6.6 Integration and Differentiation

Problem 6.R:13

Let $f(x) = \int_{t=x}^{t=x+1} \sin(t^2)dt$.

a

Show that when $x > 0$, $|f(x)| < \frac{1}{x}$.

Proof: Note that $x > 0$ implies that the limits of integration are correct. Make the substitution $t^2 = u$ to get

$$f(x) = \frac{1}{2}\int_{u=x^2}^{u=(x+1)^2} u^{-\frac{1}{2}} \sin(u)du$$

Integrate by parts with $a = u^{\frac{1}{2}}$ and $db = \sin(u)$ to get

$$\begin{aligned} f(x) &= \frac{1}{2}\left[-u^{-\frac{1}{2}}\cos(u)]_{x^2}^{(x+1)^2} - \frac{1}{2}\int_{x^2}^{(x+1)^2} u^{-\frac{3}{2}}\cos(u)du \right] \\ &= \frac{\cos(x^2)}{2x} - \frac{\cos((x+1)^2)}{2(x+1)} - \frac{1}{4}\int_{x^2}^{(x+1)^2} u^{-\frac{3}{2}}\cos(u)du \end{aligned}$$

Evaluating the integral on the right, $\cos(x) \geq -1$, so

$$\int_{x^2}^{(x+1)^2} u^{-\frac{3}{2}}\cos(u)du \geq -\int_{x^2}^{(x+1)^2} u^{-\frac{3}{2}}du = 2\left(\frac{1}{x+1} - \frac{1}{x}\right)$$

Substituting,

$$\begin{aligned} f(x) &\leq \frac{\cos(x^2)}{2x} - \frac{\cos((x+1)^2)}{2(x+1)} - \frac{1}{2(x+1)} + \frac{1}{2x} \\ &= \frac{\cos(x^2)+1}{2x} - \frac{\cos((x+1)^2)+1}{2(x+1)} \\ &\leq \frac{2}{2x} = \frac{1}{x} \end{aligned}$$

Since $\cos(t) \leq 1$. To show that $f(x) \geq -\frac{1}{x}$, it suffices to show that $f(x) \leq \frac{1}{x}$.

$$-f(x) = \frac{\cos((x+1)^2)}{2(x+1} - \frac{\cos(x^2)}{2x} + \frac{1}{4}\int_{x^2}^{(x+1)^2} u^{-\frac{3}{2}}\cos(u)du$$

By a similar argument as before, $\cos(x) \leq 1$, so

$$\int_{x^2}^{(x+1)^2} u^{-\frac{3}{2}}\cos(u)du \leq \int_{x^2}^{(x+1)^2} u^{-\frac{3}{2}}du = 2\left(\frac{1}{x} - \frac{1}{x+1}\right)$$

Substituting,

$$\begin{aligned}
-f(x) &\le \frac{\cos((x+1)^2)}{2(x+1} - \frac{\cos(x^2)}{2x} + \frac{1}{2x} - \frac{1}{2(x+1)} \\
&\le \frac{1}{2(x+1)} + \frac{1}{2x} + \frac{1}{2x} - \frac{1}{2(x+1)} \\
&= \frac{1}{x}
\end{aligned}$$

□

b

Prove that there exists constant c and function $r(x)$ with $|r(x)| < \frac{c}{x}$ such that

$$2xf(x) = \cos(x^2) - \cos((x+1)^2) + r(x)$$

Proof: I will assume that $x > 0$, as the expression $\frac{c}{x}$ doesn't make much sense for $x = 0$, and it's impossible for $|r(x)| < \frac{c}{x}$ to be true for both positive and negative x while c is constant.

From results in Part a,

$$\begin{aligned}
2xf(x) &= \cos(x^2) - \frac{x}{x+1}\cos((x+1)^2) - \frac{x}{2}\int_{x^2}^{(x+1)^2} u^{-\frac{3}{2}}\cos(u)du \\
&= \cos(x^2) - \cos((x+1)^2) + \frac{1}{x+1}\cos((x+1)^2) - \frac{x}{2}\int_{x^2}^{(x+1)^2} u^{-\frac{3}{2}}\cos(u)du
\end{aligned}$$

From the above, it's clear that $r(x) = \frac{1}{x+1}\cos((x+1)^2) - \frac{x}{2}\int_{x^2}^{(x+1)^2} u^{-\frac{3}{2}}\cos(u)du$. Now it remains to show that $|r(x)| < \frac{c}{x}$. Using that $\cos(t)$ and $-\cos(t)$ is are bounded above by 1,

$$r(x) \le \frac{1}{x+1} + \frac{x}{2}\int_{x^2}^{(x+1)^2} u^{-\frac{3}{2}}du = \frac{1}{x+1} - x\left[\frac{1}{x+1} - \frac{1}{x}\right] = \frac{2}{x+1} < \frac{2}{x}$$

Similarly,

$$\begin{aligned}
-r(x) &= -\frac{1}{x+1}\cos((x+1)^2) + \frac{x}{2}\int_{x^2}^{(x+1)^2} u^{-\frac{3}{2}}\cos(u)du \\
&\ge -\frac{1}{x+1} - \frac{x}{2}\int_{x^2}^{(x+1)^2} u^{-\frac{3}{2}}du = -\frac{2}{x+1} \ge -\frac{2}{x}
\end{aligned}$$

Thus $|r(x)| < \frac{3}{x}$.

□

c

Find the upper and lower limits of $xf(x)$ as x approaches infinity.

We know from previous results that

$$xf(x) = \frac{\cos(x^2))}{2} - \frac{\cos((x+1)^2)}{2} + s(x)$$

where $|s(x)| \leq \frac{1}{x}$. $\lim_{x\to\infty} s(x) = 0$, so the upper and lower limits of $s(x)$ are also 0.

Note that by the periodicity of cosine, for $n \in N$, $\cos(\sqrt{2\pi n}^2) = 1$. We now show that there exist infinite $n \in N$ such that $\cos((\sqrt{2\pi n}+1)^2) = \cos(2\pi n + 2\sqrt{2\pi n}+1) = -1$, thus implying that $\limsup_{n\to\infty} xf(x) = 1$.

Theorem 1 *Let $\delta > 0$. Then there exist infinite natural numbers a such that $|2\sqrt{2a\pi}+1-\pi| < \delta (\mod 2\pi)$. In other words, $2\sqrt{2a\pi}+1$ becomes arbitrarily close to a number of the form $b\pi$, where b is an odd number.*

To prove this, we will need to analyze the behavior of $g(x) = 2\sqrt{2\pi}\sqrt{x}+1$, then evaluate it at specifically chosen a's. We first start by analyzing the Taylor series of $\sqrt{x}$.

Lemma 2 *The Taylor series of $\sqrt{x}$ about $x_0 > 0$ is*

$$\sqrt{x_0} + \frac{1}{2(1!)}x_0^{-\frac{1}{2}}(x-n) + \sum_{i=2}^{\infty} \frac{(-1)^{i-1}}{2^i} \frac{1(3)(5)...(2i-3)}{i!} x_0^{-i+\frac{1}{2}}(x-x_0)^i$$

with radius of convergence $R = x_0$.

Proof: The first few terms of the Taylor series are

$$T(x) = \sqrt{x_0} + \frac{1}{2(1!)}x_0^{-\frac{1}{2}}(x-x_0) - \frac{1}{2^2(2!)}x_0^{-\frac{3}{2}}(x-x_0)^2 + \frac{3}{2^3(3!)}x_0^{-\frac{5}{2}}(x-x_0)^3 \dots$$

To find the radius of convergence, note that

$$\frac{1(3)(5)...(2i-3)}{2^i} < \frac{1}{2}\left(\frac{1}{2}\right)\left(\frac{3}{2}\right)\left(\frac{5}{2}\right)\dots\frac{2i-3}{2} < \frac{1}{2}1(2)(3)\dots i = \frac{1}{2}i!$$

implying that when $x > x_0$,

$$\frac{1(3)(5)...(2i-3)}{2^i(i!)} x_0^{-i+\frac{1}{2}}(x-x_0)^i < \frac{\sqrt{x_0}}{2}\left(\frac{x}{x_0}-1\right)^i$$

Since $T(x)$ is alternating, it converges when $\frac{x}{x_0} - 1 < 1 \to x \in [x_0, 2x_0)$.

When $x < x_0$,

$$T(x) = \sqrt{x_0} + \frac{1}{2(1!)}x_0^{-\frac{1}{2}}(x-n) - \sqrt{x_0}\sum_{i=2}^{\infty}\frac{1(3)(5)...(2i-3)}{2^i(i!)}\left(1-\frac{x}{x_0}\right)^i$$

Since

$$\frac{1(3)(5)...(2i-3)}{2^i(i!)}\left(1-\frac{x}{x_0}\right)^i < \frac{1}{2}\left(1-\frac{x}{x_0}\right)^i$$

and the right series is a convergent geometric series under the assumption that $x \in (0, x_0]$, $T(x)$ converges.

□

We next show that viewed as a sequence over the natural numbers, (g_n)'s differences between terms become arbitrarily small.

Lemma 3 *Let* $(g_n) = 2\sqrt{2\pi}\sqrt{n} + 1$ *for* $n \in N$*, and* $\Delta g_n = g_{n+1} - g_n = 2\sqrt{2}(\sqrt{n+1} - \sqrt{n})$*. Then* $\lim_{n\to\infty} \Delta g_n = 0$.

Proof: It suffices to show that $\lim_{n\to\infty} \sqrt{n+1} - \sqrt{n} = 0$. From the results in Theorem 2, the Taylor series of $\sqrt{x}$ at n is

$$\sqrt{n+x} = \sqrt{n} + \frac{1}{2(1!)}n^{-\frac{1}{2}}(x) + \sum_{i=2}^{\infty} \frac{(-1)^{i-1}}{2^i}\frac{1(3)(5)...(2i-3)}{i!}n^{-i+\frac{1}{2}}(x)^i$$

Since the series is alternating and convergent, its partial sums that have a positive term as their highest power are larger than the series. Thus

$$\sqrt{n+1} < \sqrt{n} + \frac{1}{2\sqrt{n}}$$

implying

$$0 \leq \sqrt{n+1} - \sqrt{n} < \frac{1}{2\sqrt{n}}$$

implying that $\lim_{n\to\infty} \sqrt{n+1} - \sqrt{n} = 0$.

□

We are now in the position to prove Theorem 1.

Proof: Let (g_n) be the sequence defined by $g_n = 2\sqrt{2\pi}\sqrt{n} + 1 - \pi$. Since $\lim_{n\to\infty} \Delta g_n = 0$, there exists $n_0 \in \mathbb{N}$ such that $n \geq n_0$ implies that $\Delta g_n < \delta$. This, combined with (g_n) being strictly increasing and $\lim_{n\to\infty} g_n = \infty$, imply that (g_n) passes through all numbers greater than g_{n_0} while increasing to infinity, while taking step sizes less than δ.

Specifically, for any natural number b such that $2\pi b > g_{n_0}$, there exists an $a \geq n_0$ in the natural numbers such that

$$g_a \leq 2\pi b < g_{a+1}$$

$\Delta g_a < \delta$ implies

$$|\Delta g_a - 2\pi b| < \delta$$

which is equivalent to

$$|2\sqrt{2\pi}\sqrt{a} + 1 - (2b+1)\pi| < \delta$$

The theorem follows because for distinct b, (g_n) being strictly increasing implies that the a's are distinct. $\square$

The results of the main problem now follow.

Lemma 4 $\limsup_{n\to\infty} xf(x) = \frac{\cos(x^2))}{2} - \frac{\cos((x+1)^2)}{2} + s(x) = 1$

Proof: From Theorem 1 and the continuity of $\cos(x)$, for all $\epsilon > 0$, there exist infinite $n \in \mathbb{N}$ such that $\cos(x^2) = \cos(\sqrt{2\pi n}^2) = 1$ and $|\cos\left((x+1)^2\right) + 1| = |\cos\left((\sqrt{2\pi n} + 1)^2\right) + 1| < \epsilon$. As previously established, $\limsup_{x\to\infty} s(x) = 0$. $\square$

Corollary 5 $\liminf_{n\to\infty} xf(x) = \frac{\cos(x^2))}{2} - \frac{\cos((x+1)^2)}{2} + s(x) = -1$

Proof: Add π to the a's in Lemma 4. $\square$

d

Does $\int_0^\infty \sin(t^2)dt$ converge?

Theorem 6 *$\int_0^\infty \sin(t^2)dt$ converges.*

Proof: *For finite n,*

$$\begin{aligned}
\int_0^n \sin(t^2)dt &= \int_0^1 \sin(t^2)dt + f(1) + f(2) \cdots + f(n-1) \\
&= \int_0^1 \sin(t^2)dt + \sum_{i=1}^{n-1} f(i) \\
&= \int_0^1 \sin(t^2)dt + \frac{1}{2}\sum_{i=1}^{n-1}\left[\frac{\cos(i^2)}{i} - \frac{\cos\left((i+1)^2\right)}{i}\right] + \frac{1}{2}\sum_{i=1}^{n-1}\frac{r(i)}{i}
\end{aligned}$$

Taking limits as n approaches infinity, $\sum_{i=1}^\infty \frac{r(i)}{i}$ converges due to a comparison with $\sum_{i=1}^\infty \frac{1}{i^2}$. To show convergence, we have to show that $\sum_{i=1}^\infty \frac{\cos(i^2)}{i} - \frac{\cos\left((i+1)^2\right)}{i}$ converges. Writing out the first few terms of the partial sum,

$$\begin{aligned}
\sum_{i=1}^{n-1} \frac{\cos(i^2)}{i} - \frac{\cos\left((i+1)^2\right)}{i} &= \frac{\cos(1)}{1} - \frac{\cos(4)}{1} + \frac{\cos(4)}{2} - \frac{\cos(9)}{2} + \frac{\cos(9)}{3} - \frac{\cos(16)}{3} \cdots \\
&= \frac{\cos(1)}{1} - \frac{\cos(4)}{1*2} - \frac{\cos(9)}{2*3} \cdots - \frac{\cos\left((n-1)^2\right)}{(n-2)(n-1)} - \frac{\cos(n^2)}{n-1} \\
&= \frac{\cos(1)}{1} - \frac{\cos(n^2)}{n-1} - \sum_{i=1}^{n-2} \frac{\cos\left((i+1)^2\right)}{i(i+1)}
\end{aligned}$$

Taking the limits as n goes to infinity, $\frac{cos(n^2)}{n-1}$ goes to zero. The sum on the right is absolutely convergent by comparing it with $\sum_{i=1}^{\infty} \frac{1}{i^2}$, so the sum on the right is convergent. Thus $\sum_{i=1}^{\infty} \frac{\cos(i^2)}{i} - \frac{\cos\left((i+1)^2\right)}{i}$, and by extension $\int_0^{\infty} \sin(t^2)dt$, converge. □

Problem 6.R.14

let $f(x) = \int_x^{x+1} \sin(e^t)dt$.

a

Show that $e^x|f(x)| < 2$.

Proof: Making the substitution $u = e^t$,

$$f(x) = \int_{e^x}^{e^{x+1}} \frac{\sin(u)}{u} du$$

Integrating by parts with $a = u^{-1}$ and $db = \sin(u)$,

$$\begin{aligned} f(x) &= -u^{-1}\cos(u)\Big]_{e^x}^{e^{x+1}} - \int_{e^x}^{e^{x+1}} u^{-2}\cos(u)du \\ &= \frac{\cos(e^x)}{e^x} - \frac{\cos(e^{x+1})}{e^{x+1}} - \int_{e^x}^{e^{x+1}} u^{-2}\cos(u)du \end{aligned}$$

implies

$$\begin{aligned} xf(x) &= \cos(e^x) - e^{-1}\cos(e^{x+1}) - e^x \int_{e^x}^{e^{x+1}} u^{-2}\cos(u)du \\ &\leq 1 + \frac{1}{e} + e^x \int_{e^x}^{e^{x+1}} u^{-2}du \\ &= 1 + \frac{1}{e} - e^x \left[\frac{1}{u}\right]_{e^x}^{e^{x+1}} \\ &= 1 + \frac{1}{e} + 1 - \frac{1}{e} = 2 \end{aligned}$$

Similarly,

$$xf(x) \geq -1 - \frac{1}{e} - e^x \int_{e^x}^{e^{x+1}} u^{-2}du = -2$$

□

b

Show that $e^x f(x) = \cos(e^x) - e^{-1}\cos(e^{x+1}) + r(x)$, where $|r(x)| < Ce^{-x}$, for some constant C.

Proof: From the form above, it's clear that $r(x) = -e^x \int_{e^x}^{e^{x+1}} u^{-2}\cos(u)du$. Integrating by parts with $a = u^{-2}$ and $db = \cos(u)$,

$$\begin{aligned} r(x) &= -e^x \left[u^{-2}\sin(u)\Big|_{e^x}^{e^{x+1}} + 2\int_{e^x}^{e^{x+1}} u^{-3}\sin(u)du \right] \\ &= \frac{\sin(e^x)}{e^x} - \frac{\sin(e^{x+1})}{e^{x+2}} - 2e^x \int_{e^x}^{e^{x+1}} u^{-3}\sin(u)du \\ &\leq \frac{1}{e^x} + \frac{1}{e^{x+2}} + 2e^x \int_{e^x}^{e^{x+1}} u^{-3}du \\ &= \frac{1}{e^x} + \frac{1}{e^{x+2}} - e^x \left[\frac{1}{e^{2x+2}} - \frac{1}{e^x} \right] = \frac{2}{e^x} \end{aligned}$$

Similarly,

$$r(x) \geq -\frac{1}{e^x} - \frac{1}{e^{x+2}} - 2e^x \int_{e^x}^{e^{x+1}} u^{-3}du = \frac{-2}{e^x}$$

□

Problem 6.R.15

Let f be real and continuously differentiable on $[a,b]$, with $f(a) = f(b) = 0$ and $\int_a^b f^2(x)dx = 1$. Prove that $\int_a^b xf(x)f'(x)dx = -\frac{1}{2}$ and $\int_a^b [f'(x)]^2dx \int_a^b x^2 f^2(x)dx > \frac{1}{4}$.

Proof: Integrating $\int_a^b f^2(x)dx$ by parts with $a = f^2(x)$ and $db = 1$,

$$1 = \int_a^b f^2(x)dx = xf^2(x)\Big|_a^b - 2\int_a^b xf(x)f'(x)dx = -2\int_a^b xf(x)f'(x)dx$$

Similarly, by the Cauchy-Schwartz inequality,

$$\frac{1}{2} = \left| \int_a^b xf(x)f'(x)dx \right| \leq \left[\int_a^b (f'(x))^2dx \right]^{\frac{1}{2}} \left[\int_a^b x^2f^2(x)dx \right]^{\frac{1}{2}}$$

Lemma 7 $\int_a^b (f'(x))^2dx > 0$

Proof: $f(a) = f(b) = 0$ implies that if f is a constant function, it must be the zero function. $\int_a^b f^2(x)dx \neq 0$ implies that f is not the zero function. Thus, f' is not the zero function. Since f' is continuous, f'^2 is continuous and nonzero, implying that $\int_a^b (f'(x))^2 dx > 0$. □

Lemma 8 $\int_a^b x^2 f^2(x)dx > 0$

Proof: f is continuous and nonzero implies that f^2 and $x^2 f^2$ are continuous and nonzero. □

The Cauchy-Schwartz inequality only holds with equality when at least one of the vectors has norm zero. Since $\int_a^b (f'(x))^2 dx$ and $\int_a^b x^2 f^2(x)dx$ are nonzero, the inequality is strict.

□

Problem 6.R.16

For $1 < s < \infty$, define

$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s}$$

a

Prove that

$$\zeta(s) = s \int_1^{\infty} \frac{[x]}{x^{s+1}} dx$$

where $[x]$ denotes the greatest integer $\leq x$.

Proof: Denote $f_N(s) = s \int_1^N \frac{[x]}{x^{s+1}} dx$ for $N \in \mathbb{N}$, $N > 1$. Splitting the integral and evaluating the greatest integer function,

$$\begin{aligned}
f_N(s) &= s \int_1^N \frac{[x]}{x^{s+1}} dx \\
&= s \left(\int_1^2 \frac{1}{x^{s+1}} dx + \int_2^3 \frac{2}{x^{s+1}} dx + \cdots + \int_{N-1}^N \frac{N-1}{x^{s+1}} dx \right) \\
&= s \sum_{i=1}^{N-1} i \int_i^{i+1} \frac{1}{x^{s+1}} dx = -\sum_{i=1}^{N-1} i (x)_i^{i+1} = \sum_{i=1}^{N-1} i \left(\frac{1}{i^s} - \frac{1}{(i+1)^s} \right) \\
&= 1 \left(\frac{1}{1^s} - \frac{1}{2^s} \right) + 2 \left(\frac{1}{2^s} - \frac{1}{3^s} \right) + 3 \left(\frac{1}{3^s} - \frac{1}{4^s} \right) + \cdots + (N-1) \left(\frac{1}{(N-1)^s} - \frac{1}{N^s} \right) \\
&= \frac{1}{1^s} + \frac{1}{2^s} + \frac{1}{3^s} + \cdots + \frac{1}{(N-1)^s} - \frac{N-1}{N^s} \\
&= \sum_{i=1}^{N-1} \frac{1}{i^s} - \frac{N-1}{N^s}
\end{aligned}$$

Let $\zeta_N(s) = \sum_{i=1}^{N} \frac{1}{i^s}$ be the nth partial sum of $\zeta(s)$. Taking the difference between $f_N(s)$ and $\zeta_N(s)$,

$$\begin{aligned} |f_N(s) - \zeta_N(s)| &= \left| \sum_{i=1}^{N-1} \frac{1}{i^s} - \sum_{i=1}^{N} \frac{1}{i^s} - \frac{N-1}{N^s} \right| \\ &= \frac{1}{N^{s-1}} \end{aligned}$$

Since $s > 1$, the difference goes to 0 as N approaches infinity.

$\square$

b

Prove that

$$\zeta(s) = \frac{s}{s-1} - s \int_1^\infty \frac{x - [x]}{x^{s+1}} dx$$

Proof: Taking the integral to N and splitting the integral,

$$\frac{s}{s-1} - s \int_1^N \frac{x - [x]}{x^{s+1}} dx = \frac{s}{s-1} - s \int_1^N \frac{1}{x^s} dx + f_N(s)$$

Since $f_N s \to \zeta(s)$ as n approaches infinity, we need to show that $\frac{s}{s-1} - s \int_1^N \frac{1}{x^s} dx \to 0$. Integrating,

$$s \int_1^N \frac{1}{x^s} dx = -\frac{s}{s-1} \left(\frac{1}{x^{s-1}} \right)_1^N = -\frac{s}{s-1} \left(\frac{1}{N^{s-1}} - 1 \right)$$

As n approaches infinity, this approaches $-\frac{s}{s-1}$, so $\frac{s}{s-1} - s \int_1^N \frac{1}{x^s} dx \to 0$. $\square$

c

Prove that the integral in Part b converges for $s > 0$.

Proof:

$$\int_1^N \frac{x - [x]}{x^{s+1}} dx \leq \int_1^N \frac{1}{x^{s+1}} dx = -\frac{1}{s} \left(\frac{1}{x^s} \right)_1^N = -\frac{1}{s} \left[\frac{1}{N^s} - 1 \right]$$

When $s > 0$, this converges to $\frac{1}{s}$ as n approaches infinity. $\square$

Problem 6.R.17

Suppose that α increases monotonically on $[a, b]$, g is continuous, and $g(x) = G'(x)$ for $a \le x \le b$. Prove that

$$\int_a^b \alpha(x)g(x)dx = G(b)\alpha(b) - G(a)\alpha(a) - \int_a^b G d\alpha$$

Lemma 9 *For all partitions $P = \{x_0, x_1 \dots x_n\}$, there exist $t_i \in (x_{i-1}, x_i)$ such that $g(t_i)\Delta x_i = G(x_i) - G(x_{i-1})$.*

Proof: *G is an antiderivative of a continuous function g, and thus differentiable. The statement follows by using the Mean Value Theorem.* $\square$

We will proceed along the lines that Rudin gives in his hint. By Theorem 3.41 in the book, let $\{a_n\}$ and $\{b_n\}$ be two sequences, and let

$$A_n = \sum_{k=0}^{n} a_k$$

be the partial sum sequence of $\{a_n\}$. Let $A_{-1} = 0$. Then if $0 \le p \le q$,

$$\sum_{n=p}^{q} a_n b_n = \sum_{n=p}^{q-1} A_n(b_n - b_{n+1}) + A_q b_q - A_{p-1}b_p$$

We will let the sequence $\{a_n\}$ equal

$$a_k = G(x_k) - G(x_{k-1})$$

for $k \ge 1$, and $a_0 = 0$. Thus $A_n = G(x_n) - G(x_0)$. By Lemma 9,

$$a_k = g(t_i)\Delta x_i$$

We will let $\{b_i\} = \alpha(x_i)$. Then utilizing the formula with $p = 1, q = n$,

$$\begin{aligned}
\sum_{i=1}^{n} a_i b_i = \sum_{i=1}^{n} \alpha(x_i)g(t_i)\Delta x_i &= \sum_{i=1}^{n-1}(G(x_i) - G(x_0))(\alpha_i - \alpha_{i+1}) + (G(x_n) - G(x_0))\alpha_n - A_0 \\
&= -\sum_{i=1}^{n-1} G(x_i)\Delta\alpha_{i+1} - G(x_0)\sum_{i=1}^{n-1}(\alpha_i - \alpha_{i+1}) + (G(x_n) - G(x_0))\alpha_n \\
&= -\sum_{i=2}^{n-1} G(x_{i-1})\Delta\alpha_i - G(x_0)(\alpha_1 - \alpha_n) + (G(x_n) - G(x_0))\alpha_n \\
&= -\sum_{i=1}^{n-1} G(x_{i-1})\Delta\alpha_i + G(x_0)(\alpha_1 - \alpha_0) - G(x_0)\alpha_1 + G(x_n)\alpha_n \\
&= -\sum_{i=1}^{n} G(x_{i-1})\Delta\alpha_i + G(x_n)\alpha_n - G(x_0)\alpha_0
\end{aligned}$$

The second line occurs from distributing the first sum, and realizing that $A_0 = 0$. The third line comes from reindexing the first sum and rewriting the second sum. The fourth line comes from cancelling out the $G(x_0)\alpha_n$ terms, and adding and subtracting a $G(x_0)(\alpha_1 - \alpha_n)$ term. Thus substituting a, b for x_0, x_n, we get

$$\sum_{i=1}^{n} \alpha(x_i)g(t_i)\Delta x_i = G(b)\alpha(b) - G(a)\alpha(a) - \sum_{i=1}^{n} G(x_{i-1})\Delta\alpha_i$$

Note that if we can show that

$$\sum_{i=1}^{n} \alpha(x_i)g(t_i)\Delta x_i \approx \sum_{i=1}^{n} \alpha(x_i)g(x_i)\Delta x_i$$

and

$$\sum_{i=1}^{n} G(x_{i-1})\Delta\alpha_i \approx \sum_{i=1}^{n} G(x_i)\Delta\alpha_i$$

then

$$\begin{aligned} &\sum_{i=1}^{n} \alpha(x_i)g(x_i)\Delta x_i = G(b)\alpha(b) - G(a)\alpha(a) - \sum_{i=1}^{n} G(x_i)\Delta\alpha_i \\ \implies &\int_a^b \alpha(x)g(x)dx = G(b)\alpha(b) - G(a)\alpha(a) - \int_a^b Gd\alpha \end{aligned}$$

as the mesh approaches zero, as desired.

For the first equality, fix $\epsilon > 0$ and define $M = \sup_{x\in[a,b]} |\alpha(x)|$. Because g is uniformly continuous, there exists $\delta > 0$ such that $|x-y| < \delta \implies |g(x)-g(y)| < \frac{\epsilon}{M(b-a)}$. Taking the mesh to be finer than δ, we get that

$$|g(x_i) - g(t_i)| < \frac{\epsilon}{M(b-a)}$$

for all $i = 0, 1 \ldots n$. Then

$$\begin{aligned} &|\sum_{i=1}^{n} \alpha(x_i)g(t_i)\Delta x_i - \sum_{i=1}^{n} \alpha(x_i)g(x_i)\Delta x_i| \\ \leq &\sum_{i=1}^{n} |\alpha(x_i)||g(t_i) - g(x_i)|\Delta x_i \\ \leq &M\frac{\epsilon}{M(b-a)}\sum_{i=1}^{n} \Delta x_i \\ = &\epsilon \end{aligned}$$

Thus as the mesh goes to zero,

$$\sum_{i=1}^{n} \alpha(x_i)g(t_i)\Delta x_i \to \sum_{i=1}^{n} \alpha(x_i)g(x_i)\Delta x_i \to \int_a^b \alpha(x)g(x)dx$$

as desired. For the second equation, by the Fundamental Theorem of Calculus, G is differentiable and continuous where g is continuous. Fixing $\epsilon > 0$, there exists $\delta > 0$ such that

$$G(x_{i-1}) - G(x_i)| < \frac{\epsilon}{\alpha(b) - \alpha(a)}$$

Then

$$\begin{aligned}
&|\sum_{i=1}^{n} G(x_{i-1})\Delta\alpha_i - \sum_{i=1}^{n} G(x_i)\Delta\alpha_i| \\
\leq &\sum_{i=1}^{n} |G(x_i) - G(x_{i-1})||\Delta\alpha_i| \\
\leq &\frac{\epsilon}{\alpha(b) - \alpha(a)} \sum_{i=1}^{n} \Delta\alpha_i \\
= &\frac{\epsilon}{\alpha(b) - \alpha(a)} (\alpha(b) - \alpha(a)) = \epsilon
\end{aligned}$$

because α is monotonically increasing, so $\Delta\alpha_i$ is always positive. Thus

$$\sum_{i=1}^{n} G(x_{i-1})\Delta\alpha_i \to \sum_{i=1}^{n} G(x_i)\Delta\alpha_i \to \int_a^b G d\alpha$$

as the mesh goes to zero, as desired.

Problem 6.6:1

On $[a, b]$, let α be a strictly increasing function and f a continuous function, and for $x \in [a, b]$ define $F(x) = \int_a^x f(t)d\alpha(t)$. Show that for all $x \in [a, b]$, $\frac{dF(x)}{d\alpha(x)} = f(x)$, where the left-hand side is defined as $\lim_{t \to x} \frac{F(x)-F(t)}{\alpha(x)-\alpha(t)}$, and the equality includes the assertion that the limit exists.

Proof: First, we note that because $f \in \mathfrak{R}(\alpha)$ on $[a, b]$

$$F(x) - F(t) = \int_a^x f(s)d\alpha(s) - \int_a^t f(s)d\alpha(s) = \int_t^x f(x)d\alpha(s)$$

For all partitions P,

$$\begin{aligned}
\int_t^x f(s)d\alpha(s) &\leq \sum_{x_i \in P} M_i \Delta\alpha_i \\
&\leq \left(\sup_{s\in[x,t]} f(s) \right) \sum_{x_i\in P} \Delta\alpha_i \\
&= \left(\sup_{s\in[x,t]} f(s) \right) (\alpha(x) - \alpha(t))
\end{aligned}$$

Since $\alpha(x)$ is strictly increasing, $\alpha(x) - \alpha(t) > 0$ when $x \neq t$, so

$$\frac{F(x) - F(t)}{\alpha(x) - \alpha(t)} \leq \sup_{s\in[x,t]} f(s)$$

Taking the limit as t approaches x on both sides gives

$$\lim_{t\to x} \frac{F(x) - F(t)}{\alpha(x) - \alpha(t)} \leq \lim_{t\to x} \sup_{s\in[x,t]} f(s)$$

Lemma 10

$$\lim_{t\to x} \sup_{s\in[x,t]} f(s) = f(x)$$

Proof: *Let x_n be an arbitrary sequence such that $\forall n \in \mathbb{N}, x_n > x$ and $\lim_{n\to\infty} x_n = x$. Since $[x, x_n]$ is a closed, bounded interval on $\mathbb{R}$ and f is continuous, there exists a sequence of points $p_n \in [x, x_n]$ such that $f(p_n) = \sup_{s\in[x,x_n]} f(s)$. $x_n \to x$ implies $p_n \to x$ by the Squeeze Theorem, and the continuity of f implies that $f(p_n) \to f(x)$.*

□

Thus

$$\lim_{t\to x} \frac{F(x) - F(t)}{\alpha(x) - \alpha(t)} \leq f(x)$$

The analogous result for the lower integral and the Squeeze Theorem complete the proof.

□

Problem 6.6:2

(a)

Show that if f is continuous, then

$$\int_{t=a}^{b} \left(\int_{s=a}^{t} f(s)ds \right) dt = \int_{t=a}^{b} (b-t)f(t)dt$$

Proof: Let $x \in [a,b]$. Define $P(x) = \int_{t=a}^{x} \left(\int_{s=a}^{t} f(s)ds \right) dt$ and $Q(x) = \int_{t=a}^{x} (x-t)f(t)dt$.

$f(t)$ being continuous on $[a,b]$ implies that it is Riemann-integrable. This implies that $f^*(t) = \int_{s=a}^{t} f(s)ds$ is continuous, and that $P(x) = \int_a^x f^*(t)dt$ is continuous and differentiable. Similarly, $(b-t)f(t)$ is continuous on $[a,b]$, so $Q(x)$ is continuous and differentiable.

By the Fundamental Theorem of Calculus,

$$P'(x) = \int_{s=a}^{x} f(s)ds$$

For $Q(x)$, since t and $tf(t)$ are Riemann-integrable,

$$Q(x) = x\int_{t=a}^{x} f(t)dt - \int_{t=a}^{x} tf(t)dt$$

x is trivially differentiable. Since t and $tf(t)$ are continuous,

$$Q'(x) = \int_{t=a}^{x} f(t)dt + xf(x) - xf(x) = \int_{t=a}^{x} f(t)dt$$

Thus, $P'(x) = Q'(x)$. Integrating both sides from a to c, then setting $c = b$, produces the desired result.

□

(c)

Show that the result of Part (a) continues to hold if f is merely assumed Riemann-integrable, but not necessarily continuous.

Proof: $P(x)$ has the same derivative as in Part (a), as the derivation only assumed that $P(x)$ is Riemann-integrable. Similarly, for $x_0 \in [a,b]$ where $f(x_0)$ is continuous, the above derivations hold for $Q(x)$.

Let x_0 be a point where $f(x_0)$ is discontinuous. First, we will prove two lemmas.

Lemma 11 *If $f(x)$ is bounded, then $(x-x_0)f(x)$ is continuous at x_0.*

Proof: *Let $M = \sup|f(x)|$. Then $(x-x_0)f(x) \le |(x-x_0)f(x)| \le |(x-x_0)|M$, which can be made arbitrarily small.*

□

Lemma 12 *If $f(x)$ is continuous, then $(x-x_0)f(x)$ is differentiable at x_0 with derivative $f(x_0)$.*

Proof: *By the definition of differentiability,*

$$\lim_{x \to x_0} \frac{(x-x_0)f(x) - (x_0-x_0)f(x_0)}{x-x_0} = \lim_{x \to x_0} f(x) = f(x_0)$$

by continuity.

□

We can rewrite $Q(x)$ as

$$Q(x) = \int_{t=a}^{x} ((x-x_0)+(x_0-t))f(t)dt = (x-x_0)\int_{t=a}^{x} f(t)dt + \int_{t=a}^{x} (x_0-t)f(t)dt$$

because the sub-functions are trivially Riemann-integrable. $\int_{t=a}^{x} f(t)$ is a continuous function, so by Lemma 12 $(x-x_0)\int_{t=a}^{x} f(t)dt$ is differentiable at $x = x_0$ with derivative $\int_{t=a}^{x_0} f(t)dt$. Similarly, $f(t)$ is bounded because it is Riemann-integrable, so by Lemma 11 $(x_0 - t)f(t)$ is continuous at $t = x_0$. Therefore $\int_{t=a}^{x}(x_0-t)f(t)dt$ is differentiable at $x = x_0$, with derivative 0.

Therefore, $Q(x)$ is differentiable at $x = x_0$, and $Q'(x_0) = \int_{t=a}^{x} f(t)dt$. The proof then follows using the same logic as in Part (a).

□

Problem 6.6:4

Let f be a function on $[a, b]$, and α, β monotonically increasing nonnegative functions on $[a, b]$ such that $f \in \mathfrak{R}(\alpha) \cap \mathfrak{R}(\beta)$, $\alpha \in \mathfrak{R}(\beta)$, and $\beta \in \mathfrak{R}(\alpha)$. Prove that

$$\int f d(\alpha\beta) = \int f\alpha d(\beta) + \int f\beta d(\alpha)$$

Proof: First note that $f\alpha \in \mathfrak{R}(\beta)$ and $f\beta \in \mathfrak{R}(\alpha)$. Also note that $\alpha\beta$ is monotonically increasing, so $\alpha\beta$ is a valid integrator.

Theorem 13 *Under the assumptions of Problem 6.6.4, $f \in \mathfrak{R}(\alpha\beta)$.*

Proof: *First note that by expanding the terms,*

$$\alpha_i\beta_i - \alpha_{i-1}\beta_{i-1} = (\alpha_i - \alpha_{i-1})(\beta_i - \beta_{i-1}) + \alpha_{i-1}(\beta_i - \beta_{i-1}) + \beta_{i-1}(\alpha_i - \alpha_{i-1})$$

Writing out the difference between the upper and lower Riemann sums,

$$\sum_{i=1}^{n}(M_i - m_i)(\alpha_i\beta_i - \alpha_{i-1}\beta_{i-1})$$
$$= \sum_{i=1}^{n}(M_i - m_i)\Delta\alpha_i\Delta\beta_i + \sum_{i=1}^{n}(M_i - m_i)\alpha_{i-1}\Delta\beta_i + \sum_{i=1}^{n}(M_i - m_i)\beta_{i-1}\Delta\alpha_i$$
$$\leq \alpha(b)\sum_{i=1}^{n}(M_i - m_i)\Delta\beta_i + \alpha(b)\sum_{i=1}^{n}(M_i - m_i)\Delta\beta_i + \beta(b)\sum_{i=1}^{n}(M_i - m_i)\Delta\alpha_i$$

The third line follows because all terms are positive, and α and β are monotonically increasing. Because $f \in \mathfrak{R}(\alpha) \cap \mathfrak{R}(\beta)$, there exist partitions that make the third line arbitrarily small.

□

Now we prove the main result. For arbitrary $\epsilon > 0$, let P_1, P_2, and P_3 be partitions of $[a, b]$ such that

1. $U(P_1, f, \alpha\beta) - L(P_1, f, \alpha\beta) < \epsilon$
2. $U(P_2, f\alpha, \beta) - L(P_2, f\alpha, \beta) < \epsilon$
3. $U(P_3, f\beta, \alpha) - L(P_3, f\beta, \alpha) < \epsilon$

Let P be their common partition. Let $x_0 < x_1 ... < x_n$ denote the points of P. For all i in $(1, 2...n)$, let $t_i \in (x_{i-1}, x_i)$ be arbitrary, fixed points, and let $P^* = (x_0, t_1, x_1 ... x_{i-1}, t_i, x_i ... t_n, x_n)$. Trivially, P^* partitions $[a, b]$ and is a refinement of P.

Consider $\int f d(\alpha\beta)$ and its associated Riemann-Stieltjes sum over P^*. Since P^* is a refinement of P_1, for arbitrary points $u_i \in [x_{i-1}, t_i]$ and $v_i \in [t_i, x_i]$,

$$|\sum_{i=1}^{n}\left[f(u_i)(\alpha_{t_i}\beta_{t_i} - \alpha_{x_{i-1}}\beta_{x_{i-1}}) + f(v_i)(\alpha_{x_i}\beta_{x_i} - \alpha_{t_i}\beta_{t_i})\right] - \int f d(\alpha\beta)| < \epsilon$$

Letting $u_i = x_{i-1}$ and $v_i = x_i$ for all i,

$$|\sum_{i=1}^{n}\left[f_{x_{i-1}}(\alpha_{t_i}\beta_{t_i} - \alpha_{x_{i-1}}\beta_{x_{i-1}}) + f_{x_i}(\alpha_{x_i}\beta_{x_i} - \alpha_{t_i}\beta_{t_i})\right] - \int f d(\alpha\beta)| < \epsilon$$

Now consider $\int f\alpha d(\beta)$ and its associated Riemann-Stieltjes sum over P. Letting $u_i = x_i$ for all i,

$$|\sum_{i=1}^{n}\left[f_{x_i}\alpha_{x_i}(\beta_{x_i} - \beta_{x_{i-1}})\right] - \int f\alpha d(\beta)| < \epsilon$$

Similarly, considering $\int f\beta d(\alpha)$ over P and letting $u_i = x_{i-1}$ for all i,

$$|\sum_{i=1}^{n}\left[f_{x_{i-1}}\beta_{x_{i-1}}(\alpha_{x_i}-\alpha_{x_{i-1}})\right]-\int f\beta d(\alpha)|<\epsilon$$

Adding the inequalities and using the Triangle Inequality gives

$$\Bigg|\int fd(\alpha\beta)-\int f\alpha d(\beta)-\int f\beta d(\alpha)$$
$$+\sum_{i=1}^{n}\Big[-\left[f_{x_{i-1}}(\alpha_{t_i}\beta_{t_i}-\alpha_{x_{i-1}}\beta_{x_{i-1}})+f_{x_i}(\alpha_{x_i}\beta_{x_i}-\alpha_{t_i}\beta_{t_i})\right]$$
$$+f_{x_i}\alpha_{x_i}(\beta_{x_i}-\beta_{x_{i-1}})+f_{x_{i-1}}\beta_{x_{i-1}}(\alpha_{x_i}-\alpha_{x_{i-1}})\Big]\Bigg|<3\epsilon$$

Simplifying,

$$\left|\int fd(\alpha\beta)-\int f\alpha d(\beta)-\int f\beta d(\alpha)+\sum_{i=1}^{n}\Big[(f_{x_i}-f_{x_{i-1}})(\alpha_{t_i}\beta_{t_i}-\alpha_{x_i}\beta_{x_{i-1}})\Big]\right|<3\epsilon$$

To analyze the sum on the right, note that

$$\begin{aligned}&\left|\sum_{i=1}^{n}\Big[(f_{x_i}-f_{x_{i-1}})(\alpha_{t_i}\beta_{t_i}-\alpha_{x_i}\beta_{x_{i-1}})\right|\\ \leq&\sum_{i=1}^{n}\left|f_{x_i}-f_{x_{i-1}}\right|\left|\alpha_{t_i}\beta_{t_i}-\alpha_{x_i}\beta_{x_{i-1}}\right|\\ \leq&\sum_{i=1}^{n}\left(\sup_{x\in[x_{i-1},x_i]}f(x)-\inf_{x\in[x_{i-1},x_i]}f(x)\right)\left(\alpha_{x_i}\beta_{x_i}-\alpha_{x_{i-1}}\beta_{x_{i-1}}\right)\\ <&\epsilon\end{aligned}$$

The second inequality comes from noticing that t_i is in (x_{i-1},x_i), and that α and β are weakly increasing. The third inequality comes from P being a refinement of P_1. Thus

$$\left|\int fd(\alpha\beta)-\int f\alpha d(\beta)-\int f\beta d(\alpha)\right|<4\epsilon$$

Which can be made arbitrarily close to 0.

□