

# Proof Workshop Week 4: Limits and Sequences

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## 1 Day 4: Limits and Sequences

Today, we are in a wonderland. This wonderland is  $\mathbb{R}$ .

**Definition 1** (Sequence). A sequence in  $\mathbb{R}$  is a function  $a : \mathbb{N} \rightarrow \mathbb{R}$ .

More often than not, we will notate a sequence  $a : \mathbb{N} \rightarrow \mathbb{R}$  not as a function, but as a family of real numbers indexed by  $\mathbb{N}$ . In particular, we denote  $a$  by  $\{a_n\}_{n=1}^{\infty}$ , where  $a_n = a(n)$  for each  $n \in \mathbb{N}$ . When the entire sequence can be inferred from the first few terms, sometimes we will even write only the first few terms. For example, we might write  $1, 1, \dots$  for the constant sequence  $a_n = 1$ .

**Example 2.** Here are some examples of sequences in  $\mathbb{R}$ .

(1)  $a_n = n$ , which yields  $1, 2, 3, 4, \dots$

(2)  $a_n = \frac{1}{n}$ , which yields  $1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \dots$

(3)  $a_n = \frac{2^n - 1}{2^n}$ , which yields  $\frac{1}{2}, \frac{3}{4}, \frac{7}{8}, \frac{15}{16}, \dots$

(4)  $a_1 = a_2 = 1$ ,  $a_n = a_{n-1} + a_{n-2}$ , which yields  $1, 2, 3, 5, 8, 13, \dots$

(5) Let

$$a_n = \begin{cases} 2^n & \text{if } n \text{ odd} \\ n & \text{if } n \text{ even.} \end{cases}$$

Then  $a_n$  yields the sequence  $2, 2, 8, 4, 32, 6, \dots$

**Note.** A sequence of real numbers and a set of real numbers are not the same thing. For instance, the sequence  $1, 1/2, 1/4, 1/8, \dots$  is different from the sequence  $1/8, 1, 1/2, 4, \dots$ , even though the sets  $\{1, 1/2, 1/4, 1/8, \dots\}$ , and  $\{1/8, 1, 1/2, 4, \dots\}$  are identical.

For a sequence  $\{a_n\}$ , the set containing the sequence is written as  $\{a_n : n \in \mathbb{N}\}$ .

Something we might be curious about is how a sequence behaves in the long run, i.e., as  $n$  tends to  $\infty$ . After all, a sequence can do any number of things. It might converge to a finite value, it might tend to one extreme or another, or it might oscillate indefinitely.

**Definition 3** (Limit of a Sequence). We say that  $L$  is the **limit** of the sequence  $\{a_n\}_{n=1}^{\infty}$  as  $n$  tends to  $\infty$ , or equivalently,

$$\lim_{n \rightarrow \infty} a_n = L,$$

if for any  $\epsilon > 0$ , there exists an  $N \in \mathbb{N}$  such that  $|a_n - L| < \epsilon$  whenever  $n \geq N$ . In somewhat contrived mathematical notation,  $L$  is the limit of  $a_n$  if

$$\forall \epsilon > 0, \exists N \in \mathbb{N} \text{ such that } \forall n \geq N, |a_n - L| < \epsilon.$$

**The Limit Cookbook, for Sequences.** Suppose you have a solid guess  $L \in \mathbb{R}$  for what the limit of the function representing a sequence is. Proving that your guess is correct isn't difficult! Just follow the recipe below:

- Let  $\epsilon > 0$  be given.
- Conjure up a suitable  $N$ . This  $N$  should probably depend on  $\epsilon$  in some way.
- Verify that  $|a_n - L| < \epsilon$  for all  $n \geq N$ .

Along the way, you might find the following theorem useful.

**Theorem 4** (Archimedean properties)

The following statements are equivalent and true.

- (i) If  $a$  and  $b$  are real numbers and  $a > 0$ , then there exists an  $n > 0$  such that  $na > b$ .
- (ii) For every  $x \in \mathbb{R}$ , there exists an  $n$  such that  $n \leq x < n + 1$ .
- (iii) For every  $x > 0$ , there exists  $n > 0$  such that  $1/n \leq x$ .

**Example 1.1.** Show that  $\lim_{n \rightarrow \infty} \frac{1}{n} = 0$ .

Let  $\epsilon > 0$ . Let  $N = \lfloor \frac{1}{\epsilon} \rfloor + 1$ . Then for all  $n > N$ ,

$$|a_n - L| = \left| \frac{1}{n} - 0 \right| = \frac{1}{n} < \frac{1}{N} < \epsilon.$$

Why did we choose this  $\delta$ ? The equality  $\frac{1}{N} = \epsilon$  has solution  $N = \frac{1}{\epsilon}$ . But we need this to be an integer, so we take the floor of this number. Now  $\lfloor x \rfloor \leq x$  for all  $x$ , and so with  $N = \lfloor \frac{1}{\epsilon} \rfloor$  we have  $\frac{1}{N} \geq \epsilon!$  To turn this into a strict inequality, we add a 1.

**Example 1.2.** Show  $\lim_{n \rightarrow \infty} \frac{4n+1}{n+3} = 4$ .

Work backwards:  $|x_n - 4| = \left| \frac{4n+1}{n+3} - 4 \right| = \left| \frac{-11}{n+3} \right|$ . Therefore, as with last time we set  $N = \lfloor \frac{11}{\epsilon} - 3 \rfloor + 1$ .

Now let  $\epsilon > 0$  and let  $N = \lfloor \frac{11}{\epsilon} - 3 \rfloor + 1$ . Then

$$|x_n - 4| = \left| \frac{4n+1}{n+3} - 4 \right| = \left| \frac{-11}{n+3} \right| = \frac{11}{n+3} < \frac{11}{N+3} < \epsilon.$$

## 1.1 Characterizing nearness

**Definition 5** (Open interval). An **open interval** is a set of the form

$$(a, b) = \{x \in \mathbb{R} \mid a < x < b\}$$

for some pair of real numbers  $a < b$ .

Open intervals—and more generally, open neighbourhoods—help us characterize precisely what it means for two points in a space to be “as close as possible” to one another.

**Definition 6** (Open ball). The open ball centered at a point  $x$  of radius  $r$  is the set

$$B_r(x) = \{y \in \mathbb{R} : |x - y| < r\}$$

Notice that open balls are open intervals.

### 1.1.1 Exercises

1. Prove that  $\lim_{n \rightarrow \infty} 1 = 1$ .
2. ★ Prove that  $\lim_{n \rightarrow \infty} \frac{n-1}{n+1} = 1$ .
3. For each function  $f$  and each pair of real numbers  $c, r$  listed below, draw the graph of  $f(x)$  and highlight the set  $f^{-1}(B_r(c))$  on the  $x$ -axis. Next, write each set  $f^{-1}(B_r(c))$  as the union of open intervals.
  - (a)  $f(x) = x, c = 4, r = 1$
  - (b)  $f(x) = x^2, c = 1, r = 1/2$
  - (c)  $f(x) = 1/x, c = 0, r = 1$ .

## 1.2 Limits of Functions

**Definition 7** (Limit of a Function). We say that  $L$  is the **limit** of  $f(x)$  as  $x$  tends to  $a$ , or equivalently,

$$\lim_{x \rightarrow a} f(x) = L,$$

if for any  $\epsilon > 0$ , there exists a  $\delta > 0$  such that  $0 < |x - a| < \delta$  implies  $|f(x) - L| < \epsilon$ .

**The Limit Cookbook, for Functions.** It is likewise easy to describe a recipe for preparing the limit  $L$  for  $f(x)$ :

- Let  $\epsilon > 0$  be given.

- Conjure up a suitable  $\delta$ . This  $\delta$  should probably depend on  $\epsilon$  in some way.
- Verify that  $|f(x) - L| < \epsilon$  for any  $x$  such that  $0 < |x - a| < \delta$ .

When constructing the epsilon-delta proof, we need to determine the value for delta. To determine delta, it is helpful to begin with the final statement and work backwards.

Of course the limit of an arbitrary function  $f$  at a point  $a$  need not exist (as the following exercise demonstrates), but when it does, it is unique (convince yourself of this intuitively). We may therefore speak of *the* limit.

**Example 1.3.** Show that  $\lim_{x \rightarrow 4}(5x - 7) = 13$ .

We first work backwards. Let  $\epsilon$  be given. We want to determine  $\delta$ . We have

$$\begin{aligned} |f(x) - L| < \epsilon &\implies |(5x - 7) - 13| < \epsilon \implies |5x - 20| < \epsilon \\ &\implies |5||x - 4| < \epsilon \implies |x - 4| < \frac{\epsilon}{5} \end{aligned}$$

Note that we want to now let  $\delta = \frac{\epsilon}{5}$ . We can now write the proof:

Suppose  $\epsilon > 0$  has been provided. Define  $\delta = \frac{\epsilon}{5}$ . Since  $\epsilon > 0$ , we also have  $\delta > 0$ . Now for every  $x$ , the statement  $0 < |x - c| < \delta$  implies  $0 < |x - c| < \frac{\epsilon}{5}$ . Then

$$|5x - 20| < \epsilon \implies |(5x - 7) - 13| < \epsilon.$$

Therefore  $\lim_{x \rightarrow 4}(5x - 7) = 13$ .

**Example 1.4.** Prove that  $\lim_{x \rightarrow 5}(3x^2 - 1) = 74$ .

Let's begin with some scratch work. Recall that the statement  $|a| < b$  is equivalent to  $-b < a < b$ .

$$\begin{aligned} |f(x) - L| < \epsilon &\implies |(3x^2 - 1) - 74| < \epsilon \implies |3x^2 - 75| < \epsilon \\ &\implies -\epsilon < 3x^2 - 75 < \epsilon \implies 25 - \frac{\epsilon}{3} < x^2 < 25 + \frac{\epsilon}{3}. \end{aligned}$$

Since the square root function is increasing, it preserves  $<$ . So

$$\sqrt{25 - \frac{\epsilon}{3}} < x < \sqrt{25 + \frac{\epsilon}{3}} \implies -5 + \sqrt{25 - \frac{\epsilon}{3}} < x - 5 < -5 + \sqrt{25 + \frac{\epsilon}{3}},$$

where we subtracted 5 since we want to evaluate the limit there. There are now two candidates for  $\delta$ , and  $\delta$  needs to be less than or equal to both of them. We can just let  $\delta = \min\{\sqrt{25 - \frac{\epsilon}{3}}, -5 + \sqrt{25 + \frac{\epsilon}{3}}\}$ . However, note that the expression on the left is undefined for  $\epsilon > 75$ . We will handle this situation by introducing a smaller  $\epsilon$  in the proof.

We can now prove the limit. Suppose we are given  $\epsilon > 0$ . Let  $\epsilon_2 = \min\{\epsilon, 72\}$  (this avoids the "large  $\epsilon$ " situation. Define  $\delta = \min\{\sqrt{25 - \frac{\epsilon_2}{3}}, -5 + \sqrt{25 + \frac{\epsilon_2}{3}}\}$ . Since  $\epsilon_2 > 0$ , we also have  $\delta > 0$ . Now for every  $x$ , the expression  $0 < |x - c| < \delta$  implies

$$-\delta < x - c < \delta \implies -5 + \sqrt{25 - \frac{\epsilon_2}{3}} < x - 5 < -5 + \sqrt{25 + \frac{\epsilon_2}{3}}$$

which we have seen is equivalent to

$$-\epsilon_2 < 3x^2 - 75 < \epsilon_2.$$

Therefore

$$|3x^2 - 75| = |(3x^2 - 1) - 74| < \epsilon_2 \leq \epsilon.$$

Therefore,  $\lim_{x \rightarrow 5}(3x^2 - 1) = 74$ .

### 1.3 Continuity of Functions

**Definition 8** (Continuous function). A function  $f : \mathbb{R} \rightarrow \mathbb{R}$  is said to be **continuous** at  $a \in \mathbb{R}$  if

$$\lim_{x \rightarrow a} f(x) = f(a).$$

The same function  $f$  is said to be *continuous* if  $f$  is continuous at  $a$  for every  $a \in \mathbb{R}$ .

**Example 1.5.** For all  $p \in \mathbb{R}$ ,  $p > 0$ ,  $\lim_{x \rightarrow p} \sqrt{x} = \sqrt{p}$ .

Given  $\epsilon > 0$  we must show that  $|\sqrt{x} - \sqrt{p}| < \epsilon$ , provided that  $x$  and  $p$  are close enough. Now  $|\sqrt{x} - \sqrt{p}| = \frac{|x - p|}{|\sqrt{x} + \sqrt{p}|} < \frac{|x - p|}{\sqrt{p}}$ . Therefore, choosing  $\delta = \frac{\epsilon}{\sqrt{p}}$  gives the desired result.

#### 1.3.1 Exercises

1. Consider the function

$$f(x) = \begin{cases} -x^2 & \text{if } x \leq -2, \\ x - 1 & \text{if } -2 < x \leq 1, \\ \log(x) & \text{if } x > 1. \end{cases}$$

For which  $a$  does the limit  $\lim_{x \rightarrow a} f(x)$  exist?

2. ★ Show that the Heaviside step function

$$H(x) = \begin{cases} 0 & \text{if } x < 0 \\ 1 & \text{if } x \geq 0 \end{cases}$$

has no limit at 0.

3. ★ Show that  $\lim_{x \rightarrow 2} x^2 = 4$ .
4. Prove, formally, that limits are unique.
5. Suppose that both  $\lim_{x \rightarrow a} f(x)$  and  $\lim_{x \rightarrow a} g(x)$  exist. Prove that the limit  $\lim_{x \rightarrow a} (f(x) + g(x))$  exists, and that

$$\lim_{x \rightarrow a} (f(x) + g(x)) = \lim_{x \rightarrow a} f(x) + \lim_{x \rightarrow a} g(x).$$

Does the converse hold?

6. Suppose that both  $\lim_{x \rightarrow a} f(x)$  and  $\lim_{x \rightarrow a} g(x)$  exist. Prove that the limit  $\lim_{x \rightarrow a} f(x)g(x)$  exists, and that

$$\lim_{x \rightarrow a} f(x)g(x) = \lim_{x \rightarrow a} f(x) \cdot \lim_{x \rightarrow a} g(x).$$

Does the converse hold?

7. ★ Prove that the function  $f(x) = 2x$  is continuous.
8. Prove that the Heaviside step function is continuous everywhere except for 0.

9. Suppose  $f : \mathbb{R} \rightarrow \mathbb{R}$  and  $g : \mathbb{R} \rightarrow \mathbb{R}$  are both continuous. Prove that  $f + g$  is also continuous.
10. Suppose  $f : \mathbb{R} \rightarrow \mathbb{R}$  and  $g : \mathbb{R} \rightarrow \mathbb{R}$  are both continuous. Prove that  $f \cdot g$  is also continuous.