Script 13

Uniform Continuity and Integration

13.1 Journal

4/8: **Definition 13.1.** Let $f : A \to \mathbb{R}$ be a function. We say that f is **uniformly continuous** if for all $\epsilon > 0$, there exists a $\delta > 0$ such that for all $x, y \in A$, if $|y - x| < \delta$, then $|f(y) - f(x)| < \epsilon$.

Theorem 13.2. *If f is uniformly continuous, then f is continuous.*

Proof. To prove that f is continuous, Theorem 9.10 tells us that it will suffice to show that f is continuous at every $x \in A$. Let x be an arbitrary element of A. To show that f is continuous at x, Theorem 11.5 tells us that it will suffice to verify that for every $\epsilon > 0$, there exists a $\delta > 0$ such that if $y \in A$ and $|y - x| < \delta$, then $|f(y) - f(x)| < \epsilon$. Let $\epsilon > 0$ be arbitrary. Then since f is uniformly continuous by hypothesis, Definition 13.1 asserts that there exists a $\delta > 0$ such that for all $y \in A$ satisfying $|y - x| < \delta$, we have $|f(y) - f(x)| < \epsilon$, as desired. $\square$

Exercise 13.3. Determine with proof whether each function f is uniformly continuous on the given interval A.

(a) $f(x) = x^2$ on $A = \mathbb{R}$.

Proof. To prove that f is not uniformly continuous on $\mathbb{R}$, Definition 13.1 tells us that it will suffice to find an $\epsilon > 0$ for which no $\delta > 0$ exists such that for all $x, y \in \mathbb{R}$, if $|y - x| < \delta$, then $|y^2 - x^2| < \epsilon$. Let $\epsilon = 2$, and suppose for the sake of contradiction that $\delta > 0$ is a number such that for all $x, y \in \mathbb{R}$, if $|y - x| < \delta$, then $|y^2 - x^2| < 2$. By Theorem 5.2, there exists a number y such that $0 < y < \delta$. Since $-\delta < 0 < y < \delta$ by Lemma 7.23, it follows by Definitions 3.6 and 3.10 that $y \in (-\delta, \delta)$. Thus, by Exercise 8.9, $|y - 0| = |y| < \delta$. Consequently, $|(y + n) - n| < \delta$. It follows by the above that $|(y + n)^2 - n^2| = |y^2 + 2yn| < 2$. If we now let $n = \frac{1}{y}$, then $|y^2 + 2| < 2$. But since $y > 0$, we have that $y^2 > 0$ by Lemma 7.26. It follows that $y^2 + 2 > 2$ by Definition 7.21. Therefore, by Definition 8.4, we can also show that $|y^2 + 2| > 2$, a contradiction. $\square$

(b) $f(x) = x^2$ on $A = (-2, 2)$.

Proof. To prove that f is uniformly continuous on A, Definition 13.1 tells us that it will suffice to show that for all $\epsilon > 0$, there exists a $\delta > 0$ such that for all $x, y \in A$, if $|y - x| < \delta$, then $|f(y) - f(x)| < \epsilon$. Let $\epsilon > 0$ be arbitrary. Choose $\delta = \frac{\epsilon}{4}$, and let x, y be arbitrary elements of A that satisfy $|y - x| < \delta$. Since $x, y \in A$, consecutive applications of Equations 8.1 and the lemma from Exercise 8.9 imply that $|x| < 2$ and $|y| < 2$. It follows that $|x| + |y| < 2 + 2 = 4$. Consequently, by Lemma 8.8, $|x + y| < 4$. Additionally, since $0 \leq |y + x|$ by Definition 8.4, we have $|x - y| \cdot |x + y| \leq \frac{\epsilon}{4} \cdot |x + y|$. Combining all of the above results, we have that

$$\begin{aligned}
|f(y) - f(x)| &= |y^2 - x^2| \\
&= |y + x| \cdot |y - x| \\
&< 4 \cdot |y - x| \\
&\leq 4 \cdot \frac{\epsilon}{4} \\
&= \epsilon
\end{aligned}$$

as desired. □

(c) $f(x) = \frac{1}{x}$ on $A = (0, +\infty)$.

Proof. To prove that f is not uniformly continuous on A, Definition 13.1 tells us that it will suffice to find an $\epsilon > 0$ for which no $\delta > 0$ exists such that for all $x, y \in A$, if $|y - x| < \delta$, then $|\frac{1}{y} - \frac{1}{x}| < \epsilon$. Let $\epsilon = 1$, and suppose for the sake of contradiction that $\delta > 0$ is a number such that for all $x, y \in A$, if $|y - x| < \delta$, then $|\frac{1}{y} - \frac{1}{x}| < 1$. As in part (a), choose $0 < x < \min(\delta, \frac{1}{2})$. Consequently, $|(x + x) - x| < \delta$. It follows by the above that $|\frac{1}{2x} - \frac{1}{x}| < 1$. But this implies that $|\frac{x-2x}{2x^2}| = |\frac{-1}{2x}| = \frac{1}{2x} < 1$. However, $x < \frac{1}{2}$ implies that $1 < \frac{1}{2x}$, a contradiction. □

(d) $f(x) = \frac{1}{x}$ on $A = [1, +\infty)$.

Proof. To prove that f is uniformly continuous on A, Definition 13.1 tells us that it will suffice to show that for all $\epsilon > 0$, there exists a $\delta > 0$ such that for all $x, y \in A$, if $|y - x| < \delta$, then $|f(y) - f(x)| < \epsilon$. Let $\epsilon > 0$ be arbitrary. Choose $\delta = \epsilon$, and let x, y be arbitrary elements of A that satisfy $|y - x| < \delta$. Since $x, y \in A$, consecutive applications of Equations 8.1 imply that $1 \leq x$ and $1 \leq y$. It follows by Script 7 that $1 \leq |xy|$. This combined with the fact that $|y - x| < \delta = \epsilon$ implies that

$$\begin{aligned}
|f(y) - f(x)| &= \left|\frac{1}{y} - \frac{1}{x}\right| \\
&= \left|\frac{x - y}{yx}\right| \\
&= \frac{|y - x|}{|xy|} \\
&< \frac{\epsilon}{|xy|} \\
&\leq \frac{\epsilon}{1} \\
&= \epsilon
\end{aligned}$$

as desired. □

(e) $f(x) = \sqrt{x}$ on $A = [1, +\infty)$.

Proof. To prove that f is uniformly continuous on A, Definition 13.1 tells us that it will suffice to show that for all $\epsilon > 0$, there exists a $\delta > 0$ such that for all $x, y \in A$, if $|y - x| < \delta$, then $|f(y) - f(x)| < \epsilon$. Let $\epsilon > 0$ be arbitrary. Choose $\delta = \epsilon$, and let x, y be arbitrary elements of A that satisfy $|y - x| < \delta$. Since $x, y \in A$, consecutive applications of Equations 8.1 imply that $1 \leq x$ and $1 \leq y$. It follows by Script 7 that $1 \leq \sqrt{x}$ and $1 \leq \sqrt{y}$. Thus, by Script 7 again, $2 \leq |\sqrt{y} + \sqrt{x}|$. Note that it follows that $1 < |\sqrt{y} + \sqrt{x}|$. This combined with the fact that $|y - x| < \delta = \epsilon$ implies that

$$\begin{aligned}
|f(y) - f(x)| &= |\sqrt{y} - \sqrt{x}| \\
&< |\sqrt{y} - \sqrt{x}| \cdot |\sqrt{y} + \sqrt{x}| \\
&= |y - x| \\
&= \epsilon
\end{aligned}$$

as desired. □

Exercise 13.4. Let $f : \mathbb{R} \to \mathbb{R}$ be defined by $f(x) = x^n$ for $n \in \mathbb{N}$. Show that f is uniformly continuous if and only if $n = 1$.

Proof. Suppose first that $n = 1$. To prove that f is uniformly continuous, Definition 13.1 tells us that it will suffice to show that for all $\epsilon > 0$, there exists a $\delta > 0$ such that for all $x, y \in \mathbb{R}$, if $|y - x| < \delta$, then $|f(y) - f(x)| < \epsilon$. Let $\epsilon > 0$ be arbitrary. Choose $\delta = \epsilon$. Now let x, y be arbitrary elements of $\mathbb{R}$ that satisfy $|y - x| < \delta$. Then by the definition of f, $|f(y) - f(x)| = |y - x| < \delta = \epsilon$, as desired.

Now suppose that $n > 1$. Additionally, suppose for the sake of contradiction that f is uniformly continuous. Let $\epsilon = 1 > 0$. Then by Definition 13.1, there exists a $\delta > 0$ such that for all $x, y \in \mathbb{R}$, if $|y-x| < \delta$, then $|y^n - x^n| < 1$. Let $x = 0 \in \mathbb{R}$. By Theorem 5.2, there exists a point $y \in \mathbb{R}$ such that $0 < y < \delta$. Additionally, since $\delta > 0$, Lemma 7.23 asserts that $-\delta < 0$. This combined with the previous result demonstrates by transitivity that $-\delta < 0 < y < \delta$, so by the lemma from Exercise 8.9, we have that $|y| < \delta$. Consequently, by Script 7, we know that $|(y+a) - a| < \delta$ for any $a \in \mathbb{R}$. It follows by the above that $|(y+a)^n - a^n| < 1$. Thus, by Additional Exercise 0.7, $|\sum_{k=0}^{n} \binom{n}{k} y^{n-k} a^k - a^n| = |y^n + ny^{n-1}a + \sum_{k=2}^{n-1} \binom{n}{k} y^{n-k} a^k| < 1$. If we now choose $a = \frac{1}{ny^{n-1}}$, Script 7 reduces the above to $|y^n + 1 + \sum_{k=2}^{n-1} y^{n-k} a^k| < 1$. We now seek to reduce the previous statement further to $|y^n + 1| < 1$. To begin, Exercise 12.22 implies that $y^n > 0$ since $y > 0$ and $0^n = 0$, meaning by Script 7 that $y^n + 1 > 0$. Additionally, Script 7 asserts that $\sum_{k=2}^{n-1} y^{n-k} a^k > 0$ since $a > 0$ and $y > 0$. This combined with the previous result implies by Scripts 7 and 8 that $|y^n + 1| < |y^n + 1 + \sum_{k=2}^{n-1} y^{n-k} a^k| < 1$, as desired. However, since $y^n > 0$, Definition 7.21 asserts that $y^n + 1 > 1$. But by Definition 8.4, this implies that $|y^n + 1| > 1$, a contradiction. $\square$

Exercise 13.5. Let f and g be uniformly continuous on $A \subset \mathbb{R}$. Show that

(a) The function $f + g$ is uniformly continuous on A.

(b) For any constant $c \in \mathbb{R}$, the function $c \cdot f$ is uniformly continuous on A.

Proof of a. To prove that $f+g$ is uniformly continuous on A, Definition 13.1 tells us that it will suffice to show that for all $\epsilon > 0$, there exists a $\delta > 0$ such that for all $x, y \in A$, if $|y-x| < \delta$, then $|(f+g)(y) - (f+g)(x)| < \epsilon$. Let $\epsilon > 0$ be arbitrary. Since f, g are uniformly continuous on A, consecutive applications of Definition 13.1 reveal that there exist $\delta_1, \delta_2 > 0$ such that for all $x, y \in A$, $|y - x| < \delta_1$ implies $|f(y) - f(x)| < \frac{\epsilon}{2}$ and $|y - x| < \delta_2$ implies $|g(y) - f(x)| < \frac{\epsilon}{2}$. Choose $\delta = \min(\delta_1, \delta_2)$. Let x, y be arbitrary elements of A that satisfy $|y-x| < \delta$. It follows that $|y-x| < \delta_1$ (so $|f(y)-f(x)| < \frac{\epsilon}{2}$), and that $|y-x| < \delta_2$ (so $|g(y)-g(x)| < \frac{\epsilon}{2}$). These two results when combined imply by Script 7 that $|f(y) - f(x)| + |g(y) - g(x)| < \frac{\epsilon}{2} + \frac{\epsilon}{2}$. Therefore, since $|f(y) - f(x) + g(y) - g(x)| \leq |f(y) - f(x)| + |g(y) - g(x)|$ by Lemma 8.8, we have that

$$\begin{aligned}
|(f+g)(y) - (f+g)(x)| &= |f(y) - f(x) + g(y) - g(x)| \\
&\leq |f(y) - f(x)| + |g(y) - g(x)| \\
&< \frac{\epsilon}{2} + \frac{\epsilon}{2} \\
&= \epsilon
\end{aligned}$$

as desired. $\square$

Proof of b. To prove that $c \cdot f$ is uniformly continuous on A, Definition 13.1 tells us that it will suffice to show that for all $\epsilon > 0$, there exists a $\delta > 0$ such that for all $x, y \in A$, if $|y-x| < \delta$, then $|c \cdot f(y) - c \cdot f(x)| < \epsilon$. Let $\epsilon > 0$ be arbitrary. We divide into two cases ($c = 0$ and $c \neq 0$). Suppose first that $c = 0$. Choose $\delta = 1$. Let x, y be arbitrary elements of A that satisfy $|y - x| < \delta$. It follows that $|0 \cdot f(y) - 0 \cdot f(x)| = 0 < \epsilon$, as desired. Now suppose that $c \neq 0$. Then since f is uniformly continuous on A, Definition 13.1 tells us that there exists a $\delta > 0$ such that for all $x, y \in A$, if $|y - x| < \delta$, then $|f(y) - f(x)| < \frac{\epsilon}{|c|}$. Choose this δ to be our δ. Let x, y be arbitrary elements of A that satisfy $|y - x| < \delta$. Then by the above, we have that $|f(y) - f(x)| < \frac{\epsilon}{|c|}$. Therefore, $|c| \cdot |f(y) - f(x)| < \epsilon$, so we have that $|c \cdot f(y) - c \cdot f(x)| < \epsilon$, as desired. $\square$

4/13: **Theorem 13.6.** *Suppose that $X \subset \mathbb{R}$ is compact and $f : X \to \mathbb{R}$ is continuous. Then f is uniformly continuous.*

Proof. To prove that f is uniformly continuous, Definition 13.1 tells us that it will suffice to show that for all $\epsilon > 0$, there exists a $\delta > 0$ such that for all $x, y \in A$, if $|y - x| < \delta$, then $|f(y) - f(x)| < \epsilon$. Let $\epsilon > 0$ be arbitrary. Since f is continuous on X, Theorem 9.10 asserts that f is continuous at every $x \in X$. Thus, by Theorem 11.5, for every $x \in X$, there exists a $\delta_x > 0$ such that if $y \in X$ and $|y - x| < \delta_x$, then $|f(y) - f(x)| < \frac{\epsilon}{2}$. Let $\mathcal{G} = \{(x - \frac{\delta_x}{2}, x + \frac{\delta_x}{2}) \mid x \in X\}$. We will now confirm that $\mathcal{G}$ is an open cover of X. To do so, Definition 10.3 tells us that it will suffice to demonstrate that every $x \in X$ is an element of $(x - \frac{\delta_x}{2}, x + \frac{\delta_x}{2})$ for some $(x - \frac{\delta_x}{2}, x + \frac{\delta_x}{2}) \in \mathcal{G}$. Let x be an arbitrary element of X. We know that $|x - x| = 0 < \frac{\delta_x}{2}$. Thus, by Exercise 8.9, we have that $x \in (x - \frac{\delta_x}{2}, x + \frac{\delta_x}{2})$. Since it follows from the above that $(x - \frac{\delta_x}{2}, x + \frac{\delta_x}{2}) \in \mathcal{G}$, we are done.

Having shown that $\mathcal{G}$ is an open cover of X, the fact that X is compact implies by Definition 10.4 that there exists a finite subset $\mathcal{G}'$ of $\mathcal{G}$ that is also an open cover of X. It follows that $\mathcal{G}'$ will be of the form $\{(x_i - \frac{\delta_{x_i}}{2}, x + \frac{\delta_{x_i}}{2}) \mid 1 \leq i \leq n\}$ where n is some natural number. Thus, choose $\delta = \min_{1 \leq i \leq n}(\frac{\delta_{x_i}}{2})$.

Let x, y be arbitrary elements of X that satisfy $|y - x| < \delta$. Since $\mathcal{G}'$ is an open cover of X, Definition 10.3 implies that $x \in (x_i - \frac{\delta_{x_i}}{2}, x_i + \frac{\delta_{x_i}}{2})$ for some $(x_i - \frac{\delta_{x_i}}{2}, x_i + \frac{\delta_{x_i}}{2}) \in \mathcal{G}'$. Considering this x_i more closely, we can determine from the previous result and Exercise 8.9 that $|x - x_i| < \frac{\delta_{x_i}}{2}$. This combined with the hypothesis that $|y - x| < \delta$ implies by Script 7 that $|y - x| + |x - x_i| < \delta + \frac{\delta_{x_i}}{2}$. Additionally, note that by definition, $\delta \leq \frac{\delta_{x_i}}{2}$. Thus, combining the last few results, we have that

$$\begin{aligned}
|y - x_i| &\leq |y - x| + |x - x_i| && \text{Lemma 8.8} \\
&< \delta + \frac{\delta_{x_i}}{2} \\
&\leq \frac{\delta_{x_i}}{2} + \frac{\delta_{x_i}}{2} \\
&= \delta_{x_i}
\end{aligned}$$

At this point, we know that $|x - x_i| < \frac{\delta_{x_i}}{2} < \delta_{x_i}$ and that $|y - x_i| < \delta_{x_i}$. It follows by consecutive applications of the above that $|f(x) - f(x_i)| < \frac{\epsilon}{2}$ and $|f(y) - f(x_i)| < \frac{\epsilon}{2}$, respectively. Consequently, we have by Script 7 that $|f(y) - f(x_i)| + |f(x) - f(x_i)| < \frac{\epsilon}{2} + \frac{\epsilon}{2}$. Therefore, if we combine the last several results, we get

$$\begin{aligned}
|f(y) - f(x)| &\leq |f(y) - f(x_i)| + |f(x_i) - f(x)| && \text{Lemma 8.8} \\
&= |f(y) - f(x_i)| + |f(x) - f(x_i)| && \text{Exercise 8.5} \\
&< \frac{\epsilon}{2} + \frac{\epsilon}{2} \\
&= \epsilon
\end{aligned}$$

as desired. $\square$

Exercise 13.7. Prove that $f(x) = \sqrt{x}$ is uniformly continuous on $A = [0, +\infty)$.

Lemma. *Let x, y be arbitrary elements of A. Then $|\sqrt{y} - \sqrt{x}|^2 \leq |(\sqrt{y} - \sqrt{x})(\sqrt{y} + \sqrt{x})|$.*

Proof. We will first verify that $|\sqrt{y} - \sqrt{x}| \leq |\sqrt{y} + \sqrt{x}|$. To do so, we divide into two cases ($\sqrt{y} \geq \sqrt{x}$ and $\sqrt{y} < \sqrt{x}$). If $\sqrt{y} \geq \sqrt{x}$, then by Definition 7.21, $\sqrt{y} - \sqrt{x} \geq 0$. It follows by Definition 8.4 that $|\sqrt{y} - \sqrt{x}| = \sqrt{y} - \sqrt{x}$. Additionally, we have by an extension of Exercise 12.22 that $\sqrt{x} \geq 0$, implying that $2\sqrt{x} \geq 0$ by Definition 7.21. Thus, combining the last few results, we have that $|\sqrt{y} - \sqrt{x}| = \sqrt{y} - \sqrt{x} \leq \sqrt{y} - \sqrt{x} + 2\sqrt{x} = \sqrt{y} + \sqrt{x}$. Consequently, we know that $0 \leq |\sqrt{y} - \sqrt{x}| \leq \sqrt{y} + \sqrt{x}$, so Definition 8.4 implies that $|\sqrt{y} + \sqrt{x}| = \sqrt{y} + \sqrt{x}$. Therefore, we have that $|\sqrt{y} - \sqrt{x}| \leq \sqrt{y} + \sqrt{x} = |\sqrt{y} + \sqrt{x}|$, as desired. The argument is symmetric in the other case.

Having established that $|\sqrt{y} - \sqrt{x}| \leq |\sqrt{y} + \sqrt{x}|$ and knowing that $0 \leq |\sqrt{y} - \sqrt{x}|$, we have by Lemma 7.24 that $|\sqrt{y} - \sqrt{x}| \cdot |\sqrt{y} - \sqrt{x}| \leq |\sqrt{y} + \sqrt{x}| \cdot |\sqrt{y} - \sqrt{x}|$. It follows by basic algebra that $|\sqrt{y} - \sqrt{x}|^2 \leq |(\sqrt{y} - \sqrt{x})(\sqrt{y} + \sqrt{x})|$, as desired. $\square$

Proof of Exercise 13.7. To prove that f is uniformly continuous on A, Definition 13.1 tells us that it will suffice to show that for all $\epsilon > 0$, there exists a $\delta > 0$ such that for all $x, y \in A$, if $|y - x| < \delta$, then $|f(y) - f(x)| < \epsilon$. Let $\epsilon > 0$ be arbitrary. Choose $\delta = \epsilon^2$. Let x, y be arbitrary elements of X that satisfy $|y - x| < \delta$. Thus, since $(\sqrt{y} - \sqrt{x})(\sqrt{y} + \sqrt{x}) = y - x$, the lemma asserts that $|\sqrt{y} - \sqrt{x}|^2 \leq |(\sqrt{y} - \sqrt{x})(\sqrt{y} + \sqrt{x})| = |y - x| < \epsilon^2$. Therefore, by Script 7, $|\sqrt{y} - \sqrt{x}| < \epsilon$, i.e., $|f(y) - f(x)| < \epsilon$, as desired. □

Corollary 13.8. *Suppose that $f : [a, b] \to \mathbb{R}$ is continuous. Then f is uniformly continuous.*

Proof. By Theorem 10.14, $[a, b]$ is compact. This combined with the hypothesis that f is continuous proves by Theorem 13.6 that f is uniformly continuous. □

Exercise 13.9. Show that if f and g are bounded on A and uniformly continuous on A, then fg is uniformly continuous on A.

Proof. To prove that fg is uniformly continuous on A, Definition 13.1 tells us that it will suffice to show that for all $\epsilon > 0$, there exists a $\delta > 0$ such that for all $x, y \in A$, if $|y - x| < \delta$, then $|(fg)(y) - (fg)(x)| < \epsilon$. Let $\epsilon > 0$ be arbitrary.

Since f is bounded on A, Definition 10.1 implies that $f(A)$ is a bounded subset of $\mathbb{R}$. Thus, by consecutive applications of Definition 5.6, there exist numbers l, u such that for all $f(x) \in f(A)$, $l \leq f(x) \leq u$. Let $a = \max(|l|, |u|) + 1$. It follows by Scripts 7 and 8 that $-a < f(x) < a$ for all $f(x) \in f(A)$. Thus, by the lemma from Exercise 8.9, $|f(x)| < a$ for all $f(x) \in f(A)$. Similarly, there exists a number b such that $|g(x)| < b$ for all $g(x) \in g(A)$.

Since f is uniformly continuous on A, Definition 13.1 implies that there exists a $\delta_1 > 0$ such that for all $x, y \in A$, if $|y - x| < \delta_1$, then $|f(y) - f(x)| < \frac{\epsilon}{2b}$. Similarly, there exists a $\delta_2 > 0$ such that for all $x, y \in A$, if $|y - x| < \delta_2$, then $|g(y) - g(x)| < \frac{\epsilon}{2a}$. Choose $\delta = \min(\delta_1, \delta_2)$. Let x, y be arbitrary elements of A that satisfy $|y - x| < \delta$. It follows by consecutive applications of the above that $|f(x)| < a$ and $|g(y)| < b$. Additionally, $|y - x| < \delta \leq \delta_1$ implies that $|f(y) - f(x)| < \frac{\epsilon}{2b}$ and $|y - x| < \delta \leq \delta_2$ implies that $|g(y) - g(x)| < \frac{\epsilon}{2a}$. Therefore, combining the last four results, we have that

$$
\begin{aligned}
|(fg)(y) - (fg)(x)| &= |f(x)g(x) - f(y)g(y)| \\
&= |f(x)g(x) - f(x)g(y) + f(x)g(y) - f(y)g(y)| \\
&= |f(x)(g(x) - g(y)) + g(y)(f(x) - f(y))| \\
&\leq |f(x)| \cdot |g(x) - g(y)| + |g(y)| \cdot |f(x) - f(y)| && \text{Lemma 8.8} \\
&< a \cdot \frac{\epsilon}{2a} + b \cdot \frac{\epsilon}{2b} \\
&= \epsilon
\end{aligned}
$$

as desired. □