

Oxford M2 - Real Analysis I - Sequences and Series

1 Sheet 1

1.1

1. Prove, from the given Axioms for the Real Numbers, that, for real numbers a, b, c, d :

- (a) $a(bc) = c(ba)$;
- (b) $-(a + b) = (-a) + (-b)$;
- (c) if $ab = ac$ and $a \neq 0$, then $b = c$;
- (d) if $a < b$ and $c < d$ then $a + c < b + d$;
- (e) if $a \leq b$ and $c \leq d$ then $a + c = b + d$ only if $a = b$ and $c = d$.

[You should write out fully detailed answers, justifying each line of your argument by appeal to one, and only one, of the axioms.]

(a)

Theorem. $a(bc) = c(ba)$

Proof.

$$\begin{aligned} a(bc) &= a(cb) && \text{(M1 commutativity of multiplication)} \\ &= (ac)b && \text{(M2 associativity of multiplication)} \\ &= (ca)b && \text{(M1 commutativity of multiplication)} \\ &= c(ab) && \text{(M2 associativity of multiplication)} \\ &= c(ba) && \text{(M1 commutativity of multiplication)} \end{aligned}$$

□

(b)

Theorem. $-(a + b) = (-a) + (-b)$

Proof.

$$\begin{aligned}
(a+b) + (-(a+b)) &= 0 && \text{definition of negative} \\
((-a) + (-b)) + ((a+b) + (-(a+b))) &= (-a) + (-b) && \text{add to both sides what axiom is this?} \\
((-b) + (-a)) + ((a+b) + (-(a+b))) &= (-a) + (-b) && \text{S1 commutativity of sum} \\
(((b) + (-a)) + (a+b)) + (-(a+b)) &= (-a) + (-b) && \text{S2 associativity of sum} \\
((-b) + ((-a) + a) + b) + (-(a+b)) &= (-a) + (-b) && \text{S2 associativity of sum} \\
((-b) + (0+b)) + (-(a+b)) &= (-a) + (-b) && \text{definition of negative} \\
((-b) + b) + (-(a+b)) &= (-a) + (-b) && \text{definition of 0} \\
0 + (-(a+b)) &= (-a) + (-b) && \text{definition of negative} \\
-(a+b) &= (-a) + (-b) && \text{definition of 0}
\end{aligned}$$

□

1.2

2. Prove the following assertions, for real numbers a, b, c :

- (a) if $a < b$, then $ac > bc$ if and only if $c < 0$;
- (b) $a^2 + b^2 = 0$ if and only if $a = b = 0$;
- (c) $a^3 < b^3$ if and only if $a < b$.

[Less detailed answers are required than in Q. 1, but you should justify each step using axioms or results which have already been proved from the axioms.]

(a)

Theorem. *If $a < b$ then $ac > bc$ iff $c < 0$.*

Intuition. Multiplication by a scalar flips orientation iff the scalar is negative.

Proof.

TODO Prove carefully being explicit about which axioms are used.

Let \mathbb{P} be the strictly positive reals. We have $a < b$, i.e. $b - a \in \mathbb{P}$.

\implies :

We have $ac > bc$ i.e. $ac - bc \in \mathbb{P}$.

Therefore

$$\begin{aligned} (a - b)c &\in \mathbb{P} \\ (b - a)(-c) &\in \mathbb{P} \\ \frac{1}{b - a}(b - a)(-c) &\in \mathbb{P} \\ (-c) &\in \mathbb{P} \end{aligned}$$

\impliedby :

We have $c < 0$, i.e. $-c \in \mathbb{P}$. Therefore $(-c)(b - a) \in \mathbb{P}$ (by **P2**). Therefore $ac - bc \in \mathbb{P}$, i.e. $ac > bc$. \square

1.3

3. (a) Prove that $(a^m)^{-1} = (a^{-1})^m$, for all $a \in \mathbb{R} \setminus \{0\}$ ($m = 1, 2, \dots$).
- (b) Prove that $a^{k+1} = a^k a$ for $a \neq 0$ and $k = -1, -2, -3, \dots$.
- (c) Derive the law of indices: $a^m a^n = a^{m+n}$ for $a \neq 0$ and $m, n \in \mathbb{Z}$.

1.4

4. [In this question you may use familiar results about arithmetic and order in the real numbers. You are not expected to justify each line of your argument by citing axioms or properties derived from the axioms.] For $n = 1, 2, 3, \dots$, let

$$a_n := \left(1 + \frac{1}{n}\right)^n \quad \text{and} \quad b_n := \left(1 + \frac{1}{n}\right)^{n+1}.$$

- (a) Show that the inequality $a_n \leq a_{n+1}$ can be rearranged as

$$\left(\frac{n(n+2)}{(n+1)^2}\right)^{n+1} \geq \frac{n}{n+1}.$$

By applying Bernoulli's inequality to the left-hand side, verify this inequality.

- (b) Show that $b_{n+1} \leq b_n$ for all n .
(c) Note that $a_n \leq a_{n+1} \leq b_{n+1} \leq b_n$ for all n . Deduce that $a_n < 3$ for all n .

[The significance of the result in this exercise will be revealed later.]

1.5

5. Define $\max(a, b)$, the *maximum* of two real numbers a and b , saying which axiom(s) show that your specification is well-defined. Using your definition prove that $\max(a, b) = \frac{1}{2}(a+b) + \frac{1}{2}|a-b|$, and write down an analogous formula for $\min(a, b)$.

2 Sheet 2

2.1

1. For each of the following conditions, find and sketch the set of all pairs $(x, y) \in \mathbb{R}^2$ satisfying the condition:

(a) $|x| + |y| = 1$; (b) $|x - y| + |x + y| = 1$; (c) $\max(|x|, |y|) = 1$.

2.2

2. A student claims erroneously that

$$\frac{1}{|a+b|} \leq \frac{1}{|a|+|b|} \quad \text{if } a+b \neq 0.$$

Find an example to show that this is false in general. How might the student have come to make the error? Find an argument based on the Reverse Triangle Law which gives a valid upper bound for $1/|a+b|$ in terms of $|a|$ and $|b|$.

2.3 (COMPLETE)

3. Prove that $\{2^n \mid n \in \mathbb{N}\}$ is not bounded above. [*You may not make any use of logarithms.*]

Proof. Let $S = \{2^n \mid n \in \mathbb{N}\}$ and suppose an upper bound for S exists.

Then $\sup S$ exists by completeness of the reals.

By the Approximation Property there exists $2^k \in S$ such that

$$\sup S - \frac{1}{2} < 2^k \leq \sup S.$$

Note that $k + 1 \in \mathbb{N}$ therefore $2^{k+1} = 2^k + 2^k \in S$. Therefore

$$\begin{aligned} \sup S - \frac{1}{2} + 2^k &< 2^{k+1} \leq \sup S \\ \sup S &\leq \sup S + \frac{1}{2} - 2^k < \sup S, \end{aligned}$$

a contradiction. Therefore no upper bound for S exists. □

2.4 (COMPLETE)

4. For each of the following sets, decide which of the following exist: (i) supremum; (ii) infimum; (iii) maximum; (iv) minimum.

- (a) $\mathbb{Q} \cap [0, \sqrt{2}]$;
 (b) $\{(-1)^n + 1/n \mid n = 1, 2, \dots\}$;
 (c) $\{3^n \mid n \in \mathbb{Z}\}$;
 (d) $\bigcup_{n=1}^{\infty} [\frac{1}{2n}, \frac{1}{2n-1}]$.

In each case, either write down the value (without proof) or indicate why it is not defined.

1. $S = \mathbb{Q} \cap [0, \sqrt{2}]$

$$\begin{aligned}\sup S &= \sqrt{2} \\ \max S &= \sqrt{2} \\ \min S &= 0 \\ \inf S &= 0\end{aligned}$$

2. $S = \{(-1)^n + 1/n \mid n = 1, 2, \dots\}$

$$\begin{aligned}\sup S &= 3/2 \\ \max S &= 3/2 \\ \min S &\text{ does not exist since } \inf S \notin S \\ \inf S &= -1\end{aligned}$$

3. $S = \{3^n \mid n \in \mathbb{Z}\}$

$$\begin{aligned}\sup S &\text{ does not exist, } S \text{ has no upper bound} \\ \max S &\text{ does not exist, } S \text{ has no upper bound} \\ \min S &\text{ does not exist, } S \text{ has no lower bound} \\ \inf S &= 0\end{aligned}$$

4. $S = \bigcup_{n=1}^{\infty} [\frac{1}{2n}, \frac{1}{2n-1}]$

$$\begin{aligned}\sup S &= 1 \\ \max S &= 1 \\ \min S &\text{ does not exist, } S \text{ has no lower bound} \\ \inf S &= 0\end{aligned}$$

2.5 (COMPLETE)

5. Let S, T be non-empty subsets of \mathbb{R} .

- (a) Assume that S and T are bounded above. Prove that $S \cup T$ is bounded above and that $\sup(S \cup T) = \max(\sup S, \sup T)$.

Proof. Let $S, T \subset \mathbb{R}$ with $S, T \neq \emptyset$. Assume that S and T are bounded above. Then $\sup S$ and $\sup T$ exist. Let $b = \max(\sup S, \sup T)$.

Then $b \geq s$ for all $s \in S$ and $b \geq t$ for all $t \in T$. Therefore b is an upper bound for $S \cup T$.

Suppose there exists $a < b$ such that a is an upper bound of $S \cup T$. Then either $a < \sup S$ or $a < \sup T$. Without loss of generality, suppose $a < \sup S$. Then a is not an upper bound of S . Therefore there exists $s \in S$ such that $s > a$. But $s \in S \cup T$, therefore a is not an upper bound of $S \cup T$, a contradiction. \square

- (b) Assume that S and T are bounded below. Prove that the set

$$S + T := \{s + t \mid s \in S, t \in T\}$$

is bounded below and that $\inf(S + T) = \inf S + \inf T$.

Proof. Let $S, T \subset \mathbb{R}$ with $S, T \neq \emptyset$. Assume that S and T are bounded below. Then $\inf S$ and $\inf T$ exist. Define

$$S + T := \{s + t \mid s \in S, t \in T\}.$$

Let $a = \inf S + \inf T$.

We claim that a is a lower bound for $S + T$, i.e. $u \geq a$ for all $u \in S + T$.

Let $u \in S + T$. Then $u = s + t$ for some $s \in S, t \in T$. Therefore

$$u = (\inf S + v) + (\inf T + w) = a + (v + w) \geq a$$

for some $v, w \geq 0$. Therefore a is a lower bound for $S + T$ as claimed.

We further claim that $a = \inf S + T$.

Suppose for a contradiction that there exists $b > a$ such that b is a lower bound for $S + T$. Then

$$b = a + v + w = (\inf S + v) + (\inf T + w)$$

for some $v, w > 0$. Fix $0 < \delta < \min(v, w)$. By 4.9 (Approximation Property of the supremum/infimum) there exist $s \in S$ and $t \in T$ such that $\inf S \leq s < \inf S + \delta$ and $\inf T \leq t < \inf T + \delta$. But then $s + t \in S + T$ and $s + t < b$, so b is not a lower bound for $S + T$, a contradiction. Therefore $a = \inf S + T$ as claimed. \square

2.6

6. Prove that there exists a unique real number a such that $a^3 = 2$. [Hint: adapt the proof of the existence of $\sqrt{2}$ from lectures.]

Proof. Let $S = \{x \in \mathbb{R} \mid x^3 < 2\}$. Since S is bounded above, $\sup S$ exists. Let $a = \sup S$. By trichotomy it suffices to show that $a^3 < 2$ and $a^3 > 2$ lead to contradictions.

First suppose $a^3 < 2$. We seek $h > 0$ such that $(a + h)^3 < 2$ since then $a + h \in S$, which would contradict the definition $a := \sup S$. Note that

$$\begin{aligned} (a + h)^3 &= a^3 + 3a^2h + 3ah^2 + h^3 - 2 \\ &< a^3 + 7a^2h - 2 && \text{if } h < a \\ &< 0 && \text{if } h < \frac{2 - a^3}{7a^2}, \end{aligned}$$

therefore if we take $h < \min\left(a, \frac{2 - a^3}{7a^2}\right)$ then we have the desired contradiction.

Alternatively suppose that $a^3 > 2$. By the Approximation Property for all $0 < h < a$ we can find $s \in S$ such that $a - h < s$, therefore $(a - h)^3 < s^3$. We seek an h for which $(a - h)^3 > 2$ since then we would have $s^3 > 2$ which would contradict the definition of S . Note that

$$\begin{aligned} (a - h)^3 - 2 &= a^3 - 3a^2h + 3ah^2 - h^3 - 2 \\ &> 0 && \text{if } 3ah^2 > 3a^2h + h^3. \end{aligned}$$

So we require $3ah > 3a^2 + h^2 \iff 3a^2 - 3ah + h^2 < 0$.

Incomplete

□

2.7

7. (a) Prove that there are uncountably many irrational numbers.

Definition (Countable). A set S is countable if $S \preceq \mathbb{N}$. I.e. there exists an injection $f : S \rightarrow \mathbb{N}$.

Definition (Uncountable). A set S is uncountable if it is not countable.

Definition (Injection). A function $A \rightarrow B$ is an injection if $f(a_1) = f(a_2) \implies a_1 = a_2$.

Proof. Suppose for a contradiction that $\mathbb{R} \setminus \mathbb{Q}$ is countable. Then an injection $f : \mathbb{R} \setminus \mathbb{Q} \rightarrow \mathbb{N}$ exists. Since \mathbb{Q} is countable, an injection $g : \mathbb{Q} \rightarrow \mathbb{N}$ exists. Consider the function $h : \mathbb{R} \rightarrow \mathbb{N}$ defined by

$$h(x) = \begin{cases} 2f(x) & x \in \mathbb{R} \setminus \mathbb{Q} \\ 2g(x) + 1 & x \in \mathbb{Q}. \end{cases}$$

We claim that $h : \mathbb{R} \rightarrow \mathbb{N}$ is an injection. Note that

- (i) $h(\mathbb{R} \setminus \mathbb{Q}) \cap h(\mathbb{Q}) = \emptyset$
- (ii) The $\mathbb{R} \rightarrow \mathbb{R}$ functions defined by $x \mapsto 2x$ and $x \mapsto 2x + 1$ are both injections.
- (iii) The composition of two injections is an injection.

Suppose $h(x_1) = h(x_2)$. Then either $x_1, x_2 \in \mathbb{Q}$ or $x_1, x_2 \in \mathbb{R} \setminus \mathbb{Q}$ by (i). In both cases we have $x_1 = x_2$ by (ii) and (iii). Therefore $h : \mathbb{R} \rightarrow \mathbb{N}$ is an injection, hence \mathbb{R} is countable.

But \mathbb{R} is not countable, so we have a contradiction. Therefore no such injection f exists, i.e. $\mathbb{R} \setminus \mathbb{Q}$ is uncountable. \square

- (b) Let a, b be real numbers with $a < b$. Show that there is a natural number n such that $\frac{1}{n} < b - a$. Deduce that there is a rational number in the interval (a, b) .

Proof. Let a, b be real numbers with $a < b$. Then $b - a > 0$. Since \mathbb{N} is not bounded above (Archimedean property) there exists $n \in \mathbb{N}$ such that $n > 1/(b - a)$, therefore $1/n < b - a$.

Suppose a is rational. Then $a + 1/n \in (a, b)$ is rational. Similarly, if b is rational then $b - 1/n \in (a, b)$ is rational.

Finally, suppose neither a nor b are rational. How to prove this case? \square

(c) Show further that between any two real numbers there is an irrational number.

Let a, b be real numbers with $a < b$.

2.8

8. [Optional] A complex number is said to be *algebraic* if it is the root of a polynomial with integer coefficients and otherwise is said to be *transcendental*.

- (a) Show that there are only countably many cubic polynomials with integer coefficients.

Proof. The cardinality of the set of cubic polynomials with integer coefficients is equal to the cardinality of the set $A := \{(a, b, c, d) \mid a, b, c, d \in \mathbb{Z}, a \neq 0\} = (\mathbb{Z} \setminus \{0\}) \times \mathbb{Z}^3$.

Let $f : (\mathbb{Z} \setminus \{0\}) \times \mathbb{Z}^3 \rightarrow \mathbb{N}$ be given by $f(a, b, c, d) = 2^a 3^b 5^c 7^d$. Then f is an injection by uniqueness of prime factorization of the integers. Therefore A is countable. \square

- (b) Show that there are only countably many complex numbers which are roots of some integer-coefficient cubic polynomial.

Proof. Note that a cubic polynomial has at most 3 distinct roots. Let U be the set of complex numbers that are roots of some integer-coefficient cubic polynomial. For each such polynomial, assign a distinct label from $\{0, 1, 2\}$ to each of the distinct roots. Then the cardinality of U is equal(*) to the cardinality of $B := \mathbb{Z} \setminus \{0\} \times \mathbb{Z}^3 \times \{0, 1, 2\}$. The set B is countable since $f : T \rightarrow \mathbb{N}$ given by $f(a, b, c, d, e) = 2^a 3^b 5^c 7^d 11^e$ is an injection. (* How to properly deal with the fact that U is smaller than B due to some polynomials having fewer than 3 distinct roots?) \square

- (c) Show further that there are only countably many algebraic numbers but uncountably many transcendental numbers.

Proof. (This differs because whereas previously we were restricted to cubics, now the polynomials can be of any degree $n \in \mathbb{N}$.)

The cardinality of the set of algebraic numbers is **Incomplete**. \square