Functions of Bounded Variation

Our main theorem concerning the existence of Riemann–Stietjes integrals assures us that the integral $\int_a^b f(x)\ d\alpha(x)$ exists when f is continuous and α is monotonic. Our linearity theorem then guarantees that the integral $\int_a^b f(x)\ d\alpha(x)$ exists when f is continuous and α is the difference of two monotonic functions. In these notes, we prove that α is the difference of two monotonic functions if and only if it is of bounded variation, where

Definition 1

(a) The function $\alpha : [a,b] \to \mathbb{R}$ is said to be of bounded variation on $[a,b]$ if and only if there is a constant $M > 0$ such that

$$\sum_{i=1}^{n} \big|\alpha(x_i) - \alpha(x_{i-1})\big| \le M$$

for all partitions $\mathbb{P} = \{x_0, x_1, \cdots, x_n\}$ of $[a,b]$.

(b) If $\alpha : [a,b] \to \mathbb{R}$ is of bounded variation on $[a,b]$, then the total variation of α on $[a,b]$ is defined to be

$$V_\alpha(a,b) = \sup\Big\{ \sum_{i=1}^{n} \big|\alpha(x_i) - \alpha(x_{i-1})\big| \ \Big|\ \mathbb{P} = \{x_0, x_1, \cdots, x_n\} \text{ is a partition of } [a,b] \Big\}$$

Example 2 If $\alpha : [a,b] \to \mathbb{R}$ is monotonically increasing, then, for any partition $\mathbb{P} = \{x_0, x_1, \cdots, x_n\}$ of $[a,b]$

$$\sum_{i=1}^{n} \big|\alpha(x_i) - \alpha(x_{i-1})\big| = \sum_{i=1}^{n} \big\{\alpha(x_i) - \alpha(x_{i-1})\big\} = \alpha(x_n) - \alpha(x_0) = \alpha(b) - \alpha(a)$$

Thus α is of bounded variation and $V_f(a,b) = \alpha(b) - \alpha(a)$.

Example 3 If $\alpha : [a,b] \to \mathbb{R}$ is continuous on $[a,b]$ and differentiable on (a,b) with $\sup_{a<x<b} |\alpha'(x)| \le M$, then, for any partition $\mathbb{P} = \{x_0, x_1, \cdots, x_n\}$ of $[a,b]$, we have, by the Mean Value Theorem,

$$\sum_{i=1}^{n} \big|\alpha(x_i) - \alpha(x_{i-1})\big| = \sum_{i=1}^{n} \big|\alpha'(t_i)[x_i - x_{i-1}]\big| \le \sum_{i=1}^{n} M[x_i - x_{i-1}] = M(b-a)$$

Thus α is of bounded variation and $V_f(a,b) \le M(b-a)$.

Example 4 Define the function $\alpha : [0,1] \to \mathbb{R}$ by

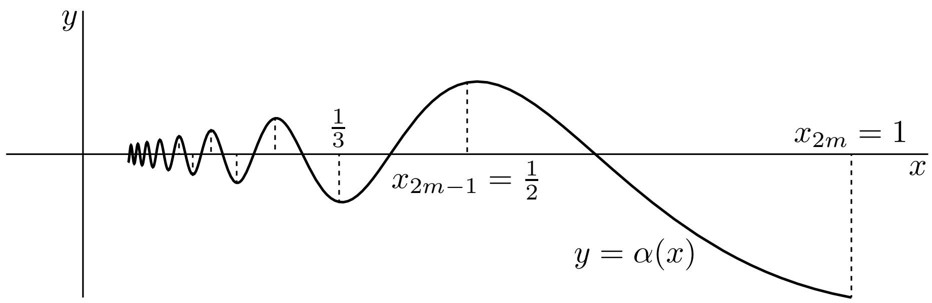
$$\alpha(x) = \begin{cases} 0 & \text{if } x = 0 \\ x\cos\frac{\pi}{x} & \text{if } x \neq 0 \end{cases}$$

This function is continuous, but is not of bounded variation because it wobbles too much near $x = 0$. To see this, consider, for each $m \in \mathbb{N}$, the partition

$$\mathbb{P}_m = \big\{x_0 = 0\,,\ x_1 = \tfrac{1}{2m}\,,\ x_2 = \tfrac{1}{2m-1}\,,\ x_3 = \tfrac{1}{2m-2}, \cdots, x_{2m-2} = \tfrac{1}{3}\,,\ x_{2m-1} = \tfrac{1}{2}\,,\ x_{2m} = 1\big\}$$

The values of α at the points of this partition are

$$\alpha(\mathbb{P}_m) = \{0, \quad \tfrac{1}{2m}, \quad -\tfrac{1}{2m-1}, \quad \tfrac{1}{2m-2}, \cdots, \quad -\tfrac{1}{3}, \quad \tfrac{1}{2}, \quad -1\}$$



For this partition,

$$\begin{aligned}
&\sum_{i=1}^{2m} \big|\alpha(x_i) - \alpha(x_{i-1})\big| \\
&\qquad = \big|\tfrac{1}{2m} - 0\big| + \big|-\tfrac{1}{2m-1} - \tfrac{1}{2m}\big| + \big|\tfrac{1}{(2m-2)} + \tfrac{1}{2m-1}\big| + \cdots + \big|-\tfrac{1}{3} - \tfrac{1}{4}\big| + \big|\tfrac{1}{2} + \tfrac{1}{3}\big| + \big|-1 - \tfrac{1}{2}\big| \\
&\qquad = \tfrac{1}{2m} + 0 + \tfrac{1}{2m-1} + \tfrac{1}{2m} + \tfrac{1}{(2m-2)} + \tfrac{1}{2m-1} + \cdots + \tfrac{1}{3} + \tfrac{1}{4} + \tfrac{1}{2} + \tfrac{1}{3} + 1 + \tfrac{1}{2} \\
&\qquad = 2\big(\tfrac{1}{2m} + \tfrac{1}{2m-1} + \cdots + \tfrac{1}{3} + \tfrac{1}{2}\big) + 1
\end{aligned}$$

The harmonic series $\sum\limits_{k=2}^{\infty} \frac{1}{k}$ diverges. So given any M, there is an $m \in \mathbb{N}$ for which the partition $\mathbb{P}_m$ obeys

$$\sum_{i=1}^{n} \big|\alpha(x_i) - \alpha(x_{i-1})\big| > M$$

Theorem 5

(a) If $\alpha, \beta : [a,b] \to \mathbb{R}$ are of bounded variation and $c, d \in \mathbb{R}$, then $c\alpha + d\beta$ is of bounded variation and

$$V_{c\alpha+d\beta}(a,b) \le |c| V_\alpha(a,b) + |d| V_\beta(a,b)$$

(b) If $\alpha : [a,b] \to \mathbb{R}$ is of bounded variation on $[a,b]$ and $[c,d] \subset [a,b]$, then α is of bounded variation on $[c,d]$ and

$$V_\alpha(c,d) \le V_\alpha(a,b)$$

(c) If $\alpha : [a,b] \to \mathbb{R}$ is of bounded variation and $c \in (a,b)$, then

$$V_\alpha(a,b) = V_\alpha(a,c) + V_\alpha(c,b)$$

(d) If $\alpha : [a,b] \to \mathbb{R}$ is of bounded variation then the functions $V(x) = V_\alpha(a,x)$ and $V(x) - \alpha(x)$ are both increasing on $[a,b]$.

(e) The function $\alpha : [a,b] \to \mathbb{R}$ is of bounded variation if and only if it is the difference of two increasing functions.

Proof: We shall use the shorthand notation

$$\sum^{\mathbb{P}} \big|\Delta_i\alpha\big| \quad \text{for} \quad \sum_{i=1}^{n} \big|\alpha(x_i) - \alpha(x_{i-1})\big|$$

where the partition $\mathbb{P} = \{x_0, x_1, \cdots, x_n\}$.

(a) follows from the observation that, for any $\mathbb{P}$ partition of $[a,b]$,

$$\sum^{\mathbb{P}} \big|\Delta_i(c\alpha + d\beta)\big| \le |c| \sum^{\mathbb{P}} \big|\Delta_i\alpha\big| + |d| \sum^{\mathbb{P}} \big|\Delta_i\beta\big| \le |c| V_\alpha(a,b) + |d| V_\beta(a,b)$$

(b) follows from the observation that, for any partition $\mathbb{P}$ of $[c,d]$,

$$\sum^{\mathbb{P}} \big|\Delta_i\alpha\big| \le \sum^{\mathbb{P}\cup\{a,b\}} \big|\Delta_i\alpha\big| \le V_\alpha(a,b)$$

(c) If $\mathbb{P} = \big\{x_0, x_1, \cdots, x_n\big\}$ is any partition of $[a,b]$ and $x_{i-1} \le c \le x_i$, then

$$\big|\alpha(x_i) - \alpha(x_{i-1})\big| \le \big|\alpha(x_i) - \alpha(c)\big| + \big|\alpha(c) - \alpha(x_{i-1})\big|$$

so that

$$\sum^{\mathbb{P}} \big|\Delta_i\alpha\big| \le \sum^{\mathbb{P}\cup\{c\}} \big|\Delta_i\alpha\big| = \sum^{(\mathbb{P}\cup\{c\})\cap[a,c]} \big|\Delta_i\alpha\big| + \sum^{(\mathbb{P}\cup\{c\})\cap[c,b]} \big|\Delta_i\alpha\big| \le V_\alpha(a,c) + V_\alpha(c,b)$$

which implies that $V_\alpha(a,b) \le V_\alpha(a,c) + V_\alpha(c,b)$. To prove the other inequality, we let $\varepsilon > 0$ and select a partition $\mathbb{P}_1$ of $[a,c]$ for which $\sum^{\mathbb{P}_1} \big|\Delta_i\alpha\big| \ge V_\alpha(a,c) - \varepsilon$ and a partition $\mathbb{P}_2$ of $[c,b]$ for which $\sum^{\mathbb{P}_2} \big|\Delta_i\alpha\big| \ge V_\alpha(c,b) - \varepsilon$. Then

$$\sum^{\mathbb{P}_1\cup\mathbb{P}_2} \big|\Delta_i\alpha\big| = \sum^{\mathbb{P}_1} \big|\Delta_i\alpha\big| + \sum^{\mathbb{P}_2} \big|\Delta_i\alpha\big| \ge V_\alpha(a,c) + V_\alpha(c,b) - 2\varepsilon$$

This assures that $V_\alpha(a,b) \ge V_\alpha(a,c) + V_\alpha(c,b) - 2\varepsilon$ for all $\varepsilon > 0$ and hence that $V_\alpha(a,b) \ge V_\alpha(a,c) + V_\alpha(c,b)$.

(d) *Proof that $V(x)$ is increasing:* Let $a \le x_1 \le x_2 \le b$. Then, by part (c),

$$V(x_2) - V(x_1) = V_\alpha(a,x_2) - V_\alpha(a,x_1) = V_\alpha(x_1,x_2) \ge 0$$

(d) *Proof that $V(x) - \alpha(x)$ is increasing:* Let $a \le x_1 \le x_2 \le b$. By part (c),

$$\begin{aligned}
\{V(x_2) - \alpha(x_2)\} - \{V(x_1) - \alpha(x_1)\} &= V_\alpha(x_1,x_2) - \{\alpha(x_2) - \alpha(x_1)\} \\
&\ge V_\alpha(x_1,x_2) - \big|\alpha(x_2) - \alpha(x_1)\big| \\
&= V_\alpha(x_1,x_2) - \sum^{\{x_1,x_2\}} \big|\Delta_i\alpha\big| \\
&\ge 0
\end{aligned}$$

(e) If α is of bounded variation then $\alpha(x) = V_\alpha(a,x) - \big[V_\alpha(a,x) - \alpha(x)\big]$ expresses α as the difference of two increasing functions. On the other hand if α is the difference $\beta - \gamma$ of two increasing functions, then β and γ are of bounded variation by Example 2 and α is of bounded variation by part (a). ■

Example 6 We know that if f is continuous and α is of bounded variation on $[a,b]$, then $f \in \mathcal{R}(\alpha)$ on $[a,b]$. If f is of bounded variation and α is continuous on $[a,b]$, then we have $f \in \mathcal{R}(\alpha)$ on $[a,b]$ with

$$\int_a^b f\,d\alpha = f(b)\alpha(b) - f(a)\alpha(a) - \int_a^b \alpha\,df$$

by our integration by parts theorem. It is possible to have $f \in \mathcal{R}(\alpha)$ on $[a,b]$ even if neither f nor α are of bounded variation on $[a,b]$. For example, we have seen, in Example 4, that

$$\alpha(x) = \begin{cases} 0 & \text{if } x = 0 \\ x\cos\frac{\pi}{x} & \text{if } x \ne 0 \end{cases}$$

is continuous but not of bounded variation on $[0,1]$, because of excessive oscillation near $x=0$. So $f(x)=\alpha(1-x)$ (still with the α of Example 4) is continuous but not of bounded variation on $[0,1]$, because of excessive oscillation near $x=1$. But $f\in\mathcal{R}(\alpha)$ on $[0,\frac{1}{2}]$, by integration by parts, because f is of bounded variation on $[0,\frac{1}{2}]$. And $f\in\mathcal{R}(\alpha)$ on $[\frac{1}{2},1]$, because α is of bounded variation on $[\frac{1}{2},1]$. So $f\in\mathcal{R}(\alpha)$ on $[0,1]$, by our linearity theorem.