

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 an 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 an ordered field, one of the statements 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 α 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 α 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 $\varepsilon > \frac{\lambda^{n-1}}{1 - \lambda} |a_1 - a_2|$.