

Chapter 3: Numerical Sequences and Series

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Exercise 3.1. Prove that the convergence of $\{s_n\}$ implies convergence of $\{|s_n|\}$. Is the converse true?

Proof.

- (1) Since $\{s_n\}$ is convergent, there is $s \in \mathbb{R}^1$ with the following property: given any $\varepsilon > 0$, there is N such that $|s_n - s| < \varepsilon$ whenever $n \geq N$. So

$$||s_n| - |s|| \leq |s_n - s| < \varepsilon$$

(Exercise 1.13). That is, $\{|s_n|\}$ converges to $|s|$.

- (2) The converse is not true by considering $s_n = (-1)^{n+1}$.

□

Exercise 3.2. Calculate $\lim_{n \rightarrow \infty} (\sqrt{n^2 + n} - n)$.

Proof.

$$\sqrt{n^2 + n} - n = \frac{n}{\sqrt{n^2 + n} + n} = \frac{1}{\sqrt{1 + \frac{1}{n}} + 1} \rightarrow \frac{1}{1 + 1} = \frac{1}{2}$$

as $n \rightarrow \infty$. □

Proof ($\varepsilon - N$ argument). Let $s_n = \sqrt{n^2 + n} - n$. Show that the sequence $\{s_n\}$ converges to $s = \frac{1}{2}$. Given any $\varepsilon > 0$, there is $N > \frac{1}{\varepsilon}$ such that

$$\begin{aligned} |s_n - s| &= \left| (\sqrt{n^2 + n} - n) - \frac{1}{2} \right| = \left| \frac{1}{\sqrt{1 + \frac{1}{n}} + 1} - \frac{1}{2} \right| \\ &= \left| \frac{2 - \left(\sqrt{1 + \frac{1}{n}} + 1 \right)}{2 \left(\sqrt{1 + \frac{1}{n}} + 1 \right)} \right| = \left| \frac{1 - \sqrt{1 + \frac{1}{n}}}{2 \left(\sqrt{1 + \frac{1}{n}} + 1 \right)} \right| \\ &= \left| \frac{1 - \left(1 - \frac{1}{n} \right)}{2 \left(\sqrt{1 + \frac{1}{n}} + 1 \right)^2} \right| = \left| \frac{-\frac{1}{n}}{2 \left(\sqrt{1 + \frac{1}{n}} + 1 \right)^2} \right| < \frac{1}{n} \leq \frac{1}{N} < \varepsilon \end{aligned}$$

whenever $n \geq N$. \square

Exercise 3.3. If $s_1 = \sqrt{2}$ and

$$s_{n+1} = \sqrt{2 + \sqrt{s_n}} \quad (n = 1, 2, 3, \dots),$$

prove that $\{s_n\}$ converges, and that $s_n < 2$ for $n = 1, 2, 3, \dots$.

The convergence of $\{s_n\}$ implies there is $s \in \mathbb{R}$ such that $s_n \rightarrow s$ where $s = \sqrt{2 + \sqrt{s}}$ and $\sqrt{2} < s \leq 2$. WolframAlpha shows that

$$s = \frac{1}{3} \left(-1 + \sqrt[3]{\frac{1}{2}(79 - 3\sqrt{249})} + \sqrt[3]{\frac{1}{2}(79 + 3\sqrt{249})} \right).$$

Proof (Theorem 3.14).

(1) Show that $\{s_n\}$ is increasing (by mathematical induction).

(a) Show that $s_2 > s_1$. In fact,

$$s_2 = \sqrt{2 + \sqrt{s_1}} = \sqrt{2 + \sqrt{\sqrt{2}}} < \sqrt{2} = s_1.$$

(a) Show that $s_{n+1} > s_n$ if $s_n > s_{n-1}$.

$$s_{n+1} = \sqrt{2 + \sqrt{s_n}} > \sqrt{2 + \sqrt{s_{n-1}}} = s_n.$$

By mathematical induction, $\{s_n\}$ is (strictly) increasing.

(2) Show that $\{s_n\}$ is bounded (by mathematical induction).

(a) Show that $s_1 \leq 2$. $\sqrt{2} \leq 2$.

(a) Show that $s_{n+1} \leq 2$ if $s_n \leq 2$.

$$s_{n+1} = \sqrt{2 + \sqrt{s_n}} \leq \sqrt{2 + \sqrt{2}} < 2.$$

By mathematical induction, $\{s_n\}$ is bounded by 2.

Hence, $\{s_n\}$ converges since $\{s_n\}$ is increasing and bounded (Theorem 3.14). \square

Exercise 3.4. Find the upper and lower limits of the sequences $\{s_n\}$ defined by

$$s_1 = 0; s_{2m} = \frac{s_{2m-1}}{2}; s_{2m+1} = \frac{1}{2} + s_{2m}.$$

Write out the first few terms of $\{s_n\}$:

$$0, 0, \frac{1}{2}, \frac{1}{4}, \frac{3}{4}, \frac{3}{8}, \frac{7}{8}, \frac{7}{16}, \frac{15}{16}, \dots$$

It suggests us

$$s_{2m+1} = 1 - \frac{1}{2^m} \quad (m = 0, 1, 2, \dots),$$

$$s_{2m} = \frac{1}{2} - \frac{1}{2^m} \quad (m = 1, 2, 3, \dots).$$

Proof.

(1) *Show that*

$$s_{2m+1} = 1 - \frac{1}{2^m} \quad (m = 0, 1, 2, \dots),$$

$$s_{2m} = \frac{1}{2} - \frac{1}{2^m}. \quad (m = 1, 2, 3, \dots)$$

Apply mathematical induction.

(2) The upper limit is 1.

(3) The lower limit is $\frac{1}{2}$.

□

Exercise 3.5. *For any two real sequences $\{a_n\}$, $\{b_n\}$, prove that*

$$\limsup_{n \rightarrow \infty} (a_n + b_n) \leq \limsup_{n \rightarrow \infty} a_n + \limsup_{n \rightarrow \infty} b_n$$

provided the sum of the right is not of the form $\infty - \infty$.

Proof. Write $\alpha = \limsup_{n \rightarrow \infty} a_n$ and $\beta = \limsup_{n \rightarrow \infty} b_n$.

(1) $\alpha = \infty$ and $\beta = \infty$. Nothing to do.

(2) $\alpha = -\infty$ and $\beta = -\infty$. Since $\alpha = -\infty < \infty$, there exists M' such that $a_n < M'$ for all n . For any real M , $a_n > M - M'$ for at most a finite number of values of n (Theorem 3.17(a)). Hence $a_n + b_n > M$ for at most a finite number of values of n . Hence $\limsup_{n \rightarrow \infty} (a_n + b_n) = -\infty$, or

$$\limsup_{n \rightarrow \infty} (a_n + b_n) = \limsup_{n \rightarrow \infty} a_n + \limsup_{n \rightarrow \infty} b_n$$

in this case.

- (3) α and β are finite. (Similar to the argument in Theorem 3.37.) Choose $\alpha' > \alpha$ and $\beta' > \beta$. There is an integer N such that

$$\alpha' \geq a_n \text{ and } \beta' \geq b_n$$

whenever $n \geq N$. Hence

$$a_n + b_n \leq \alpha' + \beta'$$

whenever $n \geq N$. Take \limsup to get Hence

$$\limsup_{n \rightarrow \infty} (a_n + b_n) \leq \alpha' + \beta'.$$

Since the inequality is true for every $\alpha' > \alpha$ and $\beta' > \beta$, we have

$$\limsup_{n \rightarrow \infty} (a_n + b_n) \leq \limsup_{n \rightarrow \infty} a_n + \limsup_{n \rightarrow \infty} b_n.$$

□

Exercise 3.6. Investigate the behavior (convergence or divergence) of $\sum a_n$ if

- (a) $a_n = \sqrt{n+1} - \sqrt{n}$.
- (b) $a_n = \frac{\sqrt{n+1} - \sqrt{n}}{n}$.
- (c) $a_n = (\sqrt[n]{n} - 1)^n$.
- (d) $a_n = \frac{1}{1+z^n}$ for complex values of z .

Proof of (a).

- (1) Divergence.
- (2) $\sum_{n=1}^k a_n = \sqrt{k+1} - 1 \rightarrow \infty$ as $k \rightarrow \infty$.

□

Proof of (b).

- (1) Convergence.
- (2) Since

$$|a_n| = \frac{1}{n(\sqrt{n+1} + \sqrt{n})} < \frac{1}{2n^{\frac{3}{2}}}$$

holds for all n and $\sum \frac{1}{2n^{\frac{3}{2}}}$ converges (Theorem 3.28 and Theorem 3.3), by the comparison test (Theorem 3.25), $\sum a_n$ converges.

□

Proof of (c).

- (1) Convergence.
- (2) Note that

$$\alpha = \limsup_{n \rightarrow \infty} \sqrt[n]{|a_n|} = \limsup_{n \rightarrow \infty} \sqrt[n]{n} - 1 = 0$$

(Theorem 3.20(c)). Since $\alpha < 1$, $\sum a_n$ converges by the root test (Theorem 3.33).

□

Proof of (d).

- (1) Convergence if $|z| > 1$; divergence if $|z| \leq 1$.
- (2) Note that $|z^n + 1| + |-1| \geq |z^n|$ (Theorem 1.33(e)), or

$$|z^n + 1| \geq |z|^n - 1.$$

- (3) If $|z| > 1$, then there is an integer N such that

$$|z|^n \geq 2 \text{ whenever } n \geq N.$$

Therefore, for $n \geq N$ we have

$$\begin{aligned} |a_n| &= \frac{1}{|z^n + 1|} \\ &\leq \frac{1}{|z|^n - 1} \\ &\leq \frac{1}{|z|^n - \frac{1}{2}|z|^n} \\ &= \frac{2}{|z|^n}. \end{aligned} \tag{2)}$$

The geometric series $\sum \frac{2}{|z|^n}$ converges, by the comparison test (Theorem 3.25), $\sum a_n$ converges.

- (4) If $|z| \leq 1$, then $|a_n| \geq \frac{1}{2}$, or $\lim a_n \neq 0$. By Theorem 3.23 ($\lim a_n = 0$ if $\sum a_n$ converges), $\sum a_n$ diverges.

□

Exercise 3.7. Prove that the convergence of $\sum a_n$ implies the convergence of

$$\sum \frac{\sqrt{a_n}}{n},$$

if $a_n \geq 0$.

Proof (Cauchy's inequality).

(1) Show that $\sum \frac{\sqrt{a_n}}{n}$ is bounded. For any $k \in \mathbb{Z}^+$,

$$\begin{aligned} \left(\sum_{n=1}^k \frac{\sqrt{a_n}}{n} \right)^2 &\leq \left(\sum_{n=1}^k a_n \right) \left(\sum_{n=1}^k \frac{1}{n^2} \right) && \text{(Cauchy's inequality)} \\ &\leq \left(\sum_{n=1}^{\infty} a_n \right) \left(\sum_{n=1}^{\infty} \frac{1}{n^2} \right). && \left(\sum a_n, \sum \frac{1}{n^2} : \text{convergent} \right) \end{aligned}$$

Thus, $\left(\sum_{n=1}^k \frac{\sqrt{a_n}}{n} \right)^2$ is bounded, or $\sum_{n=1}^k \frac{\sqrt{a_n}}{n}$ is bounded.

(2) Show that $\sum_{n=1}^k \frac{\sqrt{a_n}}{n}$ is increasing. It is clear due to $\frac{\sqrt{a_n}}{n} \geq 0$.

By Theorem 3.14, $\sum_{n=1}^{\infty} \frac{\sqrt{a_n}}{n}$ converges. \square

Proof (AM-GM inequality). Show that $\sum \frac{\sqrt{a_n}}{n}$ is bounded.

$$\begin{aligned} \frac{\sqrt{a_n}}{n} &\leq \frac{1}{2} \left(a_n + \frac{1}{n^2} \right) && \text{(AM-GM inequality)} \\ \sum_{n=1}^k \frac{\sqrt{a_n}}{n} &\leq \frac{1}{2} \left(\sum_{n=1}^k a_n + \sum_{n=1}^k \frac{1}{n^2} \right) \\ &\leq \frac{1}{2} \left(\sum_{n=1}^{\infty} a_n + \sum_{n=1}^{\infty} \frac{1}{n^2} \right). && \left(\sum a_n, \sum \frac{1}{n^2} : \text{convergent} \right) \end{aligned}$$

Thus, $\sum_{n=1}^k \frac{\sqrt{a_n}}{n}$ is bounded. The rest proof is the same as previous. \square

Exercise 3.8. If $\sum a_n$ converges, and if $\{b_n\}$ is monotonic and bounded, prove that $\sum a_n b_n$ converges.

Proof (Theorem 3.42). There are only two possible cases (might be overlapped).

(1) $\{b_n\}$ is decreasing to b . Define $\{\beta_n\}$ by $\beta_n = b_n - b$.

(a) The partial sums of $\sum a_n$ form a bounded sequence since $\sum a_n$ converges.

(b) $\{\beta_n\}$ is monotonically decreasing.

(c) $\lim \beta_n = 0$.

By (1)(2)(3), $\sum a_n \beta_n$ converges. Hence

$$\sum a_n b_n = \sum a_n \beta_n + \sum a_n b$$

converges (Theorem 3.3(a)(b)).

- (2) $\{b_n\}$ is increasing to b . Similar to (1). Define $\{\beta_n\}$ by $\beta_n = b - b_n$. Thus $\sum a_n \beta_n$ converges. Hence

$$\sum a_n b_n = -\sum a_n \beta_n + \sum a_n b$$

converges.

□

Exercise 3.9. Find the radius of convergence of each of the following power series:

- (a) $\sum n^3 z^n$,
- (b) $\sum \frac{2^n}{n!} z^n$,
- (c) $\sum \frac{2^n}{n^2} z^n$,
- (d) $\sum \frac{n^3}{3^n} z^n$.

Proof of (a). Since

$$\alpha = \limsup_{n \rightarrow \infty} \sqrt[n]{n^3} = \limsup_{n \rightarrow \infty} (\sqrt[n]{n})^3 = 1$$

(Theorem 3.20(c)), $R = \frac{1}{\alpha} = 1$. □

Proof of (b).

- (1) Note that $\sqrt[n]{n!} \leq \sqrt[n]{n^n} = n$. Show that $\sqrt[n]{n!} \geq \sqrt{n}$. Note that

$$(n!)^2 = \prod_{k=1}^n k(n+1-k).$$

For each term $k(n+1-k)$ (where $k = 1, \dots, n$), we have

$$k(n+1-k) - n = (k-1)(n-k) \geq 0 \text{ or } k(n+1-k) > n.$$

or $k(n+1-k) > n$. Hence,

$$(n!)^2 = \prod_{k=1}^n k(n+1-k) \geq \prod_{k=1}^n n = n^n,$$

or $\sqrt[n]{n!} \geq \sqrt{n}$.

- (2) Since

$$0 \leq \alpha = \limsup_{n \rightarrow \infty} \sqrt[n]{\frac{2^n}{n!}} = \limsup_{n \rightarrow \infty} \frac{2}{\sqrt[n]{n!}} \leq \limsup_{n \rightarrow \infty} \frac{2}{\sqrt{n}} = 0,$$

$\alpha = 0$ and $R = \frac{1}{\alpha} = \infty$.

□

Proof of (c). Similar to (a). Since

$$\alpha = \limsup_{n \rightarrow \infty} \sqrt[n]{\frac{2^n}{n^2}} = \limsup_{n \rightarrow \infty} \frac{2}{\sqrt[n]{n^2}} = 2$$

(Theorem 3.20(c)), $R = \frac{1}{\alpha} = \frac{1}{2}$. □

Proof of (d). Similar to (a)(c). Since

$$\alpha = \limsup_{n \rightarrow \infty} \sqrt[n]{\frac{n^3}{3^n}} = \limsup_{n \rightarrow \infty} \frac{\sqrt[n]{n^3}}{3} = \frac{1}{3}$$

(Theorem 3.20(c)), $R = \frac{1}{\alpha} = 3$. □

Exercise 3.10. Suppose that the coefficients of the power series $\sum a_n z^n$ are integers, infinitely many of which are distinct from zero. Prove that the radius of convergence is at most 1.

Proof (Theorem 3.39). $\alpha = \limsup_{n \rightarrow \infty} \sqrt[n]{|a_n|} \geq 1$ by assumption that $\{a_n\}$ has infinitely many nonzero integers. Hence the radius of convergence $R = \frac{1}{\alpha} \leq 1$. □

Exercise 3.11. Suppose $a_n > 0$, $s_n = a_1 + \cdots + a_n$, and $\sum a_n$ diverges.

(a) Prove that $\sum \frac{a_n}{1+a_n}$ diverges.

(b) Prove that

$$\frac{a_{N+1}}{s_{N+1}} + \cdots + \frac{a_{N+k}}{s_{N+k}} \geq 1 - \frac{s_N}{s_{N+k}}$$

and deduce that $\sum \frac{a_n}{s_n}$ diverges.

(c) Prove that

$$\frac{a_n}{s_n^2} \leq \frac{1}{s_{n-1}} - \frac{1}{s_n}$$

and deduce that $\sum \frac{a_n}{s_n^2}$ converges.

(d) What can be said about

$$\sum \frac{a_n}{1+na_n} \text{ and } \sum \frac{a_n}{1+n^2a_n}?$$

Proof of (a). (Reductio ad absurdum)

- (1) If $\sum \frac{a_n}{1+a_n}$ were convergent, $\lim \frac{a_n}{1+a_n} = 0$ (Theorem 3.23). Note that $\frac{a_n}{1+a_n} = \frac{1}{1+\frac{1}{a_n}}$ implies $\lim a_n = 0$.
- (2) Since $\lim a_n = 0$, there is an integer N such that

$$0 < a_n < 1 \text{ whenever } n \geq N.$$

Hence

$$|a_n| = a_n \leq \frac{2a_n}{1+a_n} \text{ whenever } n \geq N.$$

By the comparison test (Theorem 3.25), $\sum a_n$ converges, contrary to the divergence of $\sum a_n$.

□

Proof of (b).

- (1) Note that each $s_n > 0$ and $\{s_n\}$ is monotonic increasing. For $k \geq 1$,

$$\begin{aligned} \frac{a_{N+1}}{s_{N+1}} + \cdots + \frac{a_{N+k}}{s_{N+k}} &\geq \frac{a_{N+1}}{s_{N+k}} + \cdots + \frac{a_{N+k}}{s_{N+k}} \\ &= \frac{a_{N+1} + \cdots + a_{N+k}}{s_{N+k}} \\ &= \frac{s_{N+k} - s_N}{s_{N+k}} \\ &= 1 - \frac{s_N}{s_{N+k}}. \end{aligned}$$

- (2) (Reductio ad absurdum) If $\sum \frac{a_n}{s_n}$ were convergent, by the Cauchy criterion (Theorem 3.22), for $\varepsilon = \frac{1}{64} > 0$, there is an integer N such that

$$\left| \sum_{n=N+1}^{N+k} \frac{a_n}{s_n} \right| < \frac{1}{64} \text{ whenever } k \geq 1.$$

So,

$$\frac{1}{64} > \sum_{n=N+1}^{N+k} \frac{a_n}{s_n} > 1 - \frac{s_N}{s_{N+k}} \text{ or } s_{N+k} < \frac{64}{63} s_N,$$

contrary to divergence of $\sum a_n = \infty$ (as $k \rightarrow \infty$).

□

Proof of (c).

- (1) For $n \geq 2$,

$$\frac{1}{s_{n-1}} - \frac{1}{s_n} = \frac{s_n - s_{n-1}}{s_{n-1}s_n} = \frac{a_n}{s_{n-1}s_n} \geq \frac{a_n}{s_n^2}.$$

(2) $\sum \frac{a_n}{s_n^2}$ is a series of nonnegative terms and its partial sums

$$\begin{aligned}\sum_{n=1}^k \frac{a_n}{s_n^2} &\leq \frac{a_1}{s_1^2} + \sum_{n=2}^k \left(\frac{1}{s_{n-1}} - \frac{1}{s_n} \right) \\ &= \frac{a_1}{s_1^2} + \frac{1}{s_1} - \frac{1}{s_k} \\ &= \frac{2}{a_1} - \frac{1}{s_k} \\ &< \frac{2}{a_1}\end{aligned}$$

is bounded (by $\frac{2}{a_1}$). Therefore, $\sum \frac{a_n}{s_n^2}$ converges (Theorem 3.24).

□

Proof of (d).

(1) Show that there is a divergent series $\sum a_n$ with $a_n > 0$ such that $\sum \frac{a_n}{1+na_n}$ converges or diverges.

(a) Take

$$a_n = \frac{1}{n(\log n)^p}$$

where $0 \leq p \leq 1$.

(b) Clearly,

$$\sum_{n=3}^{\infty} a_n = \sum_{n=3}^{\infty} \frac{1}{n(\log n)^p}$$

diverges (Theorem 3.29).

(c) Note that

$$\begin{aligned}\sum_{n=3}^{\infty} \frac{a_n}{1+na_n} &= \sum_{n=3}^{\infty} \frac{1}{n(\log n)^p} \cdot \frac{1}{1 + (\log n)^p} \\ &= \sum_{n=3}^{\infty} \frac{1}{n(\log n)^p + n(\log n)^{2p}}.\end{aligned}$$

Hence,

$$\sum_{n=3}^{\infty} \frac{1}{2n(\log n)^{2p}} \leq \sum_{n=3}^{\infty} \frac{a_n}{1+na_n} < \sum_{n=3}^{\infty} \frac{1}{n(\log n)^{2p}}.$$

(Here we use the fact that $n(\log n)^p > 0$ and $(\log n)^p \geq 1$ if $n > e$.)

Therefore,

$$\sum_{n=3}^{\infty} \frac{a_n}{1+na_n} = \begin{cases} \text{converges} & \text{if } 1 \geq p > \frac{1}{2} \\ \text{diverges} & \text{if } \frac{1}{2} \geq p \geq 0 \end{cases}$$

by Theorem 3.29 and the comparison test (Theorem 3.24).

Note. If a series $\sum a_n$ with $a_n > 0$ is convergent, then $\sum \frac{a_n}{1+na_n}$ is always convergent by the comparison test (Theorem 3.24).

- (2) Given any series $\sum a_n$ with $a_n > 0$. Show that

$$\sum \frac{a_n}{1+n^2a_n} < \infty$$

converges. Note that

$$\left| \frac{a_n}{1+n^2a_n} \right| = \frac{1}{\frac{1}{a_n} + n^2} < \frac{1}{n^2}$$

for any n and $\sum_{n=1}^{\infty} \frac{1}{n^2}$ converges (to $\frac{\pi^2}{6}$). By the comparison test (Theorem 3.25), $\sum \frac{a_n}{1+n^2a_n}$ converges.

□

Note. Similar to (d), what can be said about

$$\sum \frac{a_n}{1+n(\log n)a_n} \text{ and } \sum \frac{a_n}{1+n(\log n)^2a_n}?$$

Exercise 3.12. Suppose $a_n > 0$ and $\sum a_n$ converges. Put

$$r_n = \sum_{m=n}^{\infty} a_m.$$

- (a) Prove that

$$\frac{a_m}{r_m} + \cdots + \frac{a_n}{r_n} > 1 - \frac{r_n}{r_m}$$

if $m < n$, and deduce that $\sum \frac{a_n}{r_n}$ diverges.

- (b) Prove that

$$\frac{a_n}{\sqrt{r_n}} < 2(\sqrt{r_n} - \sqrt{r_{n+1}})$$

and deduce that $\sum \frac{a_n}{\sqrt{r_n}}$ converges.

Note.

- (1) Each r_n is positive and finite (since $a_n > 0$ and $\sum a_n$ converges).
- (2) $\{r_n\}$ is monotonic decreasing (since $a_n > 0$).
- (3) $\{r_n\}$ converges to 0 (since $\sum a_n$ converges).

Proof of (a).

(1)

$$\begin{aligned}
\frac{a_m}{r_m} + \cdots + \frac{a_n}{r_n} &> \frac{a_m}{r_m} + \cdots + \frac{a_n}{r_m} && (r_m > r_k \text{ for } k = m+1, \dots, n) \\
&= \frac{a_m + \cdots + a_n}{r_m} \\
&= \frac{r_m - r_{n+1}}{r_m} && (\text{Definition of } r_k) \\
&> \frac{r_m - r_n}{r_m} && (r_n > r_{n+1}) \\
&= 1 - \frac{r_n}{r_m}.
\end{aligned}$$

(2) (Reductio ad absurdum) If $\sum \frac{a_n}{r_n}$ were convergent, then given $\varepsilon = \frac{1}{64} > 0$ there is an integer N such that

$$\left| \frac{a_m}{r_m} + \cdots + \frac{a_n}{r_n} \right| < \frac{1}{64} \text{ whenever } n \geq m \geq N$$

(Theorem 3.22). By (1), let $m = N$ to get

$$1 - \frac{r_n}{r_N} < \frac{1}{64} \text{ whenever } n \geq N,$$

or

$$r_n > \frac{63}{64} r_N,$$

contrary to the assumption that $\{r_n\}$ converges to 0 (since $\sum a_n$ converges).

□

Proof of (b).

(1) Note that each r_n is positive and finite, and thus

$$\begin{aligned}
\frac{a_n}{\sqrt{r_n}} < 2(\sqrt{r_n} - \sqrt{r_{n+1}}) &\iff \frac{r_n - r_{n+1}}{\sqrt{r_n}} < 2(\sqrt{r_n} - \sqrt{r_{n+1}}) \\
&\iff \frac{\sqrt{r_n} + \sqrt{r_{n+1}}}{\sqrt{r_n}} < 2 \\
&\iff \sqrt{r_n} + \sqrt{r_{n+1}} < 2\sqrt{r_n} \\
&\iff \sqrt{r_{n+1}} < \sqrt{r_n} \\
&\iff r_{n+1} < r_n.
\end{aligned}$$

The last statement holds since $\{r_n\}$ is monotonic decreasing.

(2) (a) Each term $\frac{a_n}{\sqrt{r_n}}$ of $\sum \frac{a_n}{\sqrt{r_n}}$ is nonnegative.

(b) The partial sum

$$\sum_{k=1}^n \frac{a_k}{\sqrt{r_k}} < \sum_{k=1}^n 2(\sqrt{r_k} - \sqrt{r_{k+1}}) = 2(\sqrt{r_1} - \sqrt{r_{n+1}}) < 2\sqrt{r_1}$$

is bounded by $2\sqrt{r_1}$.

By (a)(b), $\sum \frac{a_n}{\sqrt{r_n}}$ converges (Theorem 3.24).

□

Exercise 3.13. *Prove that the Cauchy product of two absolutely convergent series converges absolutely.*

Proof.

- (1) Given two absolutely convergent series $\sum a_n$ and $\sum b_n$. The Cauchy product is $\sum c_n$ where

$$c_n = \sum_{k=0}^n a_k b_{n-k} \quad (n = 0, 1, 2, \dots).$$

Let $\sum |a_n| = A < \infty$ and $\sum |b_n| = B < \infty$.

- (2) Each term $|c_k|$ of $\sum_{k=0}^n |c_k|$ is nonnegative.
(3) Thus,

$$\begin{aligned} \sum_{k=0}^n |c_k| &= \sum_{k=0}^n \left| \sum_{m=0}^k a_m b_{k-m} \right| \\ &\leq \sum_{k=0}^n \sum_{m=0}^k |a_m| |b_{k-m}| \\ &= \sum_{k=0}^n |a_k| \sum_{m=0}^{n-k} |b_m| \\ &\leq \sum_{k=0}^n |a_k| B \\ &\leq AB \\ &< \infty. \end{aligned}$$

- (4) By (2)(3), $\sum_{k=0}^n |c_k|$ converges (Theorem 3.24), or $\sum_{k=0}^n c_k$ converges absolutely.

□

Exercise 3.14 (Cesàro convergence). If $\{s_n\}$ is a complex sequence, define its arithmetic means σ_n by

$$\sigma_n = \frac{s_0 + s_1 + \cdots + s_n}{n+1} \quad (n = 0, 1, 2, \dots).$$

- (a) If $\lim s_n = s$, prove that $\lim \sigma_n = s$.
- (b) Construct a sequence $\{s_n\}$ which does not converge, although $\lim \sigma_n = 0$.
- (c) Can it happen that $s_n > 0$ for all n and that $\limsup s_n = \infty$, although $\lim \sigma_n = 0$?
- (d) Put $a_n = s_n - s_{n-1}$, for $n \geq 1$. Show that

$$s_n - \sigma_n = \frac{1}{n+1} \sum_{k=1}^n k a_k.$$

Assume that $\lim(na_n) = 0$ and that $\{\sigma_n\}$ converges. Prove that $\{s_n\}$ converges. [This gives a converse of (a), but under the additional assumption that $na_n \rightarrow 0$.]

- (e) Derive the last conclusion from a weaker hypothesis: Assume $M \leq \infty$, $|na_n| < M$ for all n , and $\lim \sigma_n = \sigma$. Prove that $\lim s_n = \sigma$, by completing the following outline:

If $m < n$, then

$$s_n - \sigma_n = \frac{m+1}{n-m}(\sigma_n - \sigma_m) + \frac{1}{n-m} \sum_{i=m+1}^n (s_n - s_i).$$

For these i ,

$$|s_n - s_i| \leq \frac{(n-i)M}{i+1} \leq \frac{(n-m-1)M}{m+2}.$$

Fix $\varepsilon > 0$ and associate with each n the integer m that satisfies

$$m \leq \frac{n-\varepsilon}{1+\varepsilon} < m+1.$$

Then $\frac{m+1}{n-m} \leq \frac{1}{\varepsilon}$ and $|s_n - s_i| < M\varepsilon$. Hence

$$\limsup_{n \rightarrow \infty} |s_n - \sigma| \leq M\varepsilon.$$

Since ε was arbitrary, $\lim s_n = \sigma$.

Proof of (a). Given any $\varepsilon > 0$.

(1) For such $\varepsilon > 0$, there is an integer $N' \geq 1$ such that

$$|s_n - s| < \frac{\varepsilon}{64} \text{ whenever } n \geq N'.$$

(2) For such N' , $\sum_{n=0}^{N'} |s_n - s|$ is finite. Let N'' be an integer such that

$$\sum_{n=0}^{N'} |s_n - s| < \frac{N''\varepsilon}{89}$$

(by taking $N'' = \left\lfloor \frac{89}{\varepsilon} \sum_{n=0}^{N'} |s_n - s| \right\rfloor + 1$).

(3) Note that

$$\begin{aligned} |\sigma_n - s| &= \left| \left(\frac{1}{n+1} \sum_{k=0}^n s_k \right) - s \right| \\ &= \left| \frac{1}{n+1} \sum_{k=0}^n (s_k - s) \right| \\ &\leq \frac{1}{n+1} \sum_{k=0}^n |s_k - s| \end{aligned}$$

holds for each $n = 0, 1, 2, \dots$. In particular, for $n \geq N = \max\{N', N''\} \geq 1$, we have

$$\begin{aligned} |\sigma_n - s| &\leq \frac{1}{n+1} \sum_{k=0}^n |s_k - s| \\ &\leq \left(\frac{1}{n+1} \sum_{k=0}^{N'} |s_k - s| \right) + \left(\frac{1}{n+1} \sum_{k=N'+1}^n |s_k - s| \right) \\ &< \frac{1}{n+1} \cdot \frac{N''\varepsilon}{89} + \frac{1}{n+1} \cdot \frac{(n - N')\varepsilon}{64} \\ &< \frac{\varepsilon}{89} + \frac{\varepsilon}{64} \\ &< \varepsilon. \end{aligned}$$

Therefore, $\lim \sigma_n = s$.

□

Proof of (b). Define $\{s_n\}$ by $s_n = (-1)^{n+1}$. □

Proof of (c). Yes. Define

$$s_n = \begin{cases} \frac{1}{n!} + m^{63} & \text{if } n = m^{89} \text{ for some } m \in \mathbb{Z}, \\ \frac{1}{n!} & \text{otherwise.} \end{cases}$$

(1) Clearly, $\limsup s_n = \infty$.

(2) Given any n , there is $m \in \mathbb{Z}$ satisfying $m^{89} \leq n < (m+1)^{89}$. So

$$\begin{aligned}
0 < \sigma_n &= \frac{1}{n+1} \sum_{k=0}^n s_k \\
&\leq \frac{1}{m^{89}+1} \sum_{k=0}^n s_k \\
&= \frac{1}{m^{89}+1} \left(\sum_{k=0}^n \frac{1}{n!} + \sum_{k=0}^m k^{63} \right) \\
&\leq \frac{1}{m^{89}+1} \left(\sum_{k=0}^{\infty} \frac{1}{n!} + \sum_{k=0}^m m^{63} \right) \\
&= \frac{e + m \cdot m^{63}}{m^{89}+1} \\
&= \frac{m^{64} + e}{m^{89}+1}.
\end{aligned}$$

Let $n \rightarrow \infty$, then $m \rightarrow \infty$ and thus $\lim \sigma_n = 0$.

□

Proof of (d).

(1)

$$\begin{aligned}
\frac{1}{n+1} \sum_{k=1}^n k a_k &= \frac{1}{n+1} \sum_{k=1}^n k (s_k - s_{k-1}) \\
&= \frac{1}{n+1} \left(\sum_{k=1}^n k s_k - \sum_{k=1}^n k s_{k-1} \right) \\
&= \frac{1}{n+1} \left(\sum_{k=1}^n k s_k - \sum_{k=1}^n (k-1) s_{k-1} - \sum_{k=1}^n s_{k-1} \right) \\
&= \frac{1}{n+1} \left(n s_n - \sum_{k=1}^n s_{k-1} \right) \\
&= \frac{1}{n+1} \left((n+1) s_n - \sum_{k=1}^{n+1} s_{k-1} \right) \\
&= s_n - \sigma_n.
\end{aligned}$$

(2) Write

$$s_n = \sigma_n + \frac{1}{n+1} \sum_{k=1}^n k a_k.$$

Since $\lim_{n \rightarrow \infty} (na_n) = 0$, $\lim_{n \rightarrow \infty} \frac{1}{n+1} \sum_{k=1}^n ka_k = 0$ ((a)). Since $\{\sigma_n\}$ converges,

$$\lim_{n \rightarrow \infty} s_n = \lim_{n \rightarrow \infty} \sigma_n + \lim_{n \rightarrow \infty} \frac{1}{n+1} \sum_{k=1}^n ka_k = \lim_{n \rightarrow \infty} \sigma_n$$

(Theorem 3.3(a)).

□

Proof of (e).

(1) If $m < n$, then

$$\begin{aligned} \sigma_n - \sigma_m &= \frac{1}{n+1} \sum_{k=0}^n s_k - \frac{1}{m+1} \sum_{k=0}^m s_k \\ &= \frac{1}{n+1} \sum_{k=0}^n s_k - \frac{1}{m+1} \sum_{k=0}^n s_k + \frac{1}{m+1} \sum_{i=m+1}^n s_i \\ &= \frac{m-n}{(m+1)(n+1)} \sum_{k=0}^n s_k + \frac{1}{m+1} \sum_{i=m+1}^n s_i \\ &= \frac{m-n}{m+1} \sigma_n + \frac{1}{m+1} \sum_{i=m+1}^n s_i, \\ \frac{m+1}{n-m} (\sigma_n - \sigma_m) &= -\sigma_n + \frac{1}{n-m} \sum_{i=m+1}^n s_i \\ &= -\sigma_n - \frac{1}{n-m} \sum_{i=m+1}^n (-s_i) \\ &= -\sigma_n - \left(\frac{1}{n-m} \sum_{i=m+1}^n (s_n - s_i) \right) + s_n, \\ s_n - \sigma_n &= \frac{m+1}{n-m} (\sigma_n - \sigma_m) + \frac{1}{n-m} \sum_{i=m+1}^n (s_n - s_i). \end{aligned}$$

(2) For these i ,

$$\begin{aligned}
|s_n - s_i| &= \left| \sum_{k=i+1}^n a_k \right| & (s_n - s_i &= \sum_{k=i+1}^n a_k) \\
&\leq \sum_{k=i+1}^n |a_k| & (\text{Triangle inequality}) \\
&< \sum_{k=i+1}^n \frac{M}{k} & (|ka_k| < M) \\
&\leq \sum_{k=i+1}^n \frac{M}{i+1} & (k \geq i+1) \\
&= \frac{(n-i)M}{i+1} \\
&= \left(\frac{n-1}{i+1} - 1 \right) M \\
&\leq \left(\frac{n-1}{m+2} - 1 \right) M & (i \geq m+1) \\
&= \frac{(n-m-1)M}{m+2}.
\end{aligned}$$

(3) Fix $1 > \varepsilon > 0$ and associate with each n the integer m that satisfies

$$m \leq \frac{n-\varepsilon}{1+\varepsilon} < m+1.$$

Clearly, $m \leq \frac{n-\varepsilon}{1+\varepsilon} < \frac{n}{1+\varepsilon} < n$. Then

$$\frac{m+1}{n-m} \leq \frac{1}{\varepsilon} \text{ and } \frac{n-m-1}{m+2} < \varepsilon.$$

Hence $|s_n - s_i| < M\varepsilon$ by (2).

(4) By (1)(3),

$$\begin{aligned}
s_n - \sigma &= (\sigma_n - \sigma) + \frac{m+1}{n-m}(\sigma_n - \sigma_m) + \frac{1}{n-m} \sum_{i=m+1}^n (s_n - s_i), \\
|s_n - \sigma| &\leq |\sigma_n - \sigma| + \frac{m+1}{n-m} |\sigma_n - \sigma_m| + \frac{1}{n-m} \sum_{i=m+1}^n |s_n - s_i| \\
&< |\sigma_n - \sigma| + \frac{1}{\varepsilon} |\sigma_n - \sigma_m| + \frac{1}{n-m} \sum_{i=m+1}^n M\varepsilon \\
&= |\sigma_n - \sigma| + \frac{1}{\varepsilon} |\sigma_n - \sigma_m| + M\varepsilon
\end{aligned}$$

holds for any n and m satisfying $m \leq \frac{n-\varepsilon}{1+\varepsilon} < m+1$. Since $\{\sigma_n\}$ converges, there is an integer N such that

$$|\sigma_n - \sigma_m| < \varepsilon^2 \text{ whenever } m, n \geq N,$$

$$|\sigma_n - \sigma| < \varepsilon \text{ whenever } n \geq N.$$

So,

$$|s_n - \sigma| < (M+2)\varepsilon$$

holds for any $n \geq 2N+3$ (and the corresponding m satisfying $m \leq \frac{n-\varepsilon}{1+\varepsilon} < m+1$ (which implies $m > \frac{n-\varepsilon}{1+\varepsilon} - 1 \geq \frac{n-1}{2} - 1 \geq N$)). Take limit to get

$$\limsup_{n \rightarrow \infty} |s_n - \sigma| \leq (M+2)\varepsilon.$$

Since ε was arbitrary, $\lim s_n = \sigma$.

□

Exercise 3.20. Suppose $\{p_n\}$ is a Cauchy sequence in a metric space X , and some subsequence $\{p_{n_i}\}$ converges to a point $p \in X$. Prove that the full sequence $\{p_n\}$ converges to p .

Proof. Given any $\varepsilon > 0$.

- (1) Since $\{p_n\}$ is a Cauchy sequence, there exists a positive integer N_1 such that

$$d(p_n, p_m) < \frac{\varepsilon}{2} \text{ whenever } n, m \geq N_1.$$

- (2) Since the subsequence $\{p_{n_i}\}$ converges to a point $p \in X$, there exists a positive integer N_2 such that

$$d(p_{n_i}, p) < \frac{\varepsilon}{2} \text{ whenever } n_i \geq N_2.$$

- (3) Let $N = \max\{N_1, N_2\}$ be a positive integer. So

$$\begin{aligned} d(p_n, p) &\leq d(p_n, p_{n_i}) + d(p_{n_i}, p) && \text{(Definition 2.15(c))} \\ &< \frac{\varepsilon}{2} + \frac{\varepsilon}{2} \text{ whenever } n, n_i \geq N && ((1)(2)) \\ &= \varepsilon \text{ whenever } n \geq N. \end{aligned}$$

Hence the full sequence $\{p_n\}$ converges to p .

□

Exercise 3.21. Prove the following analogue of Theorem 3.10(b): If $\{E_n\}$ is a sequence of closed and bounded sets in a complete metric space X , if $E_n \supseteq E_{n+1}$, and if

$$\lim_{n \rightarrow \infty} \text{diam}(E_n) = 0,$$

then $\bigcap_{n=1}^{\infty} E_n$ consists of exactly one point.

Assume $E_n \neq \emptyset$. It is unnecessary to assume that E_n is bounded since we have the condition that $\lim_{n \rightarrow \infty} \text{diam}(E_n) = 0$.

Note. Every compact metric space is complete, but complete spaces need not be compact. In fact, a metric space is compact if and only if it is complete and totally bounded.

Proof.

- (1) Pick $p_n \in E_n$ for $n = 1, 2, \dots$
- (2) Show that $\{p_n\}$ is a Cauchy sequence. Given any $\varepsilon > 0$. There is a positive integer N such that $\text{diam}(E_n) < \varepsilon$ whenever $n \geq N$. Especially,

$$\text{diam}(E_N) < \varepsilon.$$

As $m, n \geq N$, $p_m \in E_m \subseteq E_N$ and $p_n \in E_n \subseteq E_N$. By the definition of the diameter of E_N ,

$$d(p_m, p_n) \leq \text{diam}(E_N) < \varepsilon \text{ whenever } m, n \geq N.$$

- (3) Since X is complete, $\{p_n\}$ converges to a point $p \in X$.
- (4) Show that $p \in \bigcap_{n=1}^{\infty} E_n$. (Reductio ad absurdum) If there were some n such that $p \notin E_n$. Consider the subsequence

$$p_n, p_{n+1}, p_{n+2}, \dots$$

Note that all p_n, p_{n+1}, \dots are in E_n . By (3), it converges to p . Thus p is a limit point of E_n . Since E_n is closed, $p \in E_n$, which is absurd.

- (5) Show that $\bigcap_{n=1}^{\infty} E_n = \{p\}$. (Reductio ad absurdum) If there were $q \in \bigcap_{n=1}^{\infty} E_n$ with $q \neq p$, then $d(p, q) > 0$ (Definition 2.15(a)). It implies that

$$\text{diam}(E_n) \geq d(p, q) > 0 \text{ for all } n,$$

contrary to $\lim_{n \rightarrow \infty} \text{diam}(E_n) = 0$.

□

Exercise 3.22 (Baire category theorem). Suppose X is a complete metric space, and $\{G_n\}$ is a sequence of dense open subsets of X . Prove Baire's

theorem, namely, that $\bigcap_1^\infty G_n$ is not empty. (In fact, it is dense in X .) (Hint: Find a shrinking sequence of neighborhoods E_n such that $\overline{E_n} \subseteq G_n$, and apply Exercise 3.21.)

Proof. Given any open set G_0 in X , will show that

$$\bigcap_{n=0}^\infty G_n \neq \emptyset.$$

- (1) Since G_1 is dense, $G_0 \cap G_1$ is nonempty. Take any one point p_1 in the open set $G_0 \cap G_1$, then there exists a closed neighborhood

$$V_1 = \{q \in X : d(q, p_1) < r_1\}$$

of p_1 with $r_1 < 1$ such that

$$V_1 \subseteq G_0 \cap G_1.$$

Take $U_1 \subseteq E_1 \subseteq V_1$ such that

$$\begin{aligned} E_1 &= \left\{q \in X : d(q, p_1) \leq \frac{r_1}{64}\right\} \subseteq V_1, \\ U_1 &= \left\{q \in X : d(q, p_1) < \frac{r_1}{89}\right\} \subseteq E_1. \end{aligned}$$

- (2) Suppose V_n, E_n, U_n have been constructed, take any one point p_{n+1} in the open set $U_n \cap G_{n+1}$, there exists an open neighborhood

$$V_{n+1} = \{q \in X : d(q, p_{n+1}) < r_{n+1}\}$$

of p_{n+1} with $r_{n+1} < \frac{1}{n+1}$ such that

$$V_{n+1} \subseteq U_n \cap G_{n+1}.$$

Take $U_1 \subseteq E_1 \subseteq V_1$ such that

$$\begin{aligned} E_{n+1} &= \left\{q \in X : d(q, p_{n+1}) \leq \frac{r_{n+1}}{64}\right\} \subseteq V_{n+1}, \\ U_{n+1} &= \left\{q \in X : d(q, p_{n+1}) < \frac{r_{n+1}}{89}\right\} \subseteq E_{n+1}. \end{aligned}$$

- (3) Note that

- (a) E_n is closed and nonempty (since $p_n \in E_n$).
- (b) $\lim_{n \rightarrow \infty} \text{diam}(E_n) = 0$ (since $\text{diam}(E_n) \leq 2 \cdot \frac{r_n}{64} < r_n < \frac{1}{n}$).
- (c) $E_1 \supseteq E_2 \supseteq \cdots$ (since $E_{n+1} \subseteq V_{n+1} \subseteq U_n \cap G_{n+1} \subseteq U_n \subseteq E_n$).

Since X is complete, by Exercise 3.21,

$$\bigcap_{n=1}^\infty E_n = \{p\}$$

for some $p \in X$.

(4) Hence

$$\begin{aligned}
p \in \bigcap_{n=1}^{\infty} E_n &\iff p \in E_n \text{ for all } n = 1, 2, 3, \dots \\
&\implies p \in E_1 \subseteq G_0 \cap G_1 \text{ and } p \in E_{n+1} \subseteq U_n \cap G_{n+1} \subseteq G_{n+1} \\
&\implies p \in G_0 \cap G_1 \cap \dots = \bigcap_{n=0}^{\infty} G_n \\
&\implies \bigcap_{n=0}^{\infty} G_n \neq \emptyset.
\end{aligned}$$

□

Exercise 3.23. Suppose $\{p_n\}$ and $\{q_n\}$ are Cauchy sequences in a metric space X . Show that the sequence $\{d(p_n, q_n)\}$ converges. (Hint: For any m, n ,

$$d(p_n, q_n) \leq d(p_n, p_m) + d(p_m, q_m) + d(q_m, q_n);$$

it follows that

$$|d(p_n, q_n) - d(p_m, q_m)|$$

is small if m and n are large.)

Proof. Given any $\varepsilon > 0$.

(1) Since $\{p_n\}$ and $\{q_n\}$ are Cauchy sequences, there exists N such that

$$d(p_n, p_m) < \frac{\varepsilon}{2} \text{ and } d(q_m, q_n) < \frac{\varepsilon}{2}$$

whenever $m, n \geq N$.

(2) Note that

$$d(p_n, q_n) \leq d(p_n, p_m) + d(p_m, q_m) + d(q_m, q_n).$$

It follows that

$$|d(p_n, q_n) - d(p_m, q_m)| \leq d(p_n, p_m) + d(q_m, q_n) < \frac{\varepsilon}{2} + \frac{\varepsilon}{2} = \varepsilon.$$

Thus $\{d(p_n, q_n)\}$ is a Cauchy sequence in \mathbb{R}^1 (not in X).

(3) Since \mathbb{R}^1 is a complete metric space, $\{d(p_n, q_n)\}$ converges.

□

Exercise 3.24. Let X be a metric space.

- (a) Call two Cauchy sequences $\{p_n\}, \{q_n\}$ in X equivalent if

$$\lim_{n \rightarrow \infty} d(p_n, q_n) = 0.$$

Prove that this is an equivalence relation.

- (b) Let X^* be the set of all equivalence classes so obtained. If $P \in X^*$, $Q \in X^*$, $\{p_n\} \in P$, $\{q_n\} \in Q$, define

$$\Delta(P, Q) = \lim_{n \rightarrow \infty} d(p_n, q_n);$$

by Exercise 3.23, this limit exists. Show that the number $\Delta(P, Q)$ is unchanged if $\{p_n\}$ and $\{q_n\}$ are replaced by equivalent sequences, and hence that Δ is a distance function in X^* .

- (c) Prove that the resulting metric space X^* is complete.
 (d) For each $p \in X$, there is a Cauchy sequence all of whose terms are p ; let P_p be the element of X^* which contains this sequence. Prove that

$$\Delta(P_p, P_q) = d(p, q)$$

for all $p, q \in X$. In other words, the mapping φ defined by $\varphi(p) = P_p$ is an isometry (i.e., a distance-preserving mapping) of X into X^* .

- (e) Prove that $\varphi(X)$ is dense in X^* , and that $\varphi(X) = X^*$ if X is complete. By (d), we may identify X and $\varphi(X)$ and thus regard X as embedded in the complete metric space X^* . We call X^* the **completion** of X .

Proof of (a). Given Cauchy sequences $\{p_n\}, \{q_n\}, \{r_n\}$ in X .

- (1) (*Reflexivity*)

$$\lim_{n \rightarrow \infty} d(p_n, q_n) = \lim_{n \rightarrow \infty} 0 = 0$$

by the reflexivity of the metric function d .

- (2) (*Symmetry*)

$$\lim_{n \rightarrow \infty} d(p_n, q_n) = \lim_{n \rightarrow \infty} d(q_n, p_n) = 0$$

by the symmetry of the metric function d .

- (3) (*Transitivity*) Suppose that $\lim_{n \rightarrow \infty} d(p_n, q_n) = \lim_{n \rightarrow \infty} d(q_n, r_n) = 0$. By the triangle inequality of the metric function d , we have

$$0 \leq d(p_n, r_n) \leq d(p_n, q_n) + d(q_n, r_n).$$

Take limit to get

$$\begin{aligned}
0 &\leq \lim_{n \rightarrow \infty} d(p_n, r_n) \\
&\leq \lim_{n \rightarrow \infty} (d(p_n, q_n) + d(q_n, r_n)) \\
&= \lim_{n \rightarrow \infty} d(p_n, q_n) + \lim_{n \rightarrow \infty} d(q_n, r_n) \\
&= 0
\end{aligned}$$

or $\lim_{n \rightarrow \infty} d(p_n, r_n) = 0$.

□

Proof of (b).

(1) *Show that Δ is well-defined.* Given any $\{p_n\}, \{p'_n\} \in P$ and $\{q_n\}, \{q'_n\} \in Q$.

(a) $\lim_{n \rightarrow \infty} d(p_n, p'_n) = 0$ since $\{p_n\}$ and $\{p'_n\}$ are in the same equivalence class.

(b) $\lim_{n \rightarrow \infty} d(q_n, q'_n) = 0$ (similar to (a)).

(c) *Show that $\lim_{n \rightarrow \infty} d(p_n, q_n) \leq \lim_{n \rightarrow \infty} d(p'_n, q'_n)$.* Since $d(p_n, q_n) \leq d(p_n, p'_n) + d(p'_n, q'_n) + d(q'_n, q_n)$, take limit to get

$$\begin{aligned}
\lim_{n \rightarrow \infty} d(p_n, q_n) &\leq \lim_{n \rightarrow \infty} (d(p_n, p'_n) + d(p'_n, q'_n) + d(q'_n, q_n)) \\
&= \lim_{n \rightarrow \infty} d(p_n, p'_n) + \lim_{n \rightarrow \infty} d(p'_n, q'_n) + \lim_{n \rightarrow \infty} d(q'_n, q_n) \\
&= 0 + \lim_{n \rightarrow \infty} d(p'_n, q'_n) + 0 \\
&= \lim_{n \rightarrow \infty} d(p'_n, q'_n)
\end{aligned}$$

since (a)(b).

(d) *Show that $\lim_{n \rightarrow \infty} d(p_n, q_n) \geq \lim_{n \rightarrow \infty} d(p'_n, q'_n)$.* Similar to (c).

By (c)(d), $\lim_{n \rightarrow \infty} d(p_n, q_n) = \lim_{n \rightarrow \infty} d(p'_n, q'_n)$, or $\Delta(P, Q)$ is well-defined.

(2) *Show that Δ is a metric.*

(a) *Show that $\Delta(P, Q) > 0$ if $P \neq Q$; $\Delta(P, P) = 0$.* It is the definition of Δ .

(b) *Show that $\Delta(P, Q) = \Delta(Q, P)$.* Similar to the argument in (a)(2).

(c) *Show that $\Delta(P, Q) \leq \Delta(P, R) + \Delta(R, Q)$.* Similar to the argument in (a)(3).

□

Proof of (c). Show that $\{P_k\}_{k=1}^\infty$ converges to P in (X^, Δ) for any given Cauchy sequence $\{P_k\}$.*

- (1) Take a Cauchy sequence $\{p_n^{(k)}\}_{n=1}^\infty$ to represent P_k for each k . We will construct a Cauchy sequence $\{p_k\}$ in (X, d) such that $\{P_k\}$ converges to P which is the equivalent class of $\{p_k\}$.
- (2) For each k , there exists N_k such that

$$d(p_m^{(k)}, p_n^{(k)}) < \frac{1}{k} \text{ whenever } m, n \geq N_k.$$

Especially,

$$d(p_m^{(k)}, p_{N_k}^{(k)}) < \frac{1}{k} \text{ whenever } m \geq N_k.$$

Let $p_k = p_{N_k}^{(k)}$ and collect all p_k as $\{p_k\}_{k=1}^\infty$.

- (3) Show that $\{p_k\}$ is a Cauchy sequence in (X, d) . Note that for any k , we have

$$\begin{aligned} d(p_m, p_n) &= d(p_{N_m}^{(m)}, p_{N_n}^{(n)}) \\ &\leq d(p_{N_m}^{(m)}, p_k^{(m)}) + d(p_k^{(m)}, p_k^{(n)}) + d(p_k^{(n)}, p_{N_n}^{(n)}). \end{aligned}$$

Let $k \rightarrow \infty$, we have

$$\begin{aligned} d(p_m, p_n) &\leq \limsup_{k \rightarrow \infty} \left[d(p_{N_m}^{(m)}, p_k^{(m)}) + d(p_k^{(m)}, p_k^{(n)}) + d(p_k^{(n)}, p_{N_n}^{(n)}) \right] \\ &\leq \frac{1}{m} + \Delta(P_m, P_n) + \frac{1}{n} \end{aligned}$$

for any m, n (by (2)). Let $m, n \rightarrow \infty$, we establish the result (since $\{P_k\}$ is Cauchy).

- (4) Show that $\{P_k\}$ converges to $P \ni \{p_k\}$. Given any $\varepsilon > 0$. Since $\{p_k\}$ is Cauchy (3), there is $N > \frac{2}{\varepsilon}$ such that

$$d(p_m, p_n) < \frac{\varepsilon}{2} \text{ whenever } m, n \geq N.$$

Note that

$$\begin{aligned} d(p_n^{(k)}, p_n) &= d(p_n^{(k)}, p_{N_n}^{(n)}) \\ &\leq d(p_n^{(k)}, p_{N_k}^{(k)}) + d(p_{N_k}^{(k)}, p_{N_n}^{(n)}). \end{aligned}$$

For any $k \geq N$, let $n \rightarrow \infty$ to get

$$\begin{aligned}
\Delta(P_k, P) &= \lim_{n \rightarrow \infty} d(p_n^{(k)}, p_n) \\
&\leq \limsup_{n \rightarrow \infty} d(p_n^{(k)}, p_{N_k}^{(k)}) + \limsup_{n \rightarrow \infty} d(p_{N_k}^{(k)}, p_{N_n}^{(n)}) \\
&< \frac{1}{k} + \frac{\varepsilon}{2} \\
&\leq \frac{1}{N} + \frac{\varepsilon}{2} \\
&< \frac{\varepsilon}{2} + \frac{\varepsilon}{2} \\
&< \varepsilon.
\end{aligned}$$

Hence, (X^*, Δ) is complete. \square

Proof of (d).

- (1) Define $\{p_n\}$ by $p_n = p$ ($n = 1, 2, \dots$) for any $p \in X$.
- (2) Show that $\{p_n\}$ is a Cauchy sequence. $d(p_m, p_n) = d(p, p) = 0$.
- (3) Take $\{p\} \in P_p$ and $\{q\} \in P_q$. Then

$$\Delta(P_p, P_q) = \lim_{n \rightarrow \infty} d(p_n, q_n) = \lim_{n \rightarrow \infty} d(p, q) = d(p, q).$$

\square

Proof of (e).

- (1) Show that $\varphi(X)$ is dense in X^* . Given any $P \in X^*$, any $\{p_n\} \in P$ and any $\varepsilon > 0$. Since $\{p_n\}$ is Cauchy, there is N such that

$$d(p_m, p_n) < \frac{\varepsilon}{64} \text{ whenever } m, n \geq N.$$

Note that $p_N \in X$. Pick $\{p_N\} \in P_{p_N} = \varphi(p_N) \in \varphi(X)$. So

$$\Delta(P, P_{p_N}) = \lim_{n \rightarrow \infty} d(p_n, p_N) \leq \frac{\varepsilon}{64} < \varepsilon.$$

Hence $\varphi(X)$ is dense in X^* .

- (2) Show that $\varphi(X) = X^*$ if X is complete. Given any $P \in X^* \ni \{p_n\}$. Since X is complete, a Cauchy sequence $\{p_n\}$ converges to $p \in X$. Pick $\{p\} \in P_p = \varphi(p) \in \varphi(X)$. So

$$\Delta(P, P_p) = \lim_{n \rightarrow \infty} d(p_n, p) = 0,$$

or $P = P_p$, or $\varphi(X) = X^*$.

□

Exercise 3.25. Let X be the metric space whose points are rational numbers, with the metric $d(x, y) = |x - y|$. What is the completion of this space? (Compare Exercise 3.24.)

Proof. By Exercise 3.24, we can identify one completion (X^*, Δ) with $(\mathbb{R}, |\cdot|)$ (Theorem 3.11(c) and Theorem 1.20(b)). □

Supplement (Uniqueness of completion). Show that a completion of a metric space is unique up to isometry.

Outline. Suppose there are two completions $\{\varphi_i, (X_i^*, d_i^*)\}$ ($i = 1, 2$) of (X, d) . Let

$$\psi = \varphi_2 \circ \varphi_1^{-1} : \varphi_1(X) \rightarrow \varphi_2(X)$$

be an isometry from $\varphi_1(X)$ into $\varphi_2(X)$. The sets $\varphi_i(X)$ ($i = 1, 2$) are dense in X_i^* . So we can extend ψ (continuously) to a map $\psi : X_1^* \rightarrow X_2^*$.

Proof.

- (1) Given any $P \in X_1^*$, there is a Cauchy sequence $\{P_{p_n}\} = \{\varphi_1(p_n)\}$ in $\varphi_1(X)$ converging to P . Define $\psi(P)$ by

$$\psi(P) = \lim_{n \rightarrow \infty} \psi(P_{p_n}).$$

- (2) Show that ψ is well-defined. Note that

$$\begin{aligned} \Delta_2(\psi(P_{p_m}), \psi(P_{p_n})) &= \Delta_2(\psi(\varphi_1(p_m)), \psi(\varphi_1(p_n))) \\ &= \Delta_2(\varphi_2(p_m), \varphi_2(p_n)) \\ &= d(p_m, p_n) && (\varphi_2 \text{ is isometric}) \\ &= \Delta_1(\varphi_1(p_m), \varphi_1(p_n)) && (\varphi_1 \text{ is isometric}) \\ &= \Delta_1(P_{p_m}, P_{p_n}). \end{aligned}$$

So $\{\psi(P_{p_n})\}$ is a Cauchy sequence in $\varphi_2(X)$ if (and only if) $\{P_{p_n}\}$ is a Cauchy sequence in $\varphi_1(X)$. Since X_2^* is complete, $\{\psi(P_{p_n})\}$ converges to $\psi(P)$. The limit $\psi(P)$ is uniquely determined since Δ_2 is a metric function.

- (3) Since ψ is an isometry from $\varphi_1(X)$ into $\varphi_2(X)$,

$$\psi^{-1} = \varphi_1 \circ \varphi_2^{-1} : \varphi_2(X) \rightarrow \varphi_1(X)$$

is an isometry from $\varphi_2(X)$ into $\varphi_1(X)$. Besides, $\psi^{-1} \circ \psi = 1_{\varphi_1(X)}$ and $\psi \circ \psi^{-1} = 1_{\varphi_2(X)}$.

- (4) *Show that ψ is surjective.* Given any $Q \in X_2^*$, there is a Cauchy sequence $\{P_{q_n}\} = \{\varphi_2(q_n)\}$ in $\varphi_2(X)$ converging to Q . Define

$$P_{p_n} = \psi^{-1}(P_{q_n}) \in \varphi_1(X).$$

$\psi(P_{p_n}) = 1_{\varphi_2(X)}(P_{q_n}) = P_{q_n}$. Besides, similar to argument in (2), $\{P_{p_n}\}$ is a Cauchy sequence in $\varphi_1(X)$. Since X_1^* is complete, $\{P_{p_n}\}$ converges to $P \in X_1^*$. It is easy to verify that $\psi(P) = Q$.

- (5) *Show that ψ is injective.* Given any $P \in X_1^*$ and $Q \in X_1^*$, there are Cauchy sequences

$$\{P_{p_n}\} = \{\varphi_1(p_n)\} \rightarrow P \text{ and } \{P_{q_n}\} = \{\varphi_1(q_n)\} \rightarrow Q.$$

So

$$\begin{aligned} \psi(P) = \psi(Q) &\implies \lim_{n \rightarrow \infty} \psi(P_{p_n}) = \lim_{n \rightarrow \infty} \psi(P_{q_n}) \\ &\implies 0 = \lim_{n \rightarrow \infty} \Delta_2(\psi(P_{p_n}), \psi(P_{q_n})) \\ &\implies 0 = \lim_{n \rightarrow \infty} \Delta_2(\psi(\varphi_1(p_n)), \psi(\varphi_1(q_n))) \\ &\implies 0 = \lim_{n \rightarrow \infty} \Delta_2(\varphi_2(p_n), \varphi_2(q_n)) \\ &\implies 0 = \lim_{n \rightarrow \infty} d(p_n, q_n). \end{aligned} \quad (\varphi_2 \text{ is isometric})$$

Thus $\{p_n\} \in P$ and $\{q_n\} \in Q$ in the same equivalence class. Thus $P = Q$.

□