

Propositions of solutions for *Analysis II* by Terence Tao

Frédéric Santos

March 29, 2022

Contents

12 Metric spaces

2

Remarks. The numbering of the Exercises follows the fourth edition of *Analysis II*. In order to make the references to *Analysis I* easier, we consider that we begin with Chapter 12 here, as in earlier editions of the textbook. Thus, in particular, a reference to “Exercise 4.3.3” (for instance) will always mean “Exercise 4.3.3 from *Analysis I*”.

12. Metric spaces

EXERCISE 12.1.1. — *Prove Lemma 12.1.1*

Consider the sequence $(a_n)_{n=m}^{\infty}$ defined by $a_n := d(x_n, x) = |x_n - x|$ for all $n \geq m$. We have to prove that $\lim_{n \rightarrow \infty} a_n = 0$ if and only if $\lim_{n \rightarrow \infty} x_n = x$.

- Let be $\varepsilon > 0$. If $\lim_{n \rightarrow \infty} a_n = 0$, then there exists an $N \geq m$ such that $|a_n| < \varepsilon$ whenever $n \geq N$. Thus, there exists an $N \geq m$ such that $|x_n - x| < \varepsilon$ whenever $n \geq N$, which means that $\lim_{n \rightarrow \infty} x_n = x$.
- Let be $\varepsilon > 0$. Conversely, if $\lim_{n \rightarrow \infty} x_n = x$, then there exists an $N \geq m$ such that $|x_n - x| < \varepsilon$ whenever $n \geq N$. But since $|a_n| := |x_n - x|$, it means that $\lim_{n \rightarrow \infty} a_n = 0$, as expected.

EXERCISE 12.1.2. — *Show that the real line with the metric $d(x, y) := |x - y|$ is indeed a metric space.*

Using Proposition 4.3.3, this claim is obvious. All claims (a)–(d) of Definition 12.1.2 are satisfied because:

- (a) comes from Proposition 4.3.3(e)
- (b) also comes from Proposition 4.3.3(e)
- (c) comes from Proposition 4.3.3(f)
- (d) comes from Proposition 4.3.3(g).

EXERCISE 12.1.3. — *Let X be a set, and let $d : X \times X \rightarrow [0, \infty)$ be a function. With respect to Definition 12.1.2, give an example of a pair (X, d) which...*

- (a) obeys the axioms (bcd) but not (a).

Consider $X = \mathbb{R}$, and d defined by $d(x, x) = 1$ and $d(x, y) = 5$ for all $x \neq y \in \mathbb{R}$.

- (b) obeys the axioms (acd) but not (b).

Consider $X = \mathbb{R}$, and d defined by $d(x, y) = 0$ for all $x, y \in \mathbb{R}$.

- (c) obeys the axioms (abd) but not (c).

Consider $X = \mathbb{R}$, and d defined by $d(x, y) = \max(x - y, 0)$ for all $x, y \in \mathbb{R}$.

- (d) obeys the axioms (abc) but not (d).

Consider the finite set $X := \{1, 2, 3\}$ and the application d defined by $d(1, 2) = d(2, 1) = d(2, 3) = d(3, 2) := 1$, and $d(1, 3) = d(3, 1) := 5$, and $d(x, x) = 0$ for all $x \in X$.

EXERCISE 12.1.4. — *Show that the pair $(Y, d|_{Y \times Y})$ defined in Example 12.1.5 is indeed a metric space.*

By definition, since $Y \subseteq X$, we have $x, y \in X$ whenever $x, y \in Y$. And furthermore, since $d|_{Y \times Y}(x, y) := d(x, y)$, then the application $d|_{Y \times Y}$ obeys all four statements (a)–(d) of Definition 12.1.2. Thus, $(Y, d|_{Y \times Y})$ is indeed a metric space.

EXERCISE 12.1.5. — Let $n \geq 1$, and let a_1, a_2, \dots, a_n and b_1, b_2, \dots, b_n be real numbers. Verify the identity $(\sum_{i=1}^n a_i b_i)^2 + \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n (a_i b_j - a_j b_i)^2 = \sum_{i=1}^n a_i^2 \sum_{j=1}^n b_j^2$, and conclude the Cauchy-Schwarz inequality. Then use the Cauchy-Schwarz inequality to prove the triangle inequality.

Let's prove these three statements.

(i) To prove the first identity, let's use induction on n .

The base case $n = 1$ is obvious: on the left-hand side, we just get $(a_1 b_1)^2$, and on the right-hand side, we get $a_1^2 b_1^2$, hence the statement.

Now let's suppose inductively that this identity is true for a given positive integer $n \geq 1$, and let's prove that it is still true for $n + 1$. We have to prove that

$$\underbrace{\left(\sum_{i=1}^{n+1} a_i b_i \right)^2}_{:=A} + \underbrace{\frac{1}{2} \sum_{i=1}^{n+1} \sum_{j=1}^{n+1} (a_i b_j - a_j b_i)^2}_{:=B} = \underbrace{\left(\sum_{i=1}^{n+1} a_i^2 \right) \left(\sum_{j=1}^{n+1} b_j^2 \right)}_{:=C} \quad (12.1)$$

where we gave a name to each part of the identity for an easier computation below. Indeed,

- for A , we have

$$\begin{aligned} A &:= \left(\sum_{i=1}^{n+1} a_i b_i \right)^2 \\ &= \left(a_{n+1} b_{n+1} + \sum_{i=1}^n a_i b_i \right)^2 \\ &= (a_{n+1} b_{n+1})^2 + \left(\sum_{i=1}^n a_i b_i \right)^2 + 2(a_{n+1} b_{n+1}) \sum_{i=1}^n a_i b_i \end{aligned}$$

- for B , we have

$$\begin{aligned} B &:= \frac{1}{2} \sum_{i=1}^{n+1} \sum_{j=1}^{n+1} (a_i b_j - a_j b_i)^2 \\ &= \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^{n+1} (a_i b_j - a_j b_i)^2 + \frac{1}{2} \sum_{j=1}^{n+1} (a_{n+1} b_j - a_j b_{n+1})^2 \\ &= \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n (a_i b_j - a_j b_i)^2 + \underbrace{\frac{1}{2} \sum_{i=1}^n (a_i b_{n+1} - a_{n+1} b_i)^2}_{:=1/2 \times S} + \underbrace{\frac{1}{2} \sum_{j=1}^n (a_{n+1} b_j - a_j b_{n+1})^2}_{:=1/2 \times S} \\ &\quad + \underbrace{\frac{1}{2} (a_{n+1} b_{n+1} - b_{n+1} a_{n+1})^2}_{=0} \\ &= \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n (a_i b_j - a_j b_i)^2 + \sum_{k=1}^n (a_k b_{n+1} - a_{n+1} b_k)^2 \end{aligned}$$

- and thus, for $A + B$, we now use the induction hypothesis (IH) to get:

$$\begin{aligned}
A + B &:= (a_{n+1}b_{n+1})^2 + \left(\sum_{i=1}^n a_i b_i \right)^2 + 2(a_{n+1}b_{n+1}) \sum_{i=1}^n a_i b_i \\
&\quad + \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n (a_i b_j - a_j b_i)^2 + \sum_{k=1}^n (a_k b_{n+1} - a_{n+1} b_k)^2 \\
&= \underbrace{\left(\sum_{i=1}^n a_i b_i \right)^2 + \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n (a_i b_j - a_j b_i)^2}_{\text{apply (IH) here}} \\
&\quad + (a_{n+1}b_{n+1})^2 + 2(a_{n+1}b_{n+1}) \sum_{i=1}^n a_i b_i + \sum_{k=1}^n (a_k b_{n+1} - a_{n+1} b_k)^2 \\
&= \left(\sum_{i=1}^n a_i^2 \right) \left(\sum_{j=1}^n b_j^2 \right) \\
&\quad + (a_{n+1}b_{n+1})^2 + 2(a_{n+1}b_{n+1}) \sum_{i=1}^n a_i b_i + \sum_{k=1}^n (a_k b_{n+1} - a_{n+1} b_k)^2 \\
&= \left(\sum_{i=1}^n a_i^2 \right) \left(\sum_{j=1}^n b_j^2 \right) + (a_{n+1}b_{n+1})^2 \\
&\quad + 2 \sum_{i=1}^n a_i a_{n+1} b_i b_{n+1} + \sum_{i=1}^n (a_i^2 b_{n+1}^2 - 2a_i b_{n+1} a_{n+1} b_i + a_{n+1}^2 b_i^2) \\
&= \left(\sum_{i=1}^n a_i^2 \right) \left(\sum_{j=1}^n b_j^2 \right) + \sum_{i=1}^n (a_i^2 b_{n+1}^2 + a_{n+1}^2 b_i^2) \\
&= \left(\sum_{i=1}^{n+1} a_i^2 \right) \left(\sum_{j=1}^{n+1} b_j^2 \right) \\
&= C
\end{aligned}$$

so that the identity is indeed true for all natural number n .

- (ii) We can use this identity to prove the Cauchy-Schwarz identity,

$$\left| \sum_{i=1}^n a_i b_i \right| \leq \left(\sum_{i=1}^n a_i^2 \right)^{1/2} \left(\sum_{i=1}^n b_i^2 \right)^{1/2}. \quad (12.2)$$

Indeed, since $B \geq 0$ in the identity (12.1), we have

$$\left(\sum_{i=1}^n a_i b_i \right)^2 \leq \left(\sum_{i=1}^n a_i^2 \right) \left(\sum_{j=1}^n b_j^2 \right)$$

and thus, taking the square root on both sides, we get (12.2), as expected.

(iii) Finally, we can use the Cauchy-Schwarz inequality to prove the triangle inequality.

We have

$$\begin{aligned}
\sum_{i=1}^n (a_i^2 + b_i^2) &= \sum_{i=1}^n a_i^2 + \sum_{i=1}^n b_i^2 + 2 \sum_{i=1}^n a_i b_i \\
&\leq \sum_{i=1}^n a_i^2 + \sum_{i=1}^n b_i^2 + 2 \left(\sum_{i=1}^n a_i^2 \right)^{1/2} \left(\sum_{i=1}^n b_i^2 \right)^{1/2} \quad (\text{by eq. (12.2)}) \\
&\leq \left(\left(\sum_{i=1}^n a_i^2 \right)^{1/2} + \left(\sum_{i=1}^n b_i^2 \right)^{1/2} \right)^2
\end{aligned}$$

and, since everything is positive, we get the triangle inequality by taking square roots on both sides.

EXERCISE 12.1.6. — *Show that (\mathbb{R}^n, d_{l^2}) in Example 12.1.6 is indeed a metric space.*

We have to show the four axioms of Definition 12.1.2.

- (a) For all $x \in \mathbb{R}^n$, we have $d_{l^2}(x, x) = \sqrt{\sum_{i=1}^n (x_i - x_i)^2} = 0$, as expected.
- (b) Positivity: for all $x \neq y \in \mathbb{R}^n$, there exists at least one $1 \leq i \leq n$ such that $x_i \neq y_i$, so that $(x_i - y_i)^2 > 0$, and $d_{l^2}(x, y) = \sqrt{\sum_{i=1}^n (x_i - y_i)^2} > 0$, as expected.
- (c) Symmetry: for all $x, y \in \mathbb{R}^n$, we have

$$d_{l^2}(y, x) = \sqrt{\sum_{i=1}^n (y_i - x_i)^2} = \sqrt{\sum_{i=1}^n (x_i - y_i)^2} = d_{l^2}(x, y)$$

as expected.

- (d) Triangle inequality: for all $x, y, z \in \mathbb{R}^n$, we have

$$\begin{aligned}
d_{l^2}(x, z) &:= \left(\sum_{i=1}^n (x_i - z_i)^2 \right)^{1/2} \\
&= \left(\sum_{i=1}^n (a_i + b_i)^2 \right)^{1/2} \quad \text{with } a_i := x_i - y_i \text{ and } b_i := y_i - z_i \\
&\leq \left(\sum_{i=1}^n a_i^2 \right)^{1/2} + \left(\sum_{i=1}^n b_i^2 \right)^{1/2} \quad (\text{Exercise 12.1.5(iii)}) \\
&\leq \left(\sum_{i=1}^n (x_i - y_i)^2 \right)^{1/2} + \left(\sum_{i=1}^n (y_i - z_i)^2 \right)^{1/2} \\
&\leq d_{l^2}(x, y) + d_{l^2}(y, z)
\end{aligned}$$

as expected.

Thus, (\mathbb{R}^n, d_{l^2}) is indeed a metric space.

EXERCISE 12.1.7. — *Show that (\mathbb{R}^n, d_{l^1}) in Example 12.1.7 is indeed a metric space.*

Once again, let's show the four axioms of Definition 12.1.2.

- (a) For all $x \in \mathbb{R}^n$, we have $d_{l^1}(x, x) = \sum_{i=1}^n |x_i - x_i| = 0$, as expected.
- (b) Positivity: for all $x \neq y \in \mathbb{R}^n$, there exists at least one $1 \leq i \leq n$ such that $x_i \neq y_i$, so that $|x_i - y_i| > 0$, and $d_{l^1}(x, y) = \sum_{i=1}^n |x_i - y_i| > 0$, as expected.
- (c) Symmetry: for all $x, y \in \mathbb{R}^n$, we have

$$d_{l^1}(y, x) = \sum_{i=1}^n |y_i - x_i| = \sum_{i=1}^n |x_i - y_i| = d_{l^1}(x, y)$$

as expected.

- (d) Triangle inequality: we already know from Proposition 4.3.3(g) (generalized to real numbers) that we have the triangle inequality $|a - c| \leq |a - b| + |b - c|$ for all $a, b, c \in \mathbb{R}$. Thus, for all $x, y, z \in \mathbb{R}^n$, we have

$$d_{l^1}(x, z) := \sum_{i=1}^n |x_i - z_i| \leq \sum_{i=1}^n (|x_i - y_i| + |y_i - z_i|) =: d_{l^1}(x, y) + d_{l^1}(y, z)$$

as expected.

Thus, (\mathbb{R}^n, d_{l^1}) is indeed a metric space.

EXERCISE 12.1.8. — *Prove the two inequalities in equation (12.1).*

We have to prove that for all $x, y \in \mathbb{R}^n$, we have

$$d_{l^2}(x, y) \leq d_{l^1}(x, y) \leq \sqrt{n} d_{l^2}(x, y) \tag{12.3}$$

- The first inequality, since everything is non-negative, is equivalent to $d_{l^2}(x, y)^2 \leq d_{l^1}(x, y)^2$, and we will prove it in this form.

Indeed, using a trivial product expansion, we have

$$\begin{aligned} d_{l^1}(x, y)^2 &:= \left(\sum_{i=1}^n |x_i - y_i| \right)^2 \\ &= \left(\sum_{i=1}^n |x_i - y_i| \right) \times \left(\sum_{i=1}^n |x_i - y_i| \right) \\ &= \sum_{i=1}^n |x_i - y_i|^2 + \overbrace{\sum_{1 \leq i, j \leq n; i \neq j} |x_i - y_i| \times |x_j - y_j|}^{\geq 0} \\ &\geq \sum_{i=1}^n |x_i - y_i|^2 =: d_{l^2}(x, y)^2 \end{aligned}$$

as expected.

- For the second inequality, we use the Cauchy-Schwarz inequality, which says that

$$\begin{aligned}
d_{l^1}(x, y) &:= \sum_{i=1}^n |x_i - y_i| \\
&= \left| \sum_{i=1}^n |x_i - y_i| \times 1 \right| \\
&\leq \left(\sum_{i=1}^n |x_i - y_i|^2 \right)^{1/2} \left(\sum_{i=1}^n 1^2 \right)^{1/2} \\
&\leq d_{l^2}(x, y) \times \sqrt{n}
\end{aligned}$$

as expected.

EXERCISE 12.1.9. — *Show that the pair $(\mathbb{R}^n, d_{l^\infty})$ in Example 12.1.9 is a metric space.*

Once again, let's show the four axioms of Definition 12.1.2.

- (a) For all $x \in \mathbb{R}^n$, we clearly have $d_{l^\infty}(x, x) = \sup\{|x_i - x_i| : 1 \leq i \leq n\} = 0$, as expected.
- (b) Positivity: for all $x \neq y \in \mathbb{R}^n$, there exists at least one $1 \leq j \leq n$ such that $x_j \neq y_j$. Thus $|x_j - y_j| > 0$, and $d_{l^\infty}(x, y) = \sup\{|x_i - y_i| : 1 \leq i \leq n\} \geq |x_j - y_j| > 0$, as expected.
- (c) Symmetry: for all $x, y \in \mathbb{R}^n$, we have

$$d_{l^\infty}(x, y) = \sup\{|x_i - y_i| : 1 \leq i \leq n\} = \sup\{|y_i - x_i| : 1 \leq i \leq n\} = d_{l^\infty}(y, x)$$

as expected.

- (d) Triangle inequality. Let be $x, y, z \in \mathbb{R}^n$. We have $|x_i - z_i| \leq |x_i - y_i| + |y_i - z_i|$ for all $1 \leq i \leq n$, by Proposition 4.3.3(g). But, by definition of the supremum, we have $|x_i - y_i| \leq d_{l^\infty}(x, y)$ and $|y_i - z_i| \leq d_{l^\infty}(y, z)$ for all $1 \leq i \leq n$. Thus, we have $|x_i - z_i| \leq d_{l^\infty}(x, y) + d_{l^\infty}(y, z)$ for all $1 \leq i \leq n$; i.e., $d_{l^\infty}(x, y) + d_{l^\infty}(y, z)$ is an upper bound of the set $\{|x_i - z_i| : 1 \leq i \leq n\}$. By definition of the supremum, it implies that

$$d_{l^\infty}(x, z) := \sup\{|x_i - z_i| : 1 \leq i \leq n\} \leq d_{l^\infty}(x, y) + d_{l^\infty}(y, z)$$

as expected.

Thus, (\mathbb{R}^n, d_{l^1}) is indeed a metric space.

EXERCISE 12.1.10. — *Prove the two inequalities in equation (12.2).*

We have to prove that for all $x, y \in \mathbb{R}^n$,

$$\frac{1}{\sqrt{n}} d_{l^2}(x, y) \leq d_{l^\infty}(x, y) \leq d_{l^2}(x, y).$$

First, a preliminary remark. By definition, we have $d_{l^\infty}(x, y) := \sup\{|x_i - y_i| : 1 \leq i \leq n\}$ for all $x, y \in \mathbb{R}^n$. Since this distance is defined as the supremum of a finite set, we know (see Chapter 8 of *Analysis I*) that there exists a $1 \leq m \leq n$ such that $d_{l^\infty}(x, y) = |x_m - y_m|$ (the supremum belongs to the set). The index “ m ” will have this meaning below.

- Let's prove the first inequality.

$$\begin{aligned}
\frac{1}{\sqrt{n}}d_{l^2}(x, y) &:= \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - y_i)^2} \\
&\leq \sqrt{\frac{1}{n} \sum_{i=1}^n (x_m - y_m)^2} \\
&\leq \sqrt{\frac{n}{n} (x_m - y_m)^2} \\
&= |x_m - y_m| =: d_{l^\infty}(x, y)
\end{aligned}$$

as expected.

- Now we prove the second one. We have

$$\begin{aligned}
d_{l^2}(x, y) &:= \sqrt{\sum_{i=1}^n (x_i - y_i)^2} \\
&= \sqrt{(x_m - y_m)^2 + \sum_{1 \leq i \leq n; i \neq m} (x_i - y_i)^2} \\
&\geq \sqrt{(x_m - y_m)^2} = |x_m - y_m| =: d_{l^\infty}(x, y)
\end{aligned}$$

as expected.

EXERCISE 12.1.11. — *Show that the discrete metric (X, d_{disc}) in Example 12.1.11 is indeed a metric space.*

Once again, let's show the four axioms of Definition 12.1.2.

- (a) For all $x \in X$, we have $d_{\text{disc}}(x, x) := 0$ by definition, so that there is nothing to prove here.
- (b) Positivity: for all $x \neq y \in X$, we have $d_{\text{disc}}(x, y) := 1 > 0$ by definition, so that there's still nothing to prove.
- (c) Symmetry: for all $x, y \in X$, we have $d_{\text{disc}}(x, y) = d_{\text{disc}}(y, x) = 1$, so that d_{disc} obeys the symmetry property.
- (d) Triangle inequality. Let be $x, y, z \in X$, and let's consider $d_{\text{disc}}(x, z)$.
 - If $x = z$, then $d_{\text{disc}}(x, z) = 0$. And since d_{disc} is a non-negative application, we clearly have $0 =: d_{\text{disc}}(x, z) \leq d_{\text{disc}}(x, y) + d_{\text{disc}}(y, z)$ for all $y \in X$.
 - If $x \neq z$, then we cannot have both $x = y$ and $y = z$ (it would be a clear contradiction with $x \neq z$). Thus, at least one of the propositions " $x \neq y$ ", " $y \neq z$ " is true. Another way to say that is $d_{\text{disc}}(x, y) + d_{\text{disc}}(y, z) \geq 1$. But since $d_{\text{disc}}(x, z) := 1$, we have actually $d_{\text{disc}}(x, y) + d_{\text{disc}}(y, z) \geq d_{\text{disc}}(x, z)$, as expected.