

# Real Analysis

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## Abstract

I really don't feel like doing analysis the way I did group theory and linear algebra, where I type out my notes on a latex file. Instead, I'll do my **Analysis I** from [MIT OCW](#) and write the solutions to the problem set here.

# 1 Problem Set 1

## Problem 1.1

Let  $\mathbb{F}$  be a ordered field with  $1 \neq 0$ . Show that  $1 > 0$ .

*Solution.*

First let us prove that  $(-1) \cdot (-1) = 1$ . We know that for all  $x \in \mathbb{F}$ , there is an inverse element  $-x$  such that,

$$x + (-x) = 0$$

Thus,  $1 + (-1) = 0$  which means that

$$\begin{aligned} 0 &= (-1) \cdot 0 = (-1) \cdot (1 + (-1)) = (-1) \cdot 1 + (-1) \cdot (-1) = (-1) + (-1) \cdot (-1) \\ &\implies 1 = (-1) \cdot (-1) \end{aligned}$$

Since  $\mathbb{F}$  is a ordered field, one of the statement below must be true because of the **first axiom of order**.

$$1 < 0, \quad 1 = 0, \quad 0 < 1 \tag{1}$$

We assumed that  $1 \neq 0$  so the middle statement can't be true and if  $1 < 0$  then  $0 < (-1)$ . But from **axiom of order and multiplication**  $0 < (-1) \cdot (-1) = 1$ . Thus a contradiction.

## Problem 1.2

Define the addition of two rational numbers by

$$\frac{n}{m} + \frac{p}{q} := \frac{nq + mp}{mq}.$$

Show that it is well-defined.

*Solution.*

Suppose  $\frac{n}{m} = \frac{n_1}{m_1}$  and  $\frac{p}{q} = \frac{p_1}{q_1}$  then using the definition of when two rational numbers are equal, we get  $nm_1 = n_1m$  and  $pq_1 = p_1q$ . Thus,

$$\begin{aligned} m_1q_1(nq + pm) &= m_1q_1nq + m_1q_1pm \\ &= n_1mq_1q + p_1qm_1m \\ &= mq(n_1q_1 + m_1p_1) \end{aligned}$$

Thus,  $\frac{n}{m} + \frac{p}{q} = \frac{n_1}{m_1} + \frac{p_1}{q_1}$ .

**Problem 1.3**

Find the  $\sup E$  and  $\inf E$  for the following set  $E$ .

1.  $E = \{n \in \mathbb{Z} \mid n < \sqrt{12}\}$
2.  $E = \{r \in \mathbb{Q} \mid r < \sqrt{12}\}$
3.  $E = \{x \in \mathbb{R} \mid x^2 - x - 1 < 0\}$
4.  $E = \left\{\frac{n^2+n}{n+1} \mid n \in \mathbb{N}\right\}$

*Solution.*

1.  $\sup E = 3$  but  $\inf E$  doesn't exist.
2.  $\sup E = \sqrt{12}$  but  $\inf E$  doesn't exist.
3.  $\sup E = \frac{1+\sqrt{5}}{2}$  and  $\inf E = \frac{1-\sqrt{5}}{2}$ .
4.  $\inf E = 1$  but  $\sup E$  doesn't exist.

**Problem 1.4**

Let  $\mathbb{M}$  be the set of polynomials with integer coefficients i.e,

$$\mathbb{M} := \{f(x) = a_0 + a_1x + \cdots + a_nx^n \mid a_i \in \mathbb{Z}\}$$

Define the relation  $0 \prec f$  if  $0 < f(x)$  for  $x$  large enough. More precisely, we say

$$0 \prec f \quad \text{if there exists } M > 0 \text{ such that } f(x) > 0 \text{ for all } x > M.$$

Then define

$$f \prec g \quad \text{if } 0 \prec (g - f).$$

Show that  $(\mathbb{M}, \prec)$  is an ordered set.

*Solution.*

We'll use the fact that for large enough  $x$ ,  $f(x) > 0$  for  $a_n > 0$ . Let  $f, g \in \mathbb{M}$  such that  $f \neq g$  and

$$f(x) = a_0 + a_1x + \cdots + a_nx^n \quad \text{and} \quad g(x) = b_0 + b_1x + \cdots + b_nx^n$$

Define  $h(x) = g(x) - f(x) = (b_0 - a_0) + (b_1 - a_1)x + \cdots + (b_n - a_n)x^n$  and let  $c_i = b_i - a_i$ . Suppose  $c_k$  is the highest degree non zero coefficient, then if

1.  $c_k > 0$  then  $f \prec g$
2.  $c_k < 0$  then  $g \prec f$

Suppose  $f \prec g$  and  $g \prec h$ . Then,  $f(x) < g(x)$  and  $g(x) < h(x)$  for large  $x$  and hence  $f(x) < h(x)$  for large  $x$ . Thus,  $0 \prec (h - f)$  which means  $f \prec h$ .

**Problem 1.5**

Prove that  $(\mathbb{M}, \prec)$  **doesn't** satisfy the archimedean property.

*Solution.*

To show that it doesn't satisfy the archimedean property, we need to show that  $\exists f, g \in \mathbb{M}$  such that

$$\forall n \in \mathbb{N}, g \not\prec nf$$

If we choose  $g(x) = x^2$  and  $f(x) = x$  and assume  $g \prec nf$  then,  $0 \prec x(n - x)$  which means that  $0 < x(n - x)$  which we know is false for large  $x$ . Thus,  $g \not\prec nf$ .

**Problem 1.6**

Show that for any non-empty set  $E \subset \mathbb{R}$  which is bounded from below,  $E$  has the greatest lower bound.

*Solution.*

To show that  $E$  has greatest lower bound define

$$-E = \{-x \mid x \in E\}$$

If  $\alpha$  is any lower bound of  $E$  then  $x \geq \alpha \Rightarrow -x \leq -\alpha$ . That means that  $-E$  is bounded above by  $-\alpha$ . Since  $-E$  is bounded above by  $-\alpha$ , it must have the least upper bound property. Let

$$\sup -E = \beta$$

Thus,  $\beta \geq -x \Rightarrow x \geq -\beta$  and  $\beta \leq -\alpha$  for any lower bound  $\alpha$  of  $E$ . Thus,  $\alpha \leq -\beta$ . Hence,  $-\beta = \inf E$ .

**Problem 1.7**

Show that for any real number  $x \in \mathbb{R}$  there exists a real number  $y \in \mathbb{R}$  such that  $y^3 = x$ .

*Solution.*

If  $x = 0$  then  $y = 0^3 = 0$ . Let us define

$$A = \{a \mid a > 0 \text{ and } a^3 \leq x\}$$

for  $x > 0$ . Since  $A$  is non-empty and bounded, let  $y = \sup A$ . We will show that  $y^3 = x$ . Suppose  $x > y^3$ . Let  $h = \min\{\frac{1}{2}, \frac{x-y^3}{3y^2+3y+1}\}$  then,

$$\begin{aligned} (y+h)^3 &= y^3 + h^3 + 3yh^2 + 3y^2h \\ &< y^3 + h(1 + 3y + 3y^2) \\ &\leq y^3 + \frac{x-y^3}{3y^2+3y+1} \cdot (1 + 3y + 3y^2) \\ &\leq x \end{aligned}$$

Thus,  $y+h \in A$  but since  $y$  is the least upper bound of  $A$  we have,  $y+h \leq y \Rightarrow h \leq 0$ . This is a contradiction.

Suppose  $x < y^3$ . Let  $h = \frac{y^3 - x}{3y^2}$  then

$$\begin{aligned}(y - h)^3 &= y^3 - h^3 - 3y^2h + 3yh^2 \\ &= y^3 - h^3 - 3y^2 \cdot \frac{(y^3 - x)}{3y^2} + 3yh^2 \\ &= x - h^3 + 3yh^2\end{aligned}$$

Since  $3yh^2 - h^3 > 0$  we have  $(y - h)^3 > x$ . Let  $q \in A$  then

$$q^3 \leq x < (y - h)^3$$

Thus,  $(y - h)^3 - q^3 > 0 \Rightarrow (y - h - q)((y - h)^2 + (y - h)q + q^3) > 0$ . Since,  $(y - h)^2 + (y - h)q + q^3 > 0$  we have  $y - h > q$ . Thus  $(y - h)$  is an upper bound for  $A$ . Thus  $y \leq y - h \Rightarrow h \leq 0$ . Contradiction!!

The proof also works for  $x < 0$  as  $-x > 0$ . Thus,

$$\exists k \in \mathbb{R} \text{ s.t. } k^3 = -x$$

Let  $z := -k$  then  $z^3 = (-k)^3 = -k^3 = -(-x) = x$ .

## 2 Problem Set 2

### Problem 2.1

Let  $a_n$  and  $b_n$  be a sequence of real numbers.

1. Assume that  $\lim_{n \rightarrow \infty} a_n$  and  $\lim_{n \rightarrow \infty} b_n$  exists. Show that  $\lim_{n \rightarrow \infty} (a_n b_n) = \left( \lim_{n \rightarrow \infty} a_n \right) \left( \lim_{n \rightarrow \infty} b_n \right)$  exists.
2. Give an example in which  $\lim_{n \rightarrow \infty} (a_n b_n)$  exists but neither  $\lim_{n \rightarrow \infty} a_n$  nor  $\lim_{n \rightarrow \infty} b_n$  exists.

*Solutions.*

To show that  $\lim_{n \rightarrow \infty} a_n b_n = ab$  we need to show  $\exists N \in \mathbb{N}$  such that for all  $\varepsilon > 0$  we have

$$|a_n b_n - ab| < \varepsilon$$

for  $n \geq N$ . Now,

$$\begin{aligned} |a_n b_n - ab| &= |a_n b_n - a_n b + a_n b - ab| \\ &\leq |a_n(b_n - b)| + |b(a_n - a)| \\ &= |a_n||b_n - b| + |b||a_n - a| \end{aligned}$$

Since  $\{a_n\}$  is convergent, we know that it is bounded above. Suppose  $|a_n| < C$  then

$$|a_n||b_n - b| + |b||a_n - a| < |C||b_n - b| + |b||a_n - a|$$

Also let  $N_1 \in \mathbb{N}$  such that  $|b_n - b| < \frac{\varepsilon}{2(|C| + 1)}$  for all  $n \geq N_1$  and let  $N_2 \in \mathbb{N}$  such that  $|a_n - a| < \frac{\varepsilon}{2(|b| + 1)}$  for all  $n \geq N_2$ . Thus for  $n \geq \max\{N_1, N_2\}$  we have,

$$\begin{aligned} 2|a_n||b_n - b| + |b||a_n - a| &< |C||b_n - b| + |b||a_n - a| \\ &< |C| \cdot \frac{\varepsilon}{2(|C| + 1)} + |b| \cdot \frac{\varepsilon}{2(|b| + 1)} \\ &< \frac{\varepsilon}{2} + \frac{\varepsilon}{2} \\ &< \varepsilon \end{aligned}$$

For the second part just take  $a_n = (-1)^n$  and  $b_n = (-1)^n$ . We know that  $\lim_{n \rightarrow \infty} a_n b_n = 1$  but  $\lim_{n \rightarrow \infty} a_n$  and  $\lim_{n \rightarrow \infty} b_n$  doesn't exist.

### Problem 2.2

Find the limit of the following sequence if it exists or show that the limit doesn't exist.

1.  $a_n = \frac{n^2}{n+1} - \frac{n^2+1}{n}$
2.  $a_n = \frac{\sin(n)}{n}$
3.  $a_n = \sum_{i=1}^n \frac{n^2}{\sqrt{n^6 + i}}$

*Solution.*

For the first part we know that  $a_n = \frac{1}{n+1} - \frac{1}{n} - 1$ . Thus,

$$\begin{aligned}\lim_{n \rightarrow \infty} \frac{1}{n+1} - \frac{1}{n} - 1 &= \lim_{n \rightarrow \infty} \frac{1}{n+1} - \lim_{n \rightarrow \infty} \frac{1}{n} - \lim_{n \rightarrow \infty} 1 \\ &= 0 - 0 - 1 \\ &= -1\end{aligned}$$

The first equation is due to the algebraic property of limit.

For the second part, we need to show that

$$\left| \frac{\sin(n)}{n} \right| < \varepsilon$$

We know that  $0 \leq |\sin(n)| \leq 1 \Rightarrow 0 \leq \frac{|\sin(n)|}{|n|} \leq \frac{1}{|n|}$ . Thus, for any  $N > \frac{1}{\varepsilon}$  we have

$$\left| \frac{\sin(n)}{n} \right| \leq \frac{1}{|n|} < \frac{1}{N} < \varepsilon$$

For the third part, we will use **squeeze theorem** to show that the limit is 1. Notice that,

$$\frac{n^2}{\sqrt{n^6 + n}} < \frac{n^2}{\sqrt{n^6 + i}} < \frac{n^2}{\sqrt{n^6}}$$

for  $i = 1, 2, \dots, n$ . Thus,

$$\begin{aligned}n \cdot \frac{n^2}{\sqrt{n^6 + n}} &\leq \sum_{i=1}^n \frac{n^2}{\sqrt{n^6 + i}} \leq n \cdot \frac{n^2}{\sqrt{n^6}} \\ \Rightarrow \frac{1}{\sqrt{1 + \frac{1}{n^5}}} &\leq \sum_{i=1}^n \frac{n^2}{\sqrt{n^6 + i}} \leq 1 \\ \Rightarrow \lim_{n \rightarrow \infty} \frac{1}{\sqrt{1 + \frac{1}{n^5}}} &\leq \lim_{n \rightarrow \infty} \sum_{i=1}^n \frac{n^2}{\sqrt{n^6 + i}} \leq \lim_{n \rightarrow \infty} 1 \\ \Rightarrow 1 &\leq \lim_{n \rightarrow \infty} \sum_{i=1}^n \frac{n^2}{\sqrt{n^6 + i}} \leq 1\end{aligned}$$

Thus, by **squeeze theorem** we have  $\lim_{n \rightarrow \infty} a_n = 1$ .

### Problem 2.3

Let  $a_n$  be a sequence of real numbers and  $L$  be a real number. Show that the following two statements are equivalent. One holds if and only if the other does.

1. There exists a subsequence  $a_{n_k}$  converging to  $L$ .
2. For any  $\epsilon > 0$ , there exist infinitely many  $a_n$  in  $(L - \epsilon, L + \epsilon)$ .

*Solution.*

Suppose (1.) holds then there exists a  $N \in \mathbb{N}$  such that for all  $k \geq N$  we have,

$$|a_{n_k} - L| < \varepsilon \implies L - \varepsilon < a_{n_k} < L + \varepsilon$$

Thus, there are infinitely many  $a_i$  in the interval  $(L - \varepsilon, L + \varepsilon)$ .

Suppose (2.) holds then for any  $\varepsilon > 0$  there are infinitely many  $a_n$  such that

$$L - \varepsilon < a_n < L + \varepsilon$$

Since there are infinitely many terms in  $(L - 1, L + 1)$  choose  $n_1$  such that

$$|a_{n_1} - L| < 1$$

Since there are infinitely many terms in  $(L - \frac{1}{2}, L + \frac{1}{2})$  choose  $n_2$  such that

$$n_2 > n_1 \text{ and } |a_{n_2} - L| < \frac{1}{2}$$

Continuing inductively we can produce a sequence such that  $\{a_{n_i}\}$

$$|a_{n_k} - L| < \frac{1}{k}$$

Hence,  $a_{n_k} \rightarrow L$ .

#### Problem 2.4

Where possible, find a subsequence that is monotone and a subsequence that is convergent for the following sequences.

1.  $a_n = \sin(n\pi/8)$

2.  $a_n = (-1)^n n$

*Solution.*

Notice that

$$\sin\left(\frac{n\pi}{8}\right) = \begin{cases} 0 & \text{if } n = 8k \\ 1 & \text{if } n = 4(4k + 1) \\ -1 & \text{if } n = 4(4k - 1) \end{cases}$$

So a monotone subsequence would be  $a_{n_k} = 1$ . And the same example works for convergent subsequence.

For the second part, notice that

$$a_n = \begin{cases} 2k & \text{if } n = 2k \\ -2k - 1 & \text{if } n = 2k + 1 \end{cases}$$

So a monotone subsequence would be  $a_{n_k} = 2k$ . But there is no convergent subsequence, because we know that every subsequence would have a infinitely many odd numbers or infinitely many even numbers but we know that those aren't bounded.



### 3 Problem Set 3

#### Problem 3.1

Prove that for reals  $x < y$ , there exists a  $r \in \mathbb{Q}$  such that  $x < r < y$ .

*Solution.* Using the archimedean property of  $\mathbb{R}$

$$\begin{aligned} \exists n \in \mathbb{N}, \text{ s.t. } \frac{1}{n} < y - x \\ \implies n(y - x) > 1 \end{aligned}$$

Since the difference is greater than 1, there exists a integer  $m$  such that

$$nx < m < ny \implies x < \frac{m}{n} < y$$

Hence we are done.

#### Problem 3.2

Let  $E$  be an non-empty subset of  $\mathbb{R}$  which is bounded. Define

$$F := \{x^2 \mid x \in E\}$$

Show that  $\sup F$  exists and that  $\sup F = \max\{(\sup E)^2, (\inf E)^2\}$ .

*Solution.*

Since  $E$  is bounded  $F$  is also bounded. Then since  $\inf E \leq x \leq \sup E$  we have

$$x^2 \leq \max\{(\sup E)^2, (\inf E)^2\}$$

If  $\max\{(\sup E)^2, (\inf E)^2\} = (\sup E)^2$  then  $\sup E \geq 0$  and  $(\sup E)^2$  is an upper bound for  $F$ . Let  $C$  be any upper bound for  $F$ . Then  $C \geq x^2 \Rightarrow \sqrt{C} \geq |x| \geq x$  for all  $x \in E$ . Hence  $\sqrt{C}$  is an upper bound for  $E$ . Thus,  $\sqrt{C} \geq \sup E \Rightarrow C \geq (\sup E)^2$ . It follows that  $(\sup E)^2 = \sup F$ .

Similarly if  $\max\{(\sup E)^2, (\inf E)^2\} = (\inf E)^2$  then  $\sup F = (\inf E)^2$ .

#### Problem 3.3

Let  $E$  be an non-empty subset of  $\mathbb{R}$  which is bounded from above. Show that there exists a sequence  $\{a_n\}$  such that  $a_n \in E$  and  $\lim_{n \rightarrow \infty} a_n = \sup E$ .

*Solution.*

We know that for each  $\varepsilon > 0$  there exists at least one  $a \in E$  such that  $a > \sup E - \varepsilon$ . Let  $a_k \in E$  such that  $a_k > \sup E - \frac{1}{k}$ . Thus,  $\frac{1}{k} > \sup E - a_k \geq 0$ . Thus the sequence  $\{a_n\}$  converges to  $\sup E$  and  $\lim_{n \rightarrow \infty} a_n = \sup E$ .

**Problem 3.4**

Let  $a_1 = 4$  and define  $a_n$  inductively by

$$a_n = 4 - \frac{4}{a_{n-1}} \text{ for } n \geq 2$$

Show that  $\lim_{n \rightarrow \infty} a_n = 2$ .

*Solution.* Using induction one can prove that

$$a_n = 2 + \frac{2}{n}, \text{ for } n \geq 1$$

Thus,  $\lim_{n \rightarrow \infty} a_n = 2$ .

**Problem 3.5**

Let  $T : \mathbb{R} \rightarrow \mathbb{R}$  be a contraction map and  $x \in \mathbb{R}$  be a number. Define a sequence  $a_n$  by requiring  $a_1 = x$  and  $a_{n+1} = T(a_n)$ .

1. Show that for any  $m \in \mathbb{N}$ ,  $|a_1 - a_m| \leq \frac{1}{1-\lambda}|a_1 - a_2|$
2. Show that  $a_n$  is a Cauchy sequence.

*Solution.*

Notice that,

$$\begin{aligned} |a_n - a_{n+1}| &\leq \lambda |a_{n-1} - a_n| \\ &\leq \lambda^2 |a_{n-2} - a_{n-1}| \\ &\leq \vdots \\ &\leq \lambda^{n-1} |a_1 - a_2| \end{aligned}$$

Therefore,

$$\begin{aligned} |a_1 - a_m| &\leq |a_1 - a_{m-1}| + |a_{m-1} - a_m| \\ &\leq |a_1 - a_{m-2}| + |a_{m-2} - a_{m-1}| + |a_{m-1} - a_m| \\ &\leq \vdots \\ &\leq |a_1 - a_2| + \sum_{i=1}^{m-1} |a_i - a_{i+1}| \\ &\leq |a_1 - a_2| + \sum_{i=1}^{m-1} \lambda^i |a_1 - a_2| \\ &\leq |a_1 - a_2| \left( \sum_{i=0}^{m-1} \lambda^i \right) \\ &\leq |a_1 - a_2| \left( \frac{1 - \lambda^m}{1 - \lambda} \right) \leq \left( \frac{1}{1 - \lambda} \right) |a_1 - a_2| \end{aligned}$$

For the second part, suppose  $m > n$  then,

$$\begin{aligned} |a_n - a_m| &\leq |a_n - a_{m-1}| + |a_{m-1} - a_m| \\ &\leq \vdots \\ &\leq \sum_{i=n}^{m-1} |a_i - a_{i+1}| \\ &\leq \sum_{i=n}^{m-1} \lambda^{i-1} |a_1 - a_2| \\ &\leq |a_1 - a_2| \cdot \left( \lambda^{n-1} \cdot \frac{1 - \lambda^{m-n}}{1 - \lambda} \right) \\ &\leq \frac{\lambda^{n-1}}{1 - \lambda} |a_1 - a_2| \end{aligned}$$

So for any  $\varepsilon > 0$  we can just choose a large  $n$  such that  $\varepsilon > \frac{\lambda^{n-1}}{1 - \lambda} |a_1 - a_2|$ .

## 4 Problem Set 4

### Problem 4.1

Give an example of a sequence  $a_n$  that satisfies the following two conditions.

- $a_n$  is divergent.
- For any  $\varepsilon > 0$ , there exists  $N \in \mathbb{N}$  such that

$$|a_{n+1} - a_n| < \varepsilon \quad \text{for all } n \geq N.$$

### Problem 4.2

Let  $p > 0$  be a positive number. Consider the  $p$ -series

$$\sum_{n=1}^{\infty} \frac{1}{n^p}.$$

In the lecture we proved that the series diverges for  $p = 1$  and converges for  $p = 2$ . Show that the series converges for  $p > 1$  and diverges for  $0 < p \leq 1$ .

### Problem 4.3

Let  $r > 0$  be a positive number. Determine whether the series

$$\sum_{n=1}^{\infty} a_n$$

converges or diverges for the following cases.

1.  $a_n = \sqrt{n+r} - \sqrt{n}$
2.  $a_n = n^3 r^n$
3.  $a_n = \frac{1}{n!} r^n$

The answer may depend on the value of  $r$ .

**Problem 4.4**

Let  $b_n$  be a sequence of non-negative numbers which decreases to zero. That is,

$$b_1 \geq b_2 \geq b_3 \geq \cdots \geq 0 \quad \text{and} \quad \lim_{n \rightarrow \infty} b_n = 0.$$

Let  $a_n = (-1)^{n-1}b_n$ . The purpose of this problem is to show that

$$\sum_{n=1}^{\infty} a_n$$

converges. This is called the *alternating series test*. Let

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

1. Show that  $s_{2k+1}$  is decreasing and that  $s_{2k}$  is increasing.
2. Show that  $s_{2k+1}$  is bounded from below and that  $s_{2k}$  is bounded from above.
3. Show that both  $\lim_{k \rightarrow \infty} s_{2k+1}$  and  $\lim_{k \rightarrow \infty} s_{2k}$  exist and are identical.
4. Show that  $\sum_{n=1}^{\infty} a_n$  converges.