ is an upper bound since $\nexists y \in B$ s.t. $y > b - \frac{1}{n}$. Assume \exists some upper bound α s.t. $\alpha < b - \frac{1}{n}$. So, $b - \frac{1}{n} - \alpha > 0$. Choose $\gamma \in \mathbb{N}$ so $\frac{1}{\gamma} < b - \frac{1}{n} - \alpha$. $(b - \frac{1}{n} - \frac{1}{\gamma}) > b - \frac{1}{n} - (b - \frac{1}{n} - \alpha)$. So, α is not an upper bound. So, $\sup B = b - \frac{1}{n} < b$.

Thus, $B = \{a < \inf B \leq y < \sup B < b \forall y \in B\} = (a, b)$.

3. Let's do proof by contradiction. Assume $\bigcap_{n=1}^{\infty} (a + n, +\infty) = X$ s.t. $X = \{\beta\}, \beta \in \mathbb{R}, \beta < a + n$. Enumerate $\bigcap_{n=1}^{\infty} (a + n, +\infty) = (a + 1, \infty) \cap (a + 2, \infty) \cap \dots \cap (a + n, \infty) \cap \dots$. Take a look at set, $(a + n, \infty) = \{x \in \mathbb{R} : a + n < x < \infty\} = B$. Clearly $a + n$ is a lower bound for B since $a + n < x \forall x \in B$. Assume that k is a lower bound s.t. $k > a + n$. So, $B = \{x \in \mathbb{R} : a + n < k < x < \infty\}$. So, $k - a - n > 0$. Choose ϕ so $\phi > k - a - n$. $a + n + \phi > a + n + k - a - n$. So, k is not a lower bound. So, $\inf B = a + n \rightarrow \beta < a + n = \inf B$. $\beta \notin B$ so $\beta \notin \bigcap_{n=1}^{\infty} (a + n, +\infty)$. This establishes a contradiction so $\bigcap_{n=1}^{\infty} (a + n, +\infty) = \emptyset$. ■

Exercise 5.5. Let a_1, a_2, \dots be any enumeration of the negative rational numbers; let b_1, b_2, \dots be any enumeration of the positive rational numbers. Show that the following two equalities hold:

$$\bigcap_{j=1}^{\infty} (a_j, b_j) = \{0\}, \quad \bigcup_{j=1}^{\infty} (a_j, b_j) = \mathbb{R}.$$

1. Let's analyze one set of this general intersection, (a_n, b_n) and call it A . $\sup A$ exists by the least upper bound property since $A \subset \mathbb{R}$ is bounded above and nonempty by least upper bound property. Similar argument for existence of $\inf A$ but it is bounded below. Let us prove what $\sup A, \inf A$ are supposed to be.

- a_n is a lower bound $\rightarrow x \notin A$ s.t. $x < a_n \forall x \in A$. Assume that l is a lower bound s.t. $l > a_n$. So, $A = \{x \in \mathbb{R} : a_n < x < b_n\}$. So, $l - a_n > 0$. Choose $\alpha \in \mathbb{N}$ so $\alpha > l - a_n$. $\alpha + a_n > a_n + l - a_n$. Thus, l is not a lower bound. So, $\inf A = a_n$.
- b_n is an upper bound $\rightarrow x \notin A$ s.t. $x > b_n \forall x \in A$. Assume that u is an upper bound s.t. $u < b_n$. So, $A = \{x \in \mathbb{R} : a_n < x < u < b_n\}$. So, $u - b_n > 0$. Choose $n \in \mathbb{N}$ so $u - b_n > \frac{1}{n}$. So, $b_n - \frac{1}{n} > u$. Thus, u is not an upper bound. So, $\sup A = b_n$.

Since $a_n \in -\mathbb{Q}$ and $b_n \in +\mathbb{Q} \forall n \in \mathbb{N}, 0 \in (a_n, b_n) \forall n$ so $\bigcap_{j=1}^{\infty} (a_n, b_n) = \{0\}$.

2. Let's analyze one set of this general union, (a_n, b_n) and call it A . $\sup A$ exists by the least upper bound property since $A \subset \mathbb{R}$ is bounded above and nonempty by least upper bound property. Similar argument for existence of $\inf A$ but it is bounded below. Let us prove what $\sup A, \inf A$ are supposed to be.

- a_n is a lower bound $\rightarrow x \notin A$ s.t. $x < a_n \forall x \in A$. Assume that l is a lower bound s.t. $l > a_n$. So, $A = \{x \in \mathbb{R} : a_n < x < b_n\}$. So, $l - a_n > 0$. Choose $\alpha \in \mathbb{N}$ so $\alpha > l - a_n$. $\alpha + a_n > a_n + l - a_n$. Thus, l is not a lower bound. So, $\inf A = a_n$.
- b_n is an upper bound $\rightarrow x \notin A$ s.t. $x > b_n \forall x \in A$. Assume that u is an upper bound s.t. $u < b_n$. So, $A = \{x \in \mathbb{R} : a_n < x < u < b_n\}$. So, $u - b_n > 0$. Choose $n \in \mathbb{N}$ so $u - b_n > \frac{1}{n}$. So, $b_n - \frac{1}{n} > u$. Thus, u is not an upper bound. So, $\sup A = b_n$.

Assume that there is some $\beta \in \mathbb{R}$. If $\beta \notin A$, \exists some set in $\bigcup_{j=1}^{\infty} (a_j, b_j)$ s.t. $\beta \in \{a_n - \epsilon < x < b_n + \epsilon\}$ for any $\epsilon > 0$. So, if true for any β , $\bigcup_{j=1}^{\infty} (a_j, b_j) = \mathbb{R}$. ■

Exercise 6.4. Prove there exists no order \leq that makes $(\mathbb{C}, +, \cdot, \leq)$ into an ordered field.

Let us argue by contradiction. Assume that \mathbb{C} is an ordered field. Let us analyze the case $(0, 1) = i$.

- If $i > 0$, $x, y \in \mathbb{C}$ and $x = i, y = i, i \cdot i > 0 \implies -1 > 0$, which is a contradiction.
- If $i < 0$, $x, y \in \mathbb{C}$ and $x = -i, y = -i$ (since $x, y > 0$ for the second condition to hold), $-i \cdot -i < 0 \rightarrow i^2 > 0 \implies -1 > 0$, which is a contradiction. ■

Exercise 1.7. Let $\|\cdot\|$ be a norm on a real vector space V . Prove the *reverse triangle inequality*:

$$||x| - |y|| \leq \|x - y\|$$

$$\begin{aligned} \|x\| &= \|(x - y) + y\| \leq \|x - y\| + \|y\|. \quad ||x| - |y|| \leq ||(x - y) + \|y\| - \|y\|| = \\ &= ||(x - y)|| = \|x - y\|. \\ \|y\| &= \|(y - x) + x\| = \|y - x\| + \|x\|. \quad ||x| - |y|| \leq ||x| - (\|y - x\| + \|x\|)| \leq \|x - y\|. \end{aligned}$$

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Exercise 2.3. Let X be any set. Prove that the discrete metric $d : X \times X \rightarrow \mathbb{R}$ (defined by $d(x, y) = 1$ if $x \neq y$ and $d(x, x) = 0$ for $x \in X$) satisfies the triangle inequality and is therefore a metric on X .

Let's argue via proof by contrapositive. Assume $d(x, y) > d(x, z) + d(z, y) \forall x, y, z \in X$ so d is not a metric on X . Let $x \neq y$ and enumerate what values z can take on.

- If $z \neq y \neq x$, then $1 > 2$.
- If $z = x$ and $z \neq y$, vice versa, then $1 > 1$.
- If $z = y = x$, then $1 > 0$. However, this contradicts our initial assumption that $x \neq y$.

Clearly, all these pose contradictions, so it must be that d satisfies the triangle inequality and is a metric on X .

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Exercise 2.4. Determine which of the following functions are metrics on \mathbb{R} . Prove your answer in each case.

- $d_1(x, y) = \sqrt{|x - y|}$.
- $d_2(x, y) = |x - 2y|$.
- $d_3(x, y) = \frac{|x - y|}{1 + |x - y|}$.

1. For any $x, y \in \mathbb{R}$, $|x - y| \geq 0$ so $\sqrt{|x - y|} \geq 0$. $d_1(x, y) = \sqrt{|x - y|} = \sqrt{|(-1)y - x|} = \sqrt{|y - x|} = d_1(y, x)$. $\sqrt{|x - y|} \leq \sqrt{|x - z|} + \sqrt{|z - y|} \rightarrow |x - y| \leq |x - z| + c + |z - y|$ where $c \leq 0$. So, $-(|x - z| + c + |z - y|) \leq x - y \leq |x - z| + c + |z - y| \rightarrow -c \leq 0 \leq c$. So d_1 is a metric on \mathbb{R} .
2. Assume $d_2(x, y) = d_2(y, x) \rightarrow |x - 2y| = |y - 2x| \forall x, y \in \mathbb{R}$. Choose $x = 0$ and $y = 1$ so $d_2(x, y) = 1 = d_2(y, x) = 2$. So, d_2 is clearly not a metric on \mathbb{R} .
3. For any $x, y \in \mathbb{R}$, $|x - y| \geq 0$ so $\frac{|x - y|}{1 + |x - y|} \geq 0$. $d_3(x, y) = \frac{|x - y|}{1 + |x - y|} = \frac{|(-1)y - x|}{1 + |(-1)y - x|} = \frac{|y - x|}{1 + |y - x|} = d_3(y, x)$. Assume $\frac{|x - y|}{1 + |x - y|} > \frac{|x - y|}{1 + |x - y|} + \frac{|x - y|}{1 + |x - y|}$. Choose $x, y = 5$ and $z = 0$. So, $0 > \frac{|5|}{6} + \frac{|5|}{6}$ and clearly this is a contradiction so d_3 follows triangle inequality. So, d_3 is a metric on \mathbb{R} .

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Exercise 2.6. Consider the function $d : \mathbb{R}^2 \times \mathbb{R}^2 \rightarrow \mathbb{R}$, defined by

$$d(x, y) = |x_1 - y_1| + |x_2 - y_2|, \quad (x = (x_1, x_2), y = (y_1, y_2)).$$

1. Prove that d is a metric on \mathbb{R}^2 .
2. On a sheet of graph paper, draw the set $B_d((5, 1), 3)$. Use dotted lines to indicate the boundary, which is not included in the set you are drawing. (Hint: it may be easier to figure out what the set looks like if you first consider $B_d((0, 0), 3)$.)
3. On the same graph as in the previous part, draw $B_{d_u}((-3, 2), 1)$, where d_u denotes the square metric.

For nonnegativity, analyze two cases where $x, y \in \mathbb{R}^2$.

1. Case 1: Let $(x_1, x_2) = (y_1, y_2)$. So, $d(x, y) = |x_1 - y_1| + |x_2 - y_2| = |x_1 - x_1| + |x_2 - x_2| = 0$.
2. Case 2: Let $x \neq y \forall x, y \in \mathbb{R}^2$. Claim that $d(x, y) < 0$ so d is not a metric. $d(x, y) = |x_1 - y_1| + |x_2 - y_2| < 0$. $|x_1 - y_1| < -|x_2 - y_2|$. Choose $x = (0, 0)$ and $y = (1, 2)$. So, $|0 - 1| < -|0 - 2| \rightarrow 1 < -2$. Clearly, this is false so $d(x, y) \geq 0$.

For symmetry, $d(x, y) = |x_1 - y_1| + |x_2 - y_2| = |(-1)y_1 - x_1| + |(-1)y_2 - x_2| = |y_1 - x_1| + |y_2 - x_2| = d(y, x)$.

For triangle inequality, assume that $d(x, y) > d(x, z) + d(z, y) \rightarrow |x_1 - y_1| + |x_2 - y_2| > |x_1 - z_1| + |x_2 - z_2| + |z_1 - y_1| + |z_2 - y_2|$.

- $x_1 - y_1 + x_2 - y_2 > x_1 - z_1 + x_2 - z_2 + z_1 - y_1 + z_2 - y_2 \rightarrow 0 > 0$.
- $x_1 - y_1 + x_2 - y_2 < -1(x_1 - z_1 + x_2 - z_2 + z_1 - y_1 + z_2 - y_2) \rightarrow 0 < > 0$.

Both these cases don't hold so d holds for triangle inequality and is a metric. ■

Exercise 2.8. Let (X, d) be a metric space, and let E be a subset of X . The *diameter* of E in (X, d) is defined by the formula

$$\text{diam}_d(E) = \sup\{d(x, y) : x, y \in E\}.$$

1. Prove that for any $r > 0$ and $x \in X$, we have $\text{diam}(B(x, r)) \leq 2r$.
2. If X is any set and d is the discrete metric, show $\text{diam}(B(x, r)) = 0$ for any $r \leq 1$, while $\text{diam}(B(x, r)) = 1$ for any $r > 1$.
3. If $X = \mathbb{R}^n$ for some $n \in \mathbb{N}$ and d is the Euclidean metric, prove that $\text{diam}(B(x, r)) = 2r$.

Exercise 2.11. As in Example 2.7, let $X = \mathbb{R}^2$, $Y = [-1, 3] \times [2, 4]$, and let d denote the Euclidean metric on $X = \mathbb{R}^2$. Let $p = (3, 4)$ and let $q = (2, 4)$. Arguing *directly from the definition of an interior point* (i.e., without using Exercise 2.12), show that q is an interior point of $B_Y(p, 2)$ with respect to Y , but q is not an interior point of $B_Y(p, 2)$ with respect to X . In addition, draw a picture on a piece of graph paper that illustrates the idea of your proof.

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Exercise 2.12. Let (X, d) be a metric space, and let Y be a subset of X . Prove that for any subset U of Y , we have

$$(*) \operatorname{Int}_X(U) = \operatorname{Int}_Y(U) \cap \operatorname{Int}_X(Y).$$

In the notation of Exercise 2.11, the equality $(*)$ gives an alternate explanation of why q is not an interior point of $B_Y(p, 2)$ with respect to X : It is because $q \notin \operatorname{Int}_X(Y)$, as can be seen from the picture you drew in that Exercise.

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Exercise 2.16. Let (X, d) be a metric space, and let U be a subset of X . Use Proposition 2.15 to prove that $\operatorname{Int}_X(U)$ is open in X .

■

Exercise 2.20. Let (X, d) be a metric space. Assume that $U \subset Y \subset X$, and additionally that Y is open in X . Prove that U is open in Y if and only if U is open in X . (Note: There are at least two possible solutions; one uses Theorem 2.19, the other uses Exercise 2.12.)

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