Math40002 Analysis 1 — Problem Sheet 4

1. Consider the following properties of a sequence of real numbers $(a_n)_{n\geq 0}$:

   (i) $a_n \to a$, or

   (ii) "a_n eventually equals a" – i.e. $\exists N \in \mathbb{N}$ such that $\forall n \geq N,\ a_n = a$, or

   (iii) "(a_n) is bounded" – i.e. $\exists\, R \in \mathbb{R}$ such that $|a_n| < R \ \ \forall n \in N$.

   For each statement (a-e) below, which of (i-iii) is it equivalent to? Proof?

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

   (b) $\forall \epsilon > 0$ there are only finitely many $n \in \mathbb{N}$ for which $|a_n - a| \geq \epsilon$.

   (c) $\forall N \in \mathbb{N},\ \exists\, \epsilon > 0$ such that $n \geq N \ \Rightarrow\ |a_n - a| < \epsilon$.

   (d) $\exists\, \epsilon > 0$ such that $\forall N \in \mathbb{N},\ |a_n - a| < \epsilon\ \forall n \geq N$.

   (e) $\forall R > 0\ \exists\, N \in \mathbb{N}$ such that $n \geq N \ \Rightarrow\ a_n \in (a - \frac{1}{R}, a + \frac{1}{R})$.

2. Given a sequence $(a_n)_{n\geq 1}$ of *complex* numbers, define what $a_n \to a$ means. For $x, y \in \mathbb{R}$ and $z := x + iy \in \mathbb{C}$ show $\max(|x|,|y|) \ \leq\ |z| \ \leq\ \sqrt{2}\max(|x|,|y|)$, and

$$a_n \to a + ib \in \mathbb{C} \qquad \Longleftrightarrow \qquad \mathrm{Re}(a_n) \to a \quad \text{and} \quad \mathrm{Im}(a_n) \to b.$$

3. Suppose that $a_n \leq b_n \leq c_n\ \forall n$ and that $a_n \to a$ and $c_n \to a$. Prove that $b_n \to a$.

4. Suppose that $a_n \to 0$ and (b_n) is bounded. Prove that $a_n b_n \to 0$.

5. * Suppose that (a_n) and (b_n) are sequences of real numbers such that $a_n \to a$ and $b_n \to b \neq 0$. Prove that the set $\{a_n : n \in \mathbb{N}\}$ is bounded and that

$$\exists\, N \in \mathbb{N} \quad \text{such that} \quad n \geq N \ \Rightarrow\ |b_n| > |b|/2.$$

   Therefore $(a_n/b_n)_{n\geq N}$ is a sequence of real numbers; prove it tends to a/b.

6. Given functions $f_n\colon (0,1) \to \mathbb{R}$ and $f\colon (0,1) \to \mathbb{R}$, suppose we make the following

   Definition: f_n converges to f (or $f_n \to f$) if and only if $\forall x \in (0,1),\ f_n(x) \to f(x)$.

   Consider the examples $f_n(x) = \begin{cases} n, & x \leq 1/n \\ 0, & x > 1/n \end{cases}$ for all $n \in \mathbb{N}$. Draw them! Do they converge to some function $f\colon (0,1) \to \mathbb{R}$?
   Prove your answer. Compare with the sequence of real numbers $a_n := \int_0^1 f_n$.

7. We call a sequence *Buzzard* if it satisfies the condition

$$\forall \epsilon > 0\ \exists\, N \in \mathbb{N}\ \ n \geq N \ \Rightarrow\ |a_n - a_{n+1}| < \epsilon.$$

   Give an example of a Buzzard sequence which diverges to $+\infty$. Conclude that Buzzard is not as strong as Cauchy.

8. Give an example of a Cauchy sequence in $\mathbb{Q}$ which does not converge in $\mathbb{Q}$.

   In lectures we show that in $\mathbb{R}$, a sequence is Cauchy if and only if it is convergent. Show that it is impossible to prove this using only the arithmetic and order axioms of $\mathbb{R}$ (i.e. all the axioms except the completeness axioms – the one about the existence of least upper bounds).

*You should prepare starred questions * to discuss with your personal tutor.*