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. □

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 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 $|y^2 - x^2| < \epsilon$. Let $\epsilon = 2$, and suppose for the sake of contradiction that $\delta > 0$ is a number such that for all $x, y \in A$, 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, we have by the lemma from Exercise 8.9, that $|y| < \delta$. 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. □

(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 by Definition 7.21 $|x - y| \cdot |x + y| \leq \frac{\epsilon}{4} \cdot |x + y|$. Combining all of the above results, we have that

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

$$\begin{aligned}
&\leq |x+y| \cdot \frac{\epsilon}{4} \\
&< 4 \cdot \frac{\epsilon}{4} \\
&= \epsilon
\end{aligned}$$

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 by Lemma 7.24 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 Scripts 7 and 8, $2 \leq |\sqrt{y} + \sqrt{x}|$. 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. □

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 $|g(y) - g(x)| < \frac{\epsilon}{2}$. 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. □

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. □

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. □

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. □

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. ☐

4/15: **Definition 13.10.** A **partition** of the interval $[a, b]$ is a finite set of points in $[a, b]$ that includes a and b. We usually write partitions as $P = \{t_0, t_1, \dots, t_n\}$, with the convention that

$$a = t_0 < t_1 < \cdots < t_{n-1} < t_n = b$$

If P and Q are partitions of the interval $[a, b]$ and $P \subset Q$, we refer to Q as a **refinement** of P.

Definition 13.11. Suppose that $f : [a, b] \to \mathbb{R}$ is bounded and that $P = \{t_0, \dots, t_n\}$ is a partition of $[a, b]$. Define

$$m_i(f) = \inf\{f(x) \mid t_{i-1} \leq x \leq t_i\} \qquad M_i(f) = \sup\{f(x) \mid t_{i-1} \leq x \leq t_i\}$$

The **lower sum** of f for the partition P is the number

$$L(f, P) = \sum_{i=1}^{n} m_i(f)(t_i - t_{i-1})$$

The **upper sum** of f for the partition P is the number

$$U(f,P)=\sum_{i=1}^{n}M_i(f)(t_i-t_{i-1})$$

Notice that it is always the case that $L(f,P)\leq U(f,P)$.

Lemma 13.12. *Suppose that P and Q are partitions of $[a,b]$ and that Q is a refinement of P. Then $L(f,P)\leq L(f,Q)$ and $U(f,P)\geq U(f,Q)$.*

Lemma. *Let P be a partition of $[a,b]$ and let y be an arbitrary element of $[a,b]\setminus P$. Then $L(f,P)\leq L(f,P\cup\{y\})$ and $U(f,P)\geq U(f,P\cup\{y\})$.*

Proof. We will prove that $L(f,P)\leq L(f,P\cup\{y\})$. The proof will be symmetric in the other case. Let's begin.

By Definition 13.10, P is of the form $\{t_0,\dots,t_n\}$ where $a=t_0<\cdots<t_n=b$. This combined with the hypothesis that $y\in[a,b]\setminus P$ implies by Theorem 3.5 that $a=t_0<\cdots<t_{k-1}<y<t_k<\cdots<t_n=b$. Thus, we have by consecutive applications of Definition 13.11 that

$$\begin{aligned}L(f,P)&=\sum_{i=1}^{n}m_i(f)(t_i-t_{i-1})\\&=\sum_{i=1}^{k-1}m_i(f)(t_i-t_{i-1})+m_k(f)(t_k-t_{k-1})+\sum_{i=k+1}^{n}m_i(f)(t_i-t_{i-1})\end{aligned}$$

and that

$$L(f,P\cup\{y\})=\sum_{i=1}^{k-1}m_i(f)(t_i-t_{i-1})+m_y^-(f)(y-t_{k-1})+m_y^+(f)(t_k-y)+\sum_{i=k+1}^{n}m_i(f)(t_i-t_{i-1})$$

where

$$m_y^-(f)=\inf\{f(x)\mid t_{k-1}\leq x\leq y\}\qquad\qquad m_y^+(f)=\inf\{f(x)\mid y\leq x\leq t_k\}$$

As such, to prove that $L(f,P)\leq L(f,P\cup\{y\})$, it will suffice to show that $m_k(f)(t_k-t_{k-1})\leq m_y^-(f)(y-t_{k-1})+m_y^+(f)(t_k-y)$. To do so, it will suffice to show that $m_k(f)(y-t_{k-1})+m_k(f)(t_k-y)\leq m_y^-(f)(y-t_{k-1})+m_y^+(f)(t_k-y)$, i.e., that $m_k(f)(y-t_{k-1})\leq m_y^-(f)(y-t_{k-1})$ and that $m_k(f)(t_k-y)\leq m_y^+(f)(t_k-y)$, i.e., that $m_k(f)\leq m_y^-(f)$ and that $m_k(f)\leq m_y^+(f)$.

For the sake of proving the first expression, let $A=\{f(x)\mid t_{k-1}<x<t_k\}$ and let $B=\{f(x)\mid t_{k-1}\leq x\leq y\}$. It follows by Definition 13.10 that $m_k(f)=\inf A$ and $m_y^-(f)=\inf B$. Thus, we need only show that $\inf A\leq\inf B$. Since $y<t_k$, we know by Script 1 that $B\subset A$. Thus, since $\inf A$ is a lower bound on A, Script 5 implies that it is also a lower bound on B. Consequently, by Definition 5.7, $\inf A\leq\inf B$, as desired.

The argument is symmetric for the other statement. □

Proof of Lemma 13.12. We will prove that $L(f,P)\leq L(f,Q)$. The proof will be symmetric in the other case. Let's begin.

By Definition 13.10, $P\subset Q$. Thus, by Theorem 1.34, $|P|\leq|Q|$. It follows by Script 1 that $|Q|-|P|=n\in\mathbb{Z}^+$. Thus, to prove the claim for P and Q in general, it will suffice to prove it for each n. To do so, we divide into two cases ($n=0$ and $n\in\mathbb{N}$). If $n=0$, then $|P|=|Q|$. This combined with the fact that $P\subset Q$ implies by Script 1 that $P=Q$. Therefore, $L(f,P)=L(f,Q)$, which we can weaken to $L(f,P)\leq L(f,Q)$, as desired.

On the other hand, if $n\in\mathbb{N}$, then we induct on n. For the base case $n=1$, we have by Script 1 that $Q=P\cup\{y\}$ where $y\notin P$. Therefore, by the lemma, we have that $L(f,P)\leq L(f,P\cup\{y\})=L(f,Q)$, as desired. Now suppose inductively that the claim holds for n; we wish to prove it for $n+1$. Let y be an arbitrary element of Q. Then by Script 1, $|Q\setminus\{y\}|-|P|=n$. Thus, by the inductive hypothesis, $L(f,P)\leq L(f,Q\setminus\{x\})$. Additionally, by the lemma, $L(f,Q\setminus\{x\})\leq L(f,Q)$. Therefore, by transitivity, $L(f,P)\leq L(f,Q)$, as desired. □

Theorem 13.13. *Let P_1 and P_2 be partitions of $[a,b]$ and suppose that $f:[a,b]\to\mathbb{R}$ is bounded. Then $L(f,P_1)\leq U(f,P_2)$.*

Proof. To confirm that $P_1\cup P_2$ is a partition of $[a,b]$, Definition 13.10 tells us that it will suffice to demonstrate that it is a finite set, that it is a subset of $[a,b]$, and that it includes a and b. Since P_1,P_2 are partitions of $[a,b]$, Definition 13.10 implies that they are finite subsets of $[a,b]$ that contain a,b. It follows by Script 1 that their union is finite, a subset of $[a,b]$, and a set containing a and b. Additionally, we have by Theorem 1.7 that $P_1\subset P_1\cup P_2$ and that $P_2\subset P_1\cup P_2$. Combining the last two results with consecutive applications of Definition 13.10 reveals that $P_1\cup P_2$ is a refinement of both P_1 and P_2.

Since P_1 and $P_1\cup P_2$ are partitions of $[a,b]$ and $P_1\cup P_2$ is a refinement of P_1, Lemma 13.12 implies that $L(f,P_1)\leq L(f,P_1\cup P_2)$. Similarly, $U(f,P_1\cup P_2)\leq U(f,P_2)$. Additionally, we have by Definition 13.11 that $L(f,P_1\cup P_2)\leq U(f,P_1\cup P_2)$. Therefore, if we combine the last three results with transitivity, we have that $L(f,P_1)\leq U(f,P_2)$, as desired. ☐

Definition 13.14. Let $f:[a,b]\to\mathbb{R}$ be bounded. We define

$$L(f)=\sup\{L(f,P)\mid P\text{ is a partition of }[a,b]\}\qquad U(f)=\inf\{U(f,P)\mid P\text{ is a partition of }[a,b]\}$$

to be, respectively, the **lower integral** and **upper integral** of f from a to b.

Exercise 13.15. Why do $L(f)$ and $U(f)$ exist? Find a function f for which $L(f)=U(f)$. Find a function f for which $L(f)\neq U(f)$. Prove that $L(f)\leq U(f)$.

Lemma. *Given $a,b\in\mathbb{R}$ with $a<b$, there exists $p\in\mathbb{R}$ such that $p\notin\mathbb{Q}$ and $a<p<b$.*

Proof. By Definition 7.21, $a+\sqrt{2}<b+\sqrt{2}$. Thus, by Lemma 6.10, there exists a point $\frac{c}{d}\in\mathbb{Q}$ such that $a+\sqrt{2}<\frac{c}{d}<b+\sqrt{2}$. It follows that $a<\frac{c}{d}-\sqrt{2}<b$.

Now suppose for the sake of contradiction that $\frac{c}{d}-\sqrt{2}$ is rational. Then by Script 2, $\frac{c}{d}-\sqrt{2}=\frac{e}{f}$ where $e,f\in\mathbb{Z}$ and $f\neq 0$. It follows by Theorem 2.10 that $\sqrt{2}=\frac{cf-de}{df}$, i.e., that $\sqrt{2}$ is rational. But by the proof of Exercise 4.24, $\sqrt{2}$ is not rational, a contradiction. ☐

Proof of Exercise 13.15. Let $A=\{L(f,P)\mid P\text{ is a partition of }[a,b]\}$. To prove that $L(f)=\sup A$ exists, Theorem 5.17 tells us that it will suffice to show that A is nonempty and bounded above.

To confirm that A is nonempty, Definition 1.8 tells us that it will suffice to find an element of it. Since $\{a,b\}$ is a finite set of points in $[a,b]$ that includes a and b (by Script 1), Definition 13.10 asserts that $\{a,b\}$ is a partition of $[a,b]$. It follows by Definition 13.11 that $L(f,\{a,b\})$ exists. Therefore, by the definition of A, we have that $L(f,\{a,b\})\in A$, as desired.

To confirm that A is bounded above, Definition 5.6 tells us that it will suffice to find a point in $u\in\mathbb{R}$ such that for all $L(f,P)\in A$, $L(f,P)\leq u$. Let $u=U(f,\{a,b\})$ (since $\{a,b\}$ is a partition of $[a,b]$ by the above, Definition 13.10 guarantees that $U(f,\{a,b\})$ exists). Now let $L(f,P)$ be an arbitrary element of A. It follows from Theorem 13.13 that $L(f,P)\leq U(f,\{a,b\})=u$, as desired.

The proof is symmetric for $U(f)$.

Let $f:[0,1]\to\mathbb{R}$ be defined by $f(x)=0$. To prove that $L(f)=U(f)$, it will suffice to show that $L(f)=0$ and $U(f)=0$. To do this, Script 5 tells us that it will suffice to verify that $\{L(f,P)\mid P\text{ is a partition of }[a,b]\}=\{0\}$ and $\{U(f,P)\mid P\text{ is a partition of }[a,b]\}=\{0\}$. We will start with the first equality.

Let $L(f,P)$ be an arbitrary element of $\{L(f,P)\mid P\text{ is a partition of }[a,b]\}$. Since we have

$$\begin{aligned}m_i(f)&=\inf\{f(x)\mid t_{i-1}\leq x\leq t_i\}\\&=\inf\{0\mid t_{i-1}\leq x\leq t_i\}\\&=\inf\{0\}\\&=0\end{aligned}$$

for all $m_i(f)$, it follows that

$$\begin{aligned} L(f,P) &= \sum_{i=1}^{n} m_i(f)(t_i - t_{i-1}) \\ &= \sum_{i=1}^{n} 0(t_i - t_{i-1}) \\ &= 0 \end{aligned}$$

Therefore, since every element of $\{L(f,P) \mid P \text{ is a partition of } [a,b]\}$ is equal to 0, the set is equal to the singleton set containing 0. The argument is symmetric for the other equality.

Let $f : [0,1] \to \mathbb{R}$ be defined by

$$f(x) = \begin{cases} 1 & x \in \mathbb{Q} \\ 0 & x \notin \mathbb{Q} \end{cases}$$

To prove that $L(f) \neq U(f)$, it will suffice to show that $L(f) = 0$ and $U(f) = 1$. To do this, Script 5 tells us that it will suffice to verify that $\{L(f,P) \mid P \text{ is a partition of } [a,b]\} = \{0\}$ and $\{U(f,P) \mid P \text{ is a partition of } [a,b]\} = \{1\}$. We will start with the first equality.

Let $L(f,P)$ be an arbitrary element of $\{L(f,P) \mid P \text{ is a partition of } [a,b]\}$. To confirm that $L(f,P) = 0$, Definition 13.11 tells us that it will suffice to demonstrate that $m_i(f) = 0$ for all $m_i(f)$. Let $m_i(f)$ be an arbitrary such object. By Definition 13.10, $m_i(f) = \inf\{f(x) \mid t_{i-1} \leq x \leq t_i\}$. By the lemma, there exists $p \in \mathbb{R}$ such that $p \notin \mathbb{Q}$ and $t_{i-1} \leq p \leq t_i$. Thus, since $f(p) = 0$, $0 \in \{f(x) \mid t_{i-1} \leq x \leq t_i\}$. Additionally, since $f(x) \not< 0$ for any $x \in [0,1]$ by definition, we have that $m_i(f) = 0$. Therefore, since every element of $\{L(f,P) \mid P \text{ is a partition of } [a,b]\}$ is equal to 0, the set is equal to the singleton set containing 0.

As to the other equality, let $U(f,P)$ be an arbitrary element of $\{U(f,P) \mid P \text{ is a partition of } [a,b]\}$. To confirm that $U(f,P) = 1$, Definition 13.11 tells us that we must first demonstrate that $M_i(f) = 1$ for all $M_i(f)$. Let $M_i(f)$ be an arbitrary such object. By Definition 13.10, $M_i(f) = \sup\{f(x) \mid t_{i-1} \leq x \leq t_i\}$. By Lemma 6.10, there exists $p \in \mathbb{Q}$ such that $t_{i-1} \leq p \leq t_i$. Thus, since $f(p) = 1$, $1 \in \{f(x) \mid t_{i-1} \leq x \leq t_i\}$. Additionally, since $f(x) \not> 1$ for any $x \in [0,1]$ by definition, we have that $M_i(f) = 1$. It follows by Definition 13.11 that

$$\begin{aligned} U(f,P) &= \sum_{i=1}^{n} M_i(f)(t_i - t_{i-1}) \\ &= \sum_{i=1}^{n} (t_i - t_{i-1}) \\ &= t_n - t_0 \\ &= 1 - 0 \\ &= 1 \end{aligned}$$

Therefore, since every element of $\{U(f,P) \mid P \text{ is a partition of } [a,b]\}$ is equal to 1, the set is equal to the singleton set containing 1.

Suppose for the sake of contradiction that there exists a function $f : [a,b] \to \mathbb{R}$ for which $U(f) < L(f)$. It follows by consecutive applications of Definition 13.14 and Lemma 5.11 that there exists an $L(f,P_1)$ such that $U(f) < L(f,P_1) \leq L(f)$, and thus that there exists a $U(f,P_2)$ such that $U(f) \leq U(f,P_2) < L(f,P_1)$. But this means that there exist partitions P_1, P_2 of $[a,b]$ such that $L(f,P_1) > U(f,P_2)$, contradicting Theorem 13.13. $\square$

Definition 13.16. Let $f : [a,b] \to \mathbb{R}$ be bounded. We say that f is **integrable** on $[a,b]$ if $L(f) = U(f)$. In this case, the common value $L(f) = U(f)$ is called the **integral** of f from a to b and we write it as

$$\int_a^b f$$

Note that if f is an integrable function on $[a, b]$, it is necessarily bounded.

When we want to display the variable of integration, we write the integral as follows, including the symbol $\mathrm{d}x$ to indicate that variable of integration:

$$\int_a^b f(x)\,\mathrm{d}x$$

For example, if $f(x) = x^2$, we could write $\int_a^b x^2\,\mathrm{d}x$ but not $\int_a^b x^2$.

Exercise 13.17. Fix $c \in \mathbb{R}$ and let $f : [a, b] \to \mathbb{R}$ be defined by $f(x) = c$, for each $x \in [a, b]$. Show that f is integrable on $[a, b]$ and that $\int_a^b f = c(b - a)$.

Proof. To prove that f is integrable on $[a, b]$ and that $\int_a^b f = c(b - a)$, Definition 13.16 tells us that it will suffice to show that f is bounded on $[a, b]$, and that $L(f) = U(f) = c(b - a)$.

To confirm that f is bounded on $[a, b]$, Definition 10.1 tells us that it will suffice to demonstrate that $f([a, b])$ is a bounded subset of $\mathbb{R}$. By Definition 1.18, $f([a, b]) = \{f(x) \in \mathbb{R} \mid x \in [a, b]\}$. But since $f(x) = c$ for all $x \in [a, b]$, we have that $c \leq f(x) \leq c$ for all $x \in [a, b]$. It follows by Definition 5.6 that $f([a, b])$ is bounded. Additionally, since $c \in \mathbb{R}$, Definition 1.3 asserts that $f([a, b]) = \{c\} \subset \mathbb{R}$.

To confirm that $L(f) = U(f) = c(b - a)$, Definition 13.14 tells us that it will suffice to demonstrate that $L(f, P) = U(f, P) = c(b - a)$ for all partitions P of $[a, b]$. For similar reasons to the above (i.e., $f(x) = c$ for all $x \in [a, b]$), we can show that $m_i(f) = M_i(f) = c$ for all $m_i(f)$ and $M_i(f)$. Therefore, by Definition 13.11 that

$$\begin{aligned} L(f, P) &= \sum_{i=1}^{n} c(t_i - t_{i-1}) \\ &= c\sum_{i=1}^{n}(t_{i-1} - t_i) \\ &= c(t_n - t_0) \\ &= c(b - a) \end{aligned} \qquad \begin{aligned} U(f, P) &= \sum_{i=1}^{n} c(t_i - t_{i-1}) \\ &= c\sum_{i=1}^{n}(t_{i-1} - t_i) \\ &= c(t_n - t_0) \\ &= c(b - a) \end{aligned}$$

as desired. □

Theorem 13.18. *Let $f : [a, b] \to \mathbb{R}$ be bounded. Then f is integrable if and only if for every $\epsilon > 0$, there exists a partition P of $[a, b]$ such that $U(f, P) - L(f, P) < \epsilon$.*

Proof. Suppose first that f is integrable. Then by Definition 13.16, $L(f) = U(f)$. Let $\epsilon > 0$ be arbitrary. By Script 7, $L(f) - \frac{\epsilon}{2} < L(f)$. Thus, by Definition 13.14 and Lemma 5.11, there exists an $L(f, P_1) \in \{L(f, P) \mid P \text{ is a partition of } [a, b]\}$ such that $L(f) - \frac{\epsilon}{2} < L(f, P_1) \leq L(f)$. Similarly, there exists a $U(f, P_2) \in \{U(f, P) \mid P \text{ is a partition of } [a, b]\}$ such that $U(f) \leq U(f, P_2) < U(f) + \frac{\epsilon}{2}$. Now consider $P_1 \cup P_2$ (which we will prove is the desired partition). By Theorem 1.7, $P_1 \subset P_1 \cup P_2$ and $P_2 \subset P_1 \cup P_2$. It follows by consecutive applications of Definition 13.10 that $P_1 \cup P_2$ is a refinement of both P_1 and P_2. Thus, by Lemma 13.12, $L(f, P_1) \leq L(f, P_1 \cup P_2)$ and $U(f, P_1 \cup P_2) \leq U(f, P_2)$. Combining the last several results with transitivity yields

$$L(f) - \frac{\epsilon}{2} < L(f, P_1) \leq L(f, P_1 \cup P_2) \qquad U(f, P_1 \cup P_2) \leq U(f, P_2) < U(f) + \frac{\epsilon}{2}$$

Therefore, knowing that $U(f, P_1 \cup P_2) < U(f) + \frac{\epsilon}{2}$ and that $-L(f, P_1 \cup P_2) < \frac{\epsilon}{2} - L(f)$ (the latter by Lemma 7.24), we have by Definition 7.21 that

$$\begin{aligned} U(f, P_1 \cup P_2) - L(f, P_1 \cup P_2) &< U(f) + \frac{\epsilon}{2} + \frac{\epsilon}{2} - L(f) \\ &= \epsilon \end{aligned}$$

as desired.

Now suppose that f is not integrable; we seek to prove that there exists an $\epsilon > 0$ such that for all partitions P of $[a, b]$, $U(f, P) - L(f, P) \geq \epsilon$. Since f is not integrable, we have by Definition 13.16 that

$L(f) \neq U(f)$. It follows by Exercise 13.15 that $L(f) < U(f)$. Thus, we can define $\epsilon = \frac{U(f)-L(f)}{2} > 0$. Now let P be an arbitrary partition of $[a,b]$. It follows that $L(f,P) \leq L(f)$ by Definitions 13.14, 5.7, and 5.6. Similarly, $U(f) \leq U(f,P)$. Therefore, knowing that $U(f) \leq U(f,P)$ and that $-L(f) \leq -L(f,P)$ (the latter by Lemma 7.24), we have by Definition 7.21 that $\epsilon = \frac{U(f)-L(f)}{2} < U(f) - L(f) \leq U(f,P) - L(f,P)$, as desired. ☐

4/20: **Theorem 13.19.** *If $f : [a,b] \to \mathbb{R}$ is continuous, then f is integrable.*

Proof. To prove that f is integrable, Theorem 13.18 tells us that it will suffice to show that f is bounded and that for every $\epsilon > 0$, there exists a partition P of $[a,b]$ such that $U(f,P) - L(f,P) < \epsilon$. We will verify the two requirements separately. Let's begin.

To confirm that f is bounded, Definitions 10.1 and 5.6 tell us that it will suffice to find points $l, u \in \mathbb{R}$ such that $l \leq f(x) \leq u$ for all $x \in [a,b]$. But since $f : [a,b] \to \mathbb{R}$ is continuous, consecutive applications of Exercise 10.21 imply that there exist points $c, d \in [a,b]$ such that $f(c) \leq f(x) \leq f(d)$ for all $x \in [a,b]$, so we can just choose $l = f(c)$ and $u = f(d)$.

As to the other stipulation, let $\epsilon > 0$ be arbitrary. Since $f : [a,b] \to \mathbb{R}$ is continuous, Corollary 13.8 implies that f is uniformly continuous. Thus, by Definition 13.1, there exists a $\delta > 0$ such that for all $x, y \in [a,b]$, if $|y-x| < \delta$, then $|f(y)-f(x)| < \frac{\epsilon}{b-a}$. Considering this δ, we have by Corollary 6.12 that there exist a number $n \in \mathbb{N}$ such that $\frac{2(b-a)}{\delta} < n$. Equipped with this n, we can now define the set $P = \{\frac{b-a}{n} \cdot i + a \mid 0 \leq i \leq n\}$.

We now seek to confirm that P is a partition of $[a,b]$. To do so, Definition 13.10 tells us that it will suffice to demonstrate that P is finite, $P \subset [a,b]$, and $a, b \in P$. By Script 1, P is finite. To demonstrate that $P \subset [a,b]$, Definition 1.3 and Equations 8.1 tell us that it will suffice to show that every $t_i \in P$ satisfies $a \leq t_i \leq b$. But by Script 7, we have that

$$\begin{aligned}
0 &\leq i \leq n \\
0 &\leq \frac{b-a}{n} \cdot i \leq b-a \\
a &\leq \frac{b-a}{n} \cdot i + a \leq b
\end{aligned}$$

as desired. Lastly, consider the elements of P corresponding to $i = 0$ and $i = n$. By consecutive applications of the definition of P, we have that $a = (\frac{b-a}{n} \cdot 0 + a) \in P$ and that $b = b - a + a = (\frac{b-a}{n} \cdot n + a) \in P$.

We now seek to confirm that if $t_i, t_{i-1} \in P$, then $t_i - t_{i-1} < \delta$. Let t_i, t_{i-1} be arbitrary sequential elements of P. By Script 0, we have that $0 < n$. Additionally, we have by hypothesis that $0 < \delta$. It follows by consecutive applications of Lemma 7.24 that the fact that $\frac{2(b-a)}{\delta} < n$ implies that $\frac{2(b-a)}{n} < \delta$. Therefore, we have by Script 7 that

$$\begin{aligned}
t_i - t_{i-1} &= \left(\frac{b-a}{n} \cdot i + a\right) - \left(\frac{b-a}{n} \cdot (i-1) + a\right) \\
&= \frac{b-a}{n} \\
&\leq \frac{2(b-a)}{n} \\
&< \delta
\end{aligned}$$

as desired.

We now seek to confirm that $M_i(f) - m_i(f) < \frac{\epsilon}{b-a}$ for all i satisfying $1 \leq i \leq n$. Let i be an arbitrary such number, and consider $f|_{[t_{i-1},t_i]}$. Since f is continuous and $[t_{i-1}, t_i] \subset [a,b]$, Proposition 9.7 asserts that $f|_{[t_{i-1},t_i]}$ is continuous. Thus, by Exercise 10.21, there exist $c, d \in [t_{i-1}, t_i]$ such that $f(c) \leq f(x) \leq f(d)$ for all $x \in [t_{i-1}, t_i]$. It follows by consecutive applications of Definitions 13.11 and 3.3 as well as Exercise 5.9 that $m_i(f) = f(c)$ and $M_i(f) = f(d)$. Additionally, since $c, d \in [t_{i-1}, t_i]$, we have by Script 8 that $|d-c| \leq t_i - t_{i-1}$. This combined with the fact that $t_i - t_{i-1} < \delta$ by the above implies by transitivity that

$|d - c| < \delta$. But this implies by the above that

$$\begin{aligned} M_i(f) - m_i(f) &= f(d) - f(c) \\ &= |f(d) - f(c)| \\ &< \frac{\epsilon}{b-a} \end{aligned}$$

as desired.

Having established that $M_i(f) - m_i(f) < \frac{\epsilon}{b-a}$ for all i in the partition P, we have by Definition 13.11 and basic algebra that

$$\begin{aligned} U(f,P) - L(f,P) &= \sum_{i=1}^{n} M_i(f)(t_i - t_{i-1}) - \sum_{i=1}^{n} m_i(f)(t_i - t_{i-1}) \\ &= \sum_{i=1}^{n} (M_i(f) - m_i(f))(t_i - t_{i-1}) \\ &< \sum_{i=1}^{n} \frac{\epsilon}{b-a}(t_i - t_{i-1}) \\ &= \frac{\epsilon}{b-a} \sum_{i=1}^{n} (t_i - t_{i-1}) \\ &= \frac{\epsilon}{b-a}(b-a) \\ &= \epsilon \end{aligned}$$

as desired. $\square$

Lemma 13.20. *Let $f : [a,b] \to \mathbb{R}$ be bounded. Given $\Omega \in \mathbb{R}$, we have $\Omega = \int_a^b f$ if and only if for all $\epsilon > 0$, there is some partition P such that*

$$U(f,P) - \Omega < \epsilon \qquad\qquad \Omega - L(f,P) < \epsilon$$

Proof. Suppose first that $\Omega = \int_a^b f$. Let $\epsilon > 0$ be arbitrary. By Theorem 13.18, there exists a partition P of $[a,b]$ such that $U(f,P) - L(f,P) < \epsilon$. Choose this P to be our P. By Definition 13.16, $\Omega = L(f) = U(f)$. Thus, by consecutive applications of Definitions 13.14, 5.7, and 5.6, we have that $L(f,P) \leq L(f) = \Omega$ and $\Omega = U(f) \leq U(f,P)$. With respect to the former result, it follows by Script 7 that $-\Omega \leq -L(f,P)$. Therefore, having established that $\Omega \leq U(f,P)$, $-\Omega \leq -L(f,P)$, and $U(f,P) - L(f,P) < \epsilon$, we have that

$$\begin{aligned} \Omega - L(f,P) &\leq U(f,P) - L(f,P) \\ &< \epsilon \end{aligned} \qquad\qquad \begin{aligned} U(f,P) - \Omega &\leq U(f,P) - L(f,P) \\ &< \epsilon \end{aligned}$$

Now suppose that $\Omega \neq \int_a^b f$; we seek to prove that there exists an $\epsilon > 0$ such that for all partitions P, $U(f,P) - \Omega \geq \epsilon$ or $\Omega - L(f,P) \geq \epsilon$. We divide into two cases ($\int_a^b f$ exists and $\int_a^b f$ doesn't exist).

First, suppose that $\int_a^b f$ exists. We divide into two subcases ($\Omega > \int_a^b f$ and $\Omega < \int_a^b f$). If $\Omega > \int_a^b f$, choose $\epsilon = \Omega - \int_a^b f > 0$. Let P be an arbitrary partition. As before, we have that $L(f,P) \leq L(f)$. Additionally, Definition 13.16 asserts that $L(f) = \int_a^b f$. Thus, transitivity implies that $L(f,P) \leq \int_a^b f$. It follows by Script 7 that $-\int_a^b f \leq -L(f,P)$. Therefore,

$$\begin{aligned} \epsilon &= \Omega - \int_a^b f \\ &\leq \Omega - L(f,P) \end{aligned}$$

as desired. The argument is symmetric in the other subcase.

Second, suppose that $\int_a^b f$ does not exist. By Exercise 13.15, $L(f)$ and $U(f)$ exist. However, since $\int_a^b f$ does not exist, Definition 13.16 asserts that $L(f) \neq U(f)$. It follows by Exercise 13.15 again that $L(f) < U(f)$. We now divide into three subcases ($\Omega \leq L(f)$, $L(f) < \Omega < U(f)$, and $U(f) \leq \Omega$). If $\Omega \leq L(f)$, choose $\epsilon = U(f) - L(f) > 0$. Let P be an arbitrary partition. As above, $U(f) \leq U(f,P)$. Therefore,

$$\begin{aligned}\epsilon &= U(f) - L(f)\\ &\leq U(f,P) - L(f)\\ &\leq U(f,P) - \Omega\end{aligned}$$

as desired. If $L(f) < \Omega < U(f)$, choose $\epsilon = U(f) - \Omega > 0$. Let P be an arbitrary partition. As above, $U(f) \leq U(f,P)$. Therefore,

$$\begin{aligned}\epsilon &= U(f) - \Omega\\ &\leq U(f,P) - \Omega\end{aligned}$$

as desired. The argument for the last subcase is symmetric to that of the first. □

Exercise 13.21. Define $f : [0,b] \to \mathbb{R}$ by the formula $f(x) = x$. Show that f is integrable on $[0,b]$ and that $\int_0^b f = \frac{b^2}{2}$.

Proof. To prove that f is integrable on $[0,b]$ and that $\int_0^b f = \frac{b^2}{2}$, Lemma 13.20 tells us that it will suffice to show that for all $\epsilon > 0$, there is some partition P such that $U(f,P) - \frac{b^2}{2} < \epsilon$ and $\frac{b^2}{2} - L(f,P) < \epsilon$. Let $\epsilon > 0$ be arbitrary. Since $\frac{2\epsilon}{b^2}$ is a positive real number by Script 7, Corollary 6.12 asserts that there exists a number $n \in \mathbb{N}$ such that $\frac{1}{n} < \frac{2\epsilon}{b^2}$. Equipped with this n, we can now define the set $P = \{\frac{b}{n} \cdot i \mid 0 \leq i \leq n\}$. By a symmetric argument to that used in the proof of Theorem 13.19, we can confirm that P is a partition of $[0,b]$ and that $t_i - t_{i-1} = \frac{b}{n}$.

We now turn our attention strictly to proving that $U(f,P) - \frac{b^2}{2} < \epsilon$; the proof of the other statement will be symmetric. Under the partition P as defined, consider an arbitrary $M_i(f)$. By Definition 13.11, $M_i(f) = \sup\{f(x) \mid t_{i-1} \leq x \leq t_i\}$. Since $f(x) = x$ for all $x \in [t_{i-1}, t_i] \subset [0,b]$, we have by Equations 8.1 that $M_i(f) = \sup[t_{i-1}, t_i]$. Thus, by Script 5, $M_i(f) = t_i = \frac{bi}{n}$. Therefore,

$$\begin{aligned}U(f,P) - \frac{b^2}{2} &= \sum_{i=1}^{n} M_i(f)(t_i - t_{i-1}) - \frac{b^2}{2} && \text{Definition 13.11}\\ &= \sum_{i=1}^{n} \frac{bi}{n}\left(\frac{bi}{n} - \frac{b(i-1)}{n}\right) - \frac{b^2}{2}\\ &= \frac{b^2}{n^2}\sum_{i=1}^{n} i(i-(i-1)) - \frac{b^2}{2}\\ &= \frac{b^2}{n^2}\sum_{i=1}^{n} i - \frac{b^2}{2}\\ &= \frac{b^2}{n^2}\left(\frac{1}{2}n(n+1)\right) - \frac{b^2}{2}\\ &= \frac{b^2}{2} + \frac{b^2}{2n} - \frac{b^2}{2}\\ &= \frac{b^2}{2} \cdot \frac{1}{n}\\ &< \frac{b^2}{2} \cdot \frac{2\epsilon}{b^2}\\ &= \epsilon\end{aligned}$$

as desired. □

Exercise 13.22. Show that the converse of Theorem 13.19 is false in general.

Proof. To prove that even if f is integrable, $f : [a, b] \to \mathbb{R}$ is not necessarily continuous, we need only find an example of an integrable, discontinuous function f. Let $f : [-1, 1] \to \mathbb{R}$ be defined by

$$f(x) = \begin{cases} 1 & x \geq 0 \\ 0 & x < 0 \end{cases}$$

To confirm that f is integrable, Theorem 13.18 tells us that it will suffice to show that for every $\epsilon > 0$, there exists a partition P of $[a, b]$ such that $U(f, P) - L(f, P) < \epsilon$. Let $\epsilon > 0$ be arbitrary. Choose $P = \{-1, -\frac{\epsilon}{2}, 0, 1\}$ (clearly P is a partition of $[-1, 1]$ by Definition 13.10). It follows by consecutive applications of Definitions 13.11, 5.7, and 5.6 that

$$\begin{aligned} m_1(f) &= 0 & M_1(f) &= 0 \\ m_2(f) &= 0 & M_2(f) &= 1 \\ m_3(f) &= 1 & M_3(f) &= 1 \end{aligned}$$

Therefore,

$$\begin{aligned} U(f, P) - L(f, P) &= \sum_{i=1}^{3} M_i(f)(t_i - t_{i-1}) - \sum_{i=1}^{3} m_i(f)(t_i - t_{i-1}) && \text{Definition 13.11} \\ &= \left[0\left(-\frac{\epsilon}{2} - (-1)\right) + 1\left(0 - \left(-\frac{\epsilon}{2}\right)\right) + 1(1 - 0)\right] \\ &\quad - \left[0\left(-\frac{\epsilon}{2} - (-1)\right) + 0\left(0 - \left(-\frac{\epsilon}{2}\right)\right) + 1(1 - 0)\right] \\ &= \frac{\epsilon}{2} \\ &< \epsilon \end{aligned}$$

However, by Corollary 5.5 and Theorem 3.14, $0 \in LP([-1, 1])$. Additionally, by the proof of Exercise 11.4, $\lim_{x \to 0} f(x)$ does not exist. Combining the last two results with Theorem 11.5 reveals that f is not continuous at 0. Therefore, by Theorem 9.10, f is not continuous. ☐

Theorem 13.23. *Let $a < b < c$. A function $f : [a, c] \to \mathbb{R}$ is integrable on $[a, c]$ if and only if f is integrable on $[a, b]$ and $[b, c]$. When f is integrable on $[a, c]$, we have*

$$\int_a^c f = \int_a^b f + \int_b^c f$$

Lemma. *Let P_1, P_2 be partitions of $[a, b]$ and $[b, c]$, respectively. Define $P' = P_1 \cup P_2$. Then P' is a partition of $[a, c]$, $L(f, P') = L(f, P_1) + L(f, P_2)$, and $U(f, P') = U(f, P_1) + U(f, P_2)$.*

Proof. To prove that P' is a partition of $[a, c]$, Definition 13.10 tells us that it will suffice to show that P' is finite, that $P' \subset [a, c]$, and that $a, c \in P'$. By Definition 13.10, P_1 and P_2 are finite. Thus, by Script 1, their union $P_1 \cup P_2 = P'$ is also finite. To confirm that $P' \subset [a, c]$, Definition 1.3 tells us that it will suffice to demonstrate that every $x \in P'$ is an element of $[a, c]$. Let x be an arbitrary element of P'. Then by Definition 1.5, $x \in P_1$ or $x \in P_2$. We now divide into two cases. If $x \in P_1$, then since $P_1 \subset [a, b]$ by Definition 13.10, Definition 1.3 asserts that $x \in [a, b]$. Thus, by Equations 8.1, $a \leq x \leq b$. Moreover, by hypothesis, we have that $a \leq x \leq b < c$, from which it follows by Equations 8.1 that $x \in [a, c]$, as desired. The argument is symmetric in the other case. Lastly, by consecutive applications of Definition 13.10, $a \in P_1$ and $c \in P_2$. It follows by Definition 1.5 that $a, c \in P'$, as desired.

Additionally, if we express P_1 as containing the objects $a = t_0, \dots, t_n = b$ and P_2 as containing the objects $b = t_n, \dots, t_{n+m} = c$, we have that P' contains every object t_0 through t_{n+m}. Therefore, we have by consecutive applications of Definition 13.11 that

$$\begin{aligned} L(f,P') &= \sum_{i=1}^{n+m} m_i(f)(t_i - t_{i-1}) \\ &= \sum_{i=1}^{n} m_i(f)(t_i - t_{i-1}) + \sum_{i=n+1}^{n+m} m_i(f)(t_i - t_{i-1}) \\ &= L(f,P_1) + L(f,P_2) \end{aligned}$$

The proof is symmetric for the other statement. □

Proof of Theorem 13.23. Suppose first that f is integrable on $[a,c]$. To prove that f is integrable on $[a,b]$ and $[b,c]$, Theorem 13.18 tells us that it will suffice to show that for every $\epsilon > 0$, there exist partitions P_1, P_2 of $[a,b]$ and $[b,c]$, respectively, such that $U(f,P_1) - L(f,P_1) < \epsilon$ and $U(f,P_2) - L(f,P_2) < \epsilon$. Let $\epsilon > 0$ be arbitrary. Since f is integrable on $[a,c]$, there exists a partition P of $[a,c]$ such that $U(f,P) - L(f,P) < \epsilon$. Now define $P' = P \cup \{b\}$. Since P' is finite (by Script 1), a subset of $[a,c]$ (because $P \subset [a,c]$ by Definition 13.10 and $\{b\} \subset [a,c]$), and contains a, c (because $a, c \in P$ implies $a, c \in P \cup \{b\}$ by Definition 1.5), Definition 13.10 asserts that P' is a partition of $[a,c]$. Furthermore, since $P \subset P'$ by Theorem 1.7, Definition 13.10 implies that P' is a refinement of P. Thus, by Lemma 13.12, $L(f,P) \leq L(f,P')$ and $U(f,P) \geq U(f,P')$. This combined with the fact that $U(f,P) - L(f,P) < \epsilon$ implies by Script 7 that $U(f,P') - L(f,P') \leq U(f,P) - U(f,P) < \epsilon$.

Let $P_1 = P' \cap [a,b]$ and $P_2 = P' \cap [b,c]$. In the same manner as before, we have that P_1 is a partition of $[a,b]$ and P_2 is a partition of $[b,c]$. This combined with the fact that $P_1 \cup P_2 = P' \cap ([a,b] \cup [b,c]) = P'$ by Script 1 implies by the lemma that $L(f,P') = L(f,P_1) + L(f,P_2)$ and $U(f,P') = U(f,P_1) + U(f,P_2)$. Thus, we have that

$$\begin{aligned} (U(f,P_1) - L(f,P_1)) + (U(f,P_2) - L(f,P_2)) &= U(f,P') - L(f,P') \\ &< \epsilon \end{aligned}$$

Additionally, we have by consecutive applications of Definition 13.11 that $L(f,P_1) \leq U(f,P_1)$ and $L(f,P_2) \leq U(f,P_2)$. It follows by consecutive applications of Definition 7.21 that $0 \leq U(f,P_1) - L(f,P_1)$ and $0 \leq U(f,P_2) - L(f,P_2)$. This combined with the above result that $(U(f,P_1) - L(f,P_1)) + (U(f,P_2) - L(f,P_2)) < \epsilon$ implies by Script 7 that $U(f,P_1) - L(f,P_1) < \epsilon$ and $U(f,P_2) - L(f,P_2) < \epsilon$.

Now suppose that f is integrable on $[a,b]$ and $[b,c]$. Let $\Omega_1 = \int_a^b f$, $\Omega_2 = \int_b^c f$, and $\Omega = \Omega_1 + \Omega_2$. Thus, to prove that f is integrable on $[a,c]$ and that $\int_a^c f = \int_a^b f + \int_b^c f$, Lemma 13.20 tells us that it will suffice to show that for all $\epsilon > 0$, there is some partition P' of $[a,c]$ such that $U(f,P') - \Omega < \epsilon$ and $\Omega - L(f,P') < \epsilon$. Let $\epsilon > 0$ be arbitrary. Since f is integrable on $[a,b]$ and $[b,c]$, we have by consecutive applications of Lemma 13.20 that there exist partitions P_1 of $[a,b]$ and P_2 of $[b,c]$ such that $U(f,P_1) - \Omega_1 < \frac{\epsilon}{2}$, $\Omega_1 - L(f,P_1) < \frac{\epsilon}{2}$, $U(f,P_2) - \Omega_2 < \frac{\epsilon}{2}$, and $\Omega_2 - L(f,P_2) < \frac{\epsilon}{2}$. Choose $P' = P_1 \cup P_2$. By the lemma, P' is a partition of $[a,c]$. Combining all of the above results implies by Script 7 and the lemma that

$$\begin{aligned} U(f,P') - \Omega &= U(f,P_1) + U(f,P_2) - \Omega_1 - \Omega_2 \\ &= (U(f,P_1) - \Omega_1) + (U(f,P_2) - \Omega_2) \\ &< \frac{\epsilon}{2} + \frac{\epsilon}{2} \\ &= \epsilon \end{aligned}$$

$$\begin{aligned} \Omega - L(f,P') &= \Omega_1 + \Omega_2 - L(f,P_1) - L(f,P_2) \\ &= (\Omega_1 - L(f,P_1)) + (\Omega_2 - L(f,P_2)) \\ &< \frac{\epsilon}{2} + \frac{\epsilon}{2} \\ &= \epsilon \end{aligned}$$

Note that since the claim technically asks us to prove that $\int_a^c f = \int_a^b f + \int_b^c f$ follows from f being integrable on $[a,c]$, not $[a,b]$ and $[b,c]$, we can do this with the above using the following logic. Let f be integrable on $[a,c]$. Then by the first part of the proof, it is integrable on $[a,b]$ and $[b,c]$. It follows by the second part of the proof that $\int_a^c f = \int_a^b f + \int_b^c f$, as desired. □

4/22: If $b < a$, we define

$$\int_a^b f = -\int_b^a f$$

whenever the latter integral exists. With this notational convention, it follows that the equation

$$\int_a^c f = \int_a^b f + \int_b^c f$$

always holds, regardless of the ordering of a, b, c whenever f is integrable on the largest of the three intervals.

Theorem 13.24. *Suppose that f and g are integrable functions on $[a,b]$ and that $c \in \mathbb{R}$ is a constant. Then $f+g$ and cf are integrable on $[a,b]$ and*

(a) $\int_a^b (f+g) = \int_a^b f + \int_a^b g$.

(b) $\int_a^b cf = c\int_a^b f$.

Lemma.

(a) *Let $P = \{t_0, \dots, t_n\}$ be an arbitrary partition of $[a,b]$. Then for any $i \in [n]$, we have $M_i(f+g) \leq M_i(f) + M_i(g)$ and $m_i(f+g) \geq m_i(f) + m_i(g)$.*

(b) *Let $P = \{t_0, \dots, t_n\}$ be an arbitrary partition of $[a,b]$. Then if $c > 0$, we have $M_i(cf) = c \cdot M_i(f)$ and $m_i(cf) = c \cdot m_i(f)$ for any $i \in [n]$.*

(c) *Let $P = \{t_0, \dots, t_n\}$ be an arbitrary partition of $[a,b]$. Then if $c < 0$, we have $M_i(cf) = c \cdot m_i(f)$ and $m_i(cf) = c \cdot M_i(f)$ for any $i \in [n]$.*

Proof of Lemma (a). Let i be an arbitrary natural number satisfying $1 \leq i \leq n$. By Definitions 13.11, 5.7, and 5.6, $f(x) \leq M_i(f)$ for all $x \in [t_{i-1}, t_i]$. Similarly, $g(x) \leq M_i(g)$ for all $x \in [t_{i-1}, t_i]$. Thus, we have by Definition 7.21 that $(f+g)(x) \leq M_i(f) + M_i(g)$ for all $x \in [t_{i-1}, t_i]$. Consequently, Definition 5.6 asserts that $M_i(f) + M_i(g)$ is an upper bound on $\{(f+g)(x) \mid t_{i-1} \leq x \leq t_i\}$. Therefore, the supremum of that set will be less than or equal to $M_i(f) + M_i(g)$ by Definition 5.7. But since $M_i(f+g)$ *is* said supremum by Definition 13.11, we have that $M_i(f+g) \leq M_i(f) + M_i(g)$ as desired.

The proof is symmetric in the other case. ☐

Proof of Lemma (b). Suppose for the sake of contradiction that $M_i(cf) \neq c \cdot M_i(f)$. We divide into two cases ($M_i(cf) < c \cdot M_i(f)$ and $M_i(cf) > c \cdot M_i(f)$). If $M_i(cf) < c \cdot M_i(f)$, then since $c > 0$, Lemma 7.24 implies that $\frac{M_i(cf)}{c} < M_i(f)$. It follows by Lemma 5.11 that there exists $f(x) \in \{f(x) \mid t_{i-1} \leq x \leq t_i\}$ such that $\frac{M_i(cf)}{c} < f(x) \leq M_i(f)$, i.e., $M_i(cf) < cf(x)$. But by Definitions 13.11, 5.7, and 5.6, $cf(x) \leq M_i(cf)$ for all $x \in [t_{i-1}, t_i]$, a contradiction. The argument is symmetric in the other case.

The proof is symmetric in the other case. ☐

Proof of Lemma (c). Suppose for the sake of contradiction that $M_i(cf) \neq c \cdot m_i(f)$. We divide into two cases ($M_i(cf) < c \cdot m_i(f)$ and $M_i(cf) > c \cdot m_i(f)$). If $M_i(cf) < c \cdot m_i(f)$, then since $c < 0$, Lemma 7.24 implies that $\frac{M_i(cf)}{c} > m_i(f)$. It follows by Lemma 5.11 that there exists $f(x) \in \{f(x) \mid t_{i-1} \leq x \leq t_i\}$ such that $\frac{M_i(cf)}{c} > f(x) \geq m_i(f)$, i.e., $M_i(cf) < cf(x)$. But by Definitions 13.11, 5.7, and 5.6, $cf(x) \leq M_i(cf)$ for all $x \in [t_{i-1}, t_i]$, a contradiction. The argument is symmetric in the other case.

The proof is symmetric in the other case. ☐

Proof of Theorem 13.24a. Let $\Omega_f = \int_a^b f$, $\Omega_g = \int_a^b g$, and $\Omega = \Omega_f + \Omega_g$. To prove that $f+g$ is integrable on $[a,b]$ and that $\int_a^b (f+g) = \int_a^b f + \int_a^b g$, Lemma 13.20 tells us that it will suffice to show that for all $\epsilon > 0$, there is some partition P such that $U(f+g, P) - \Omega < \epsilon$ and $\Omega - L(f+g, P) < \epsilon$. Let $\epsilon > 0$ be arbitrary. Since f, g are integrable on $[a,b]$, we have by consecutive applications of Lemma 13.20 that there exist partitions Q, R of $[a,b]$ such that $U(f,Q) - \Omega_f < \frac{\epsilon}{2}$, $\Omega_f - L(f,Q) < \frac{\epsilon}{2}$, $U(g,R) - \Omega_g < \frac{\epsilon}{2}$, and $\Omega_g - L(g,R) < \frac{\epsilon}{2}$. As in previous proofs, $P = Q \cup R$ is also a partition of $[a,b]$ and a refinement of both Q and R. Consequently, we have that $U(f,P) - \Omega_f \leq U(f,Q) - \Omega_f < \frac{\epsilon}{2}$, $\Omega_f - L(f,P) \leq \Omega_f - L(f,Q) < \frac{\epsilon}{2}$,

$U(g,P)-\Omega_g \leq U(g,R)-\Omega_g < \frac{\epsilon}{2}$, and $\Omega_g - L(g,P) \leq \Omega_g - L(g,R) < \frac{\epsilon}{2}$. It follows by consecutive applications of Script 7 that $U(f,P) + U(g,P) - \Omega < \epsilon$ and that $\Omega - (L(f,P) + L(g,P)) < \epsilon$. Therefore, we have that

$$\begin{aligned}
U(f+g,P) - \Omega &= \sum_{i=1}^{n} M_i(f+g)(t_i - t_{i-1}) - \Omega && \text{Definition 13.11} \\
&\leq \sum_{i=1}^{n} (M_i(f) + M_i(g))(t_i - t_{i-1}) - \Omega && \text{Lemma (a)} \\
&= \sum_{i=1}^{n} M_i(f)(t_i - t_{i-1}) + \sum_{i=1}^{n} M_i(g)(t_i - t_{i-1}) - \Omega \\
&= U(f,P) + U(g,P) - \Omega && \text{Definition 13.11} \\
&< \epsilon
\end{aligned}$$

and something similar for $\Omega - L(f+g,P)$. $\square$

Proof of Theorem 13.24b. We divide into three cases ($c = 0$, $c > 0$, and $c < 0$).

If $c = 0$, then we have that $cf(x) = 0$ for all $x \in [a,b]$. Therefore, we have by Exercise 13.17 that cf is integrable on $[a,b]$ and

$$\begin{aligned}
\int_a^b cf &= 0(b-a) \\
&= 0 \\
&= 0 \cdot \int_a^b f \\
&= c \int_a^b f
\end{aligned}$$

If $c > 0$, then let $\Omega = \int_a^b f$. To prove that cf is integrable on $[a,b]$ and that $\int_a^b cf = c\int_a^b f$, Lemma 13.20 tells us that it will suffice to show that for all $\epsilon > 0$, there is some partition P such that $U(cf,P) - c\,\Omega < \epsilon$ and $c\,\Omega - L(cf,P) < \epsilon$. Let $\epsilon > 0$ be arbitrary. Since f is integrable on $[a,b]$, we have by Lemma 13.20 that there exists a partition P such that $U(f,P) - \Omega < \frac{\epsilon}{c}$ and $\Omega - L(f,P) < \frac{\epsilon}{c}$. It follows by consecutive applications of Lemma 7.24 that $c\,U(f,P) - c\,\Omega < \epsilon$ and $c\,\Omega - c\,L(f,P) < \epsilon$. Therefore, we have that

$$\begin{aligned}
U(cf,P) - c\,\Omega &= \sum_{i=1}^{n} M_i(cf)(t_i - t_{i-1}) - c\,\Omega && \text{Definition 13.11} \\
&= \sum_{i=1}^{n} c \cdot M_i(f)(t_i - t_{i-1}) - c\,\Omega && \text{Lemma (b)} \\
&= c\sum_{i=1}^{n} M_i(f)(t_i - t_{i-1}) - c\,\Omega \\
&= c\,U(f,P) - c\,\Omega && \text{Definition 13.11} \\
&< \epsilon
\end{aligned}$$

and something similar for $c\,\Omega - L(cf,P)$.

If $c < 0$, then let $\Omega = \int_a^b f$. To prove that cf is integrable on $[a,b]$ and that $\int_a^b cf = c\int_a^b f$, Lemma 13.20 tells us that it will suffice to show that for all $\epsilon > 0$, there is some partition P such that $U(cf,P) - c\,\Omega < \epsilon$ and $c\,\Omega - L(cf,P) < \epsilon$. Let $\epsilon > 0$ be arbitrary. Since f is integrable on $[a,b]$, we have by Lemma 13.20 that there exists a partition P such that $U(f,P) - \Omega < \frac{\epsilon}{-c}$ and $\Omega - L(f,P) < \frac{\epsilon}{-c}$. It follows by consecutive applications of Lemma 7.24 that $c\,\Omega - c\,U(f,P) < \epsilon$ and $c\,L(f,P) - c\,\Omega < \epsilon$. Therefore, we have that

$$\begin{aligned}
U(cf,P) - c\,\Omega &= \sum_{i=1}^{n} M_i(cf)(t_i - t_{i-1}) - c\,\Omega && \text{Definition 13.11}\\
&= \sum_{i=1}^{n} c \cdot m_i(f)(t_i - t_{i-1}) - c\,\Omega && \text{Lemma (c)}\\
&= c\sum_{i=1}^{n} m_i(f)(t_i - t_{i-1}) - c\,\Omega &&\\
&= c\,L(f,P) - c\,\Omega && \text{Definition 13.11}\\
&< \epsilon
\end{aligned}$$

and something similar for $c\,\Omega - L(cf,P)$. ☐

4/27: **Theorem 13.25.** *Suppose that f and g are integrable functions on $[a,b]$ with $f(x) \leq g(x)$ for all $x \in [a,b]$. Then*

$$\int_a^b f \leq \int_a^b g$$

Proof. Suppose for the sake of contradiction that $\int_a^b f > \int_a^b g$. Then by Definition 13.16, $L(f) > L(g)$. It follows by Lemma 5.11 that there exists a $L(f,P) \in \{L(f,P) \mid P \text{ is a partition of } [a,b]\}$ such that $L(f) \geq L(f,P) > L(g)$. Thus, since $L(g,P) \leq L(g)$ by Definitions 13.14, 5.7, and 5.6, we have that $L(g,P) < L(f,P)$. Consequently, by Definition 13.11, $\sum_{i=1}^{n} m_i(g)(t_i - t_{i-1}) < \sum_{i=1}^{n} m_i(f)(t_i - t_{i-1})$. Thus, by Script 7, there exists an i such that $m_i(g) < m_i(f)$. It follows by Lemma 5.11 that there exists a $g(x) \in \{g(x) \mid t_{i-1} \leq x \leq t_i\}$ such that $m_i(g) \leq g(x) < m_i(f)$. But this implies by Definitions 13.11, 5.7, and 5.6 that $g(x) < f(x)$, a contradiction. ☐

4/29: **Theorem 13.26.** *Suppose that f is an integrable function on $[a,b]$. Then $|f|$ is also integrable on $[a,b]$ and*

$$\left|\int_a^b f\right| \leq \int_a^b |f|$$

Lemma. *Let $P = \{t_0, \dots, t_n\}$ be an arbitrary partition of $[a,b]$. Then for any $i \in [n]$, the following inequality holds.*

$$M_i(|f|) - m_i(|f|) \leq M_i(f) - m_i(f)$$

Proof. Let i be an arbitrary natural number satisfying $1 \leq i \leq n$. We divide into three cases ($f(x) \geq 0$ for all $x \in [a,b]$, $f(x) \leq 0$ for all $x \in [a,b]$, and there exist $x, y \in [a,b]$ such that $f(x) < 0 < f(y)$). Let's begin.

First, suppose that $f(x) \geq 0$ for all $x \in [a,b]$. Then by Definition 8.4, $|f(x)| = f(x)$ for all $x \in [a,b]$. It follows that $M_i(|f|) - m_i(|f|) = M_i(f) - m_i(f)$, which can be weakened to $M_i(|f|) - m_i(|f|) \leq M_i(f) - m_i(f)$, as desired.

Second, suppose that $f(x) \leq 0$ for all $x \in [a,b]$. Then by Definition 8.4, $|f(x)| = -f(x)$ for all $x \in [a,b]$. It follows that

$$\begin{aligned}
M_i(|f|) - m_i(|f|) &= M_i(-f) - m_i(-f) &&\\
&= -m_i(f) - (-M_i(f)) && \text{Lemma (c), Theorem 13.24}\\
&= M_i(f) - m_i(f)
\end{aligned}$$

which can be weakened to $M_i(|f|) - m_i(|f|) \leq M_i(f) - m_i(f)$, as desired.

Third, suppose that there exist $x, y \in [a,b]$ such that $f(x) < 0 < f(y)$. We divide into two subcases ($|M_i(f)| \geq |m_i(f)|$ and $|M_i(f)| < |m_i(f)|$).

Suppose first that $|M_i(f)| \geq |m_i(f)|$. By Definitions 13.11, 5.7, and 5.6 as well as the hypothesis, $M_i(f) \geq f(y) > 0$. Thus, by Definition 8.4, $|M_i(f)| = M_i(f)$. Similarly, $|m_i(f)| = -m_i(f)$. It follows by

Lemma (c) from Theorem 13.24 that $-m_i(f) = M_i(-f)$. Combining the last three results, we have by the hypothesis that $M_i(f) \geq M_i(-f)$. Additionally, we clearly have that $M_i(f) \geq M_i(f)$. Consequently, since $M_i(f) \geq M_i(-f)$ and $M_i(f) \geq M_i(f)$, we have by Script 5 that $M_i(f) \geq M_i(|f|)$. Furthermore, we have by Definitions 13.11, 5.7, 5.6, and 8.4 that $m_i(|f|) \geq 0 > f(x) \geq m_i(f)$. Therefore, since $M_i(|f|) \leq M_i(f)$ and $m_i(f) < m_i(|f|)$, we have that

$$\begin{aligned} M_i(|f|) - m_i(|f|) &\leq M_i(f) - m_i(|f|) \\ &< M_i(f) - m_i(f) \end{aligned}$$

which can be weakened to $M_i(|f|) - m_i(|f|) \leq M_i(f) - m_i(f)$, as desired.

Now suppose that $|M_i(f)| < |m_i(f)|$. As before, $M_i(f) > 0$ and $m_i(|f|) \geq 0$. It follows from the former result by Lemma 7.23 that $-M_i(f) < 0$. This combined with the previous result implies by transitivity that $-M_i(f) \leq m_i(|f|)$. Additionally, we have as before that $-m_i(f) = M_i(-f)$ and $M_i(f) = |M_i(f)| < |m_i(f)| = -m_i(f) = M_i(-f)$. Thus, $M_i(|f|) = M_i(-f) = -m_i(f)$. This combined with the fact that $-M_i(f) \leq m_i(|f|)$ implies by Definition 7.21 that $M_i(|f|) - M_i(f) < m_i(|f|) - m_i(f)$. It follows by consecutive applications of Definition 7.21 that $M_i(|f|) - m_i(|f|) < M_i(f) - m_i(f)$, which can be weakened to $M_i(|f|) - m_i(|f|) \leq M_i(f) - m_i(f)$, as desired. ☐

Proof of Theorem 13.26. To prove that $|f|$ is integrable on $[a,b]$, Theorem 13.18 tells us that it will suffice to show that for every $\epsilon > 0$, there exists a partition P of $[a,b]$ such that $U(|f|,P) - L(|f|,P) < \epsilon$. Let $\epsilon > 0$ be arbitrary. By Theorem 13.18, there exists a partition P of $[a,b]$ such that $U(f,P) - L(f,P) < \epsilon$. Therefore,

$$\begin{aligned} U(|f|,P) - L(|f|,P) &= \sum_{i=1}^n M_i(|f|)(t_i - t_{i-1}) - \sum_{i=1}^n m_i(|f|)(t_i - t_{i-1}) && \text{Definition 13.11} \\ &= \sum_{i=1}^n (M_i(|f|) - m_i(|f|))(t_i - t_{i-1}) \\ &\leq \sum_{i=1}^n (M_i(f) - m_i(f))(t_i - t_{i-1}) && \text{The Lemma} \\ &= \sum_{i=1}^n M_i(f)(t_i - t_{i-1}) - \sum_{i=1}^n m_i(f)(t_i - t_{i-1}) \\ &= U(f,P) - L(f,P) && \text{Definition 13.11} \\ &< \epsilon \end{aligned}$$

as desired.

We now seek to prove that $|\int_a^b f| \leq \int_a^b |f|$. By Script 8, $-|f(x)| \leq f(x) \leq |f(x)|$ for all $x \in [a,b]$. It follows by consecutive applications of Theorem 13.25 that $\int_a^b -|f| \leq \int_a^b f \leq \int_a^b |f|$. Thus, since Theorem 13.24 asserts that $\int_a^b -|f| = -\int_a^b |f|$, we have that $-\int_a^b |f| \leq \int_a^b f \leq \int_a^b |f|$. Therefore, by the lemma to Exercise 8.9, $|\int_a^b f| \leq \int_a^b |f|$, as desired. ☐

5/4: **Theorem 13.27.** *Suppose that f is integrable on $[a,b]$ and $m \leq f(x) \leq M$ for all $x \in [a,b]$. Then*

$$m(b-a) \leq \int_a^b f \leq M(b-a)$$

Proof. Let $g,h : [a,b] \to \mathbb{R}$ be defined by $g(x) = m$ and $h(x) = M$. By consecutive applications of Exercise 13.17, g and h are integrable on $[a,b]$ with $\int_a^b g = m(b-a)$ and $\int_a^b h = M(b-a)$. Additionally, we have by the definitions of g and h that $g(x) = m \leq f(x) \leq M = h(x)$. This combined with the fact that both g and h are integrable implies by consecutive applications of Theorem 13.25 that $\int_a^b g \leq \int_a^b f \leq \int_a^b h$. But this implies by the above that $m(b-a) \leq \int_a^b f \leq M(b-a)$, as desired. ☐

Theorem 13.28. *Suppose that f is integrable on $[a,b]$. Define $F:[a,b]\to\mathbb{R}$ by*

$$F(x)=\int_a^x f$$

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 $x\in[a,b]$. Let x be an arbitrary element of $[a,b]$. 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 $y\in[a,b]$ and $|y-x|<\delta$, then $|F(y)-F(x)|<\epsilon$. Let $\epsilon>0$ be arbitrary. By Scripts 1 and 5, the fact that $\{f(x)\mid x\in[a,b]\}$ is nonempty and bounded implies that $\{|f(x)|\mid x\in[a,b]\}$ is nonempty and bounded above. Thus, by Theorem 5.17, $\sup\{|f(x)|\mid x\in[a,b]\}$ exists. As such, we may define $s=\sup\{|f(x)|\mid x\in[a,b]\}$ so that we may choose $\delta=\frac{\epsilon}{s}$. Now let y be an arbitrary element of $[a,b]$ such that $|y-x|<\delta$. Therefore,

$$\begin{aligned}
|F(y)-F(x)| &= \left|\int_a^y f-\int_a^x f\right| \\
&= \left|\int_x^y f\right| && \text{Theorem 13.23} \\
&\leq \int_x^y |f| && \text{Theorem 13.26} \\
&\leq s(y-x) && \text{Theorem 13.27} \\
&\leq s\cdot|y-x| \\
&< s\cdot\frac{\epsilon}{s} \\
&= \epsilon
\end{aligned}$$

□

Additional Exercises

2. Suppose that $|f(x)-g(x)|\leq\frac{\epsilon}{2}$ for all $x\in[a,b]$. Let $M_f=\sup\{f(x)\mid x\in[a,b]\}$ and $M_g=\sup\{g(x)\mid x\in[a,b]\}$. Prove that

$$M_f-M_g<\epsilon$$