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Integrability and the Integral of Partial Functions from $\mathbb{R}$ into $\mathbb{R}$[1]

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Summary. In this paper, we showed the linearity of the indefinite integral $\int_a^b f dx$, the form of which was introduced in [11]. In addition, we proved some theorems about the integral calculus on the subinterval of $[a, b]$. As a result, we described the fundamental theorem of calculus, that we developed in [11], by a more general expression.

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The articles [23], [25], [26], [2], [22], [4], [14], [1], [24], [5], [27], [7], [6], [21], [9], [3], [17], [16], [15], [18], [20], [8], [10], [13], [19], [12], and [11] provide the notation and terminology for this paper.

1. Preliminaries

We use the following convention: a, b, c, d, e, x are real numbers, A is a closed-interval subset of $\mathbb{R}$, and f, g are partial functions from $\mathbb{R}$ to $\mathbb{R}$.

We now state several propositions:

(1) If $a \leq b$ and $c \leq d$ and $a + c = b + d$, then $a = b$ and $c = d$.

(2) If $a \leq b$, then $]x - a, x + a[\subseteq]x - b, x + b[$.

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(3) For every binary relation R and for all sets A, B, C such that $A \subseteq B$ and $A \subseteq C$ holds $R \restriction B \restriction A = R \restriction C \restriction A$.

(4) For all sets A, B, C such that $A \subseteq B$ and $A \subseteq C$ holds $\chi_{B,B} \restriction A = \chi_{C,C} \restriction A$.

(5) If $a \leq b$, then $\mathrm{vol}([{'}a, b{'}]) = b - a$.

(6) $\mathrm{vol}([{'}\min(a, b), \max(a, b){'}]) = |b - a|$.

2. Integrability and the Integral of Partial Functions

The following propositions are true:

(7) If $A \subseteq \mathrm{dom}\, f$ and f is integrable on A and f is bounded on A, then $|f|$ is integrable on A and $|\int\limits_{A} f(x)dx| \leq \int\limits_{A} |f|(x)dx$.

(8) If $a \leq b$ and $[{'}a, b{'}] \subseteq \mathrm{dom}\, f$ and f is integrable on $[{'}a, b{'}]$ and f is bounded on $[{'}a, b{'}]$, then $|\int\limits_{a}^{b} f(x)dx| \leq \int\limits_{a}^{b} |f|(x)dx$.

(9) Let r be a real number. Suppose $A \subseteq \mathrm{dom}\, f$ and f is integrable on A and f is bounded on A. Then $r\, f$ is integrable on A and $\int\limits_{A} (r\, f)(x)dx = r \cdot \int\limits_{A} f(x)dx$.

(10) If $a \leq b$ and $[{'}a, b{'}] \subseteq \mathrm{dom}\, f$ and f is integrable on $[{'}a, b{'}]$ and f is bounded on $[{'}a, b{'}]$, then $\int\limits_{a}^{b} (c\, f)(x)dx = c \cdot \int\limits_{a}^{b} f(x)dx$.

(11) Suppose $A \subseteq \mathrm{dom}\, f$ and $A \subseteq \mathrm{dom}\, g$ and f is integrable on A and f is bounded on A and g is integrable on A and g is bounded on A. Then $f + g$ is integrable on A and $f - g$ is integrable on A and $\int\limits_{A} (f + g)(x)dx = \int\limits_{A} f(x)dx + \int\limits_{A} g(x)dx$ and $\int\limits_{A} (f - g)(x)dx = \int\limits_{A} f(x)dx - \int\limits_{A} g(x)dx$.

(12) Suppose that $a \leq b$ and $[{'}a, b{'}] \subseteq \mathrm{dom}\, f$ and $[{'}a, b{'}] \subseteq \mathrm{dom}\, g$ and f is integrable on $[{'}a, b{'}]$ and g is integrable on $[{'}a, b{'}]$ and f is bounded on $[{'}a, b{'}]$ and g is bounded on $[{'}a, b{'}]$. Then $\int\limits_{a}^{b} (f + g)(x)dx = \int\limits_{a}^{b} f(x)dx + \int\limits_{a}^{b} g(x)dx$

and $\int\limits_a^b (f-g)(x)dx = \int\limits_a^b f(x)dx - \int\limits_a^b g(x)dx$.

(13) If f is bounded on A and g is bounded on A, then $f\,g$ is bounded on A.

(14) Suppose $A \subseteq \operatorname{dom} f$ and $A \subseteq \operatorname{dom} g$ and f is integrable on A and f is bounded on A and g is integrable on A and g is bounded on A. Then $f\,g$ is integrable on A.

(15) Let n be an element of $\mathbb{N}$. Suppose $n > 0$ and $\operatorname{vol}(A) > 0$. Then there exists an element D of $\operatorname{divs} A$ such that $\operatorname{len} D = n$ and for every element i of $\mathbb{N}$ such that $i \in \operatorname{dom} D$ holds $D(i) = \inf A + \frac{\operatorname{vol}(A)}{n} \cdot i$.

3. Integrability on a Subinterval

The following propositions are true:

(16) Suppose $\operatorname{vol}(A) > 0$. Then there exists a DivSequence T of A such that
 (i) δ_T is convergent,
 (ii) $\lim(\delta_T) = 0$, and
 (iii) for every element n of $\mathbb{N}$ there exists an element T_1 of $\operatorname{divs} A$ such that T_1 divides into equal $n+1$ and $T(n) = T_1$.

(17) Suppose $a \leq b$ and f is integrable on $['a, b']$ and f is bounded on $['a, b']$ and $['a, b'] \subseteq \operatorname{dom} f$ and $c \in ['a, b']$. Then f is integrable on $['a, c']$ and f is integrable on $['c, b']$ and $\int\limits_a^b f(x)dx = \int\limits_a^c f(x)dx + \int\limits_c^b f(x)dx$.

(18) Suppose $a \leq c$ and $c \leq d$ and $d \leq b$ and f is integrable on $['a, b']$ and f is bounded on $['a, b']$ and $['a, b'] \subseteq \operatorname{dom} f$. Then f is integrable on $['c, d']$ and f is bounded on $['c, d']$ and $['c, d'] \subseteq \operatorname{dom} f$.

(19) Suppose that $a \leq c$ and $c \leq d$ and $d \leq b$ and f is integrable on $['a, b']$ and g is integrable on $['a, b']$ and f is bounded on $['a, b']$ and g is bounded on $['a, b']$ and $['a, b'] \subseteq \operatorname{dom} f$ and $['a, b'] \subseteq \operatorname{dom} g$. Then $f + g$ is integrable on $['c, d']$ and $f + g$ is bounded on $['c, d']$.

(20) Suppose $a \leq b$ and f is integrable on $['a, b']$ and f is bounded on $['a, b']$ and $['a, b'] \subseteq \operatorname{dom} f$ and $c \in ['a, b']$ and $d \in ['a, b']$. Then $\int\limits_a^d f(x)dx = \int\limits_a^c f(x)dx + \int\limits_c^d f(x)dx$.

(21) Suppose $a \leq b$ and f is integrable on $['a, b']$ and f is bounded on $['a, b']$ and $['a, b'] \subseteq \operatorname{dom} f$ and $c \in ['a, b']$ and $d \in ['a, b']$. Then $['\min(c, d), \max(c, d)'] \subseteq \operatorname{dom}|f|$ and $|f|$ is integrable on

$['\min(c,d), \max(c,d)']$ and $|f|$ is bounded on $['\min(c,d), \max(c,d)']$ and $|\int\limits_{c}^{d} f(x)dx| \le \int\limits_{\min(c,d)}^{\max(c,d)} |f|(x)dx$.

(22) Suppose $a \le b$ and $c \le d$ and f is integrable on $['a, b']$ and f is bounded on $['a, b']$ and $['a, b'] \subseteq \operatorname{dom} f$ and $c \in ['a, b']$ and $d \in ['a, b']$. Then $['c, d'] \subseteq \operatorname{dom}|f|$ and $|f|$ is integrable on $['c, d']$ and $|f|$ is bounded on $['c, d']$ and $|\int\limits_{c}^{d} f(x)dx| \le \int\limits_{c}^{d} |f|(x)dx$ and $|\int\limits_{d}^{c} f(x)dx| \le \int\limits_{c}^{d} |f|(x)dx$.

(23) Suppose that $a \le b$ and $c \le d$ and f is integrable on $['a, b']$ and f is bounded on $['a, b']$ and $['a, b'] \subseteq \operatorname{dom} f$ and $c \in ['a, b']$ and $d \in ['a, b']$ and for every real number x such that $x \in ['c, d']$ holds $|f(x)| \le e$. Then $|\int\limits_{c}^{d} f(x)dx| \le e \cdot (d - c)$ and $|\int\limits_{d}^{c} f(x)dx| \le e \cdot (d - c)$.

(24) Suppose that $a \le b$ and f is integrable on $['a, b']$ and g is integrable on $['a, b']$ and f is bounded on $['a, b']$ and g is bounded on $['a, b']$ and $['a, b'] \subseteq \operatorname{dom} f$ and $['a, b'] \subseteq \operatorname{dom} g$ and $c \in ['a, b']$ and $d \in ['a, b']$. Then $\int\limits_{c}^{d} (f + g)(x)dx = \int\limits_{c}^{d} f(x)dx + \int\limits_{c}^{d} g(x)dx$ and $\int\limits_{c}^{d} (f - g)(x)dx = \int\limits_{c}^{d} f(x)dx - \int\limits_{c}^{d} g(x)dx$.

(25) Suppose $a \le b$ and f is integrable on $['a, b']$ and f is bounded on $['a, b']$ and $['a, b'] \subseteq \operatorname{dom} f$ and $c \in ['a, b']$ and $d \in ['a, b']$. Then $\int\limits_{c}^{d} (e\, f)(x)dx = e \cdot \int\limits_{c}^{d} f(x)dx$.

(26) Suppose $a \le b$ and $['a, b'] \subseteq \operatorname{dom} f$ and for every real number x such that $x \in ['a, b']$ holds $f(x) = e$. Then f is integrable on $['a, b']$ and f is bounded on $['a, b']$ and $\int\limits_{a}^{b} f(x)dx = e \cdot (b - a)$.

(27) Suppose $a \le b$ and for every real number x such that $x \in ['a, b']$ holds $f(x) = e$ and $['a, b'] \subseteq \operatorname{dom} f$ and $c \in ['a, b']$ and $d \in ['a, b']$. Then $\int\limits_{c}^{d} f(x)dx = e \cdot (d - c)$.

4. Fundamental Theorem of Calculus

Next we state two propositions:

(28) Let x_0 be a real number and F be a partial function from $\mathbb{R}$ to $\mathbb{R}$. Suppose that $a \leq b$ and f is integrable on $['a, b']$ and f is bounded on $['a, b']$ and $['a, b'] \subseteq \operatorname{dom} f$ and $]a, b[\subseteq \operatorname{dom} F$ and for every real number x such that $x \in]a, b[$ holds $F(x) = \int\limits_{a}^{x} f(x)dx$ and $x_0 \in]a, b[$ and f is continuous in x_0. Then F is differentiable in x_0 and $F'(x_0) = f(x_0)$.

(29) Let x_0 be a real number. Suppose $a \leq b$ and f is integrable on $['a, b']$ and f is bounded on $['a, b']$ and $['a, b'] \subseteq \operatorname{dom} f$ and $x_0 \in]a, b[$ and f is continuous in x_0. Then there exists a partial function F from $\mathbb{R}$ to $\mathbb{R}$ such that $]a, b[\subseteq \operatorname{dom} F$ and for every real number x such that $x \in]a, b[$ holds $F(x) = \int\limits_{a}^{x} f(x)dx$ and F is differentiable in x_0 and $F'(x_0) = f(x_0)$.

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