

Multivariate integration of functions depending explicitly on the minimum and the maximum of the variables

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Abstract

By using some basic calculus of multiple integration, we provide an alternative expression of the integral

$$\int_{[a,b]^n} f(\mathbf{x}, \min x_i, \max x_i) d\mathbf{x},$$

in which the minimum and the maximum are replaced with two single variables. We demonstrate the usefulness of that expression in the computation of orness and andness average values of certain aggregation functions. By generalizing our result to Riemann-Stieltjes integrals, we also provide a method for the calculation of certain expected values and distribution functions.

Keywords: Multivariate integration, aggregation function, Cauchy mean, distribution function, expected value, andness, orness.

1 Introduction

Let $a, b \in \mathbb{R} \cup \{-\infty, +\infty\}$, with $a < b$, and consider an integral over $[a, b]^n$ whose integrand displays an explicit dependence on the minimum and/or the maximum of the variables, that is, an integral of the form

$$\int_{[a,b]^n} f(\mathbf{x}, \min x_i, \max x_i) d\mathbf{x}. \quad (1)$$

In this note we provide an alternative expression of this integral, in which the minimum and the maximum are replaced with two single variables. When the integral is tractable, that alternative expression generally makes the integral much easier to evaluate. For instance, when the integrand depends only on the minimum and the maximum of the variables, we ob-

tain the following identity

$$\begin{aligned} & \int_{[a,b]^n} f(\min x_i, \max x_i) d\mathbf{x} \\ &= n(n-1) \int_a^b dv \int_a^v f(u, v)(v-u)^{n-2} du, \quad (2) \end{aligned}$$

and hence, for certain functions f , the integral becomes very easy to evaluate.

The alternative expression we present for integral (1) is given in the next section (see Theorem 2.1). The method we employ to obtain that expression merely consists in dividing the domain $[a, b]^n$ into n polyhedra chosen in such a way that the minimum and maximum functions simply become single variables.

This method can be very efficient in the evaluation of many integrals that would normally require difficult and tedious computations. As an example, consider the variance of a sample $\mathbf{x} \in [a, b]^n$ from a given population, namely

$$s^2(\mathbf{x}) = \frac{1}{n-1} \sum_{i=1}^n \left(x_i - \frac{1}{n} \sum_{j=1}^n x_j \right)^2.$$

The average value over $[a, b]^n$ of the variance-to-range ratio function can be easily calculated by using our method. We merely obtain

$$\frac{1}{(b-a)^n} \int_{[a,b]^n} \frac{s^2(\mathbf{x})}{\max x_i - \min x_i} d\mathbf{x} = \frac{n+2}{12n} (b-a). \quad (3)$$

This note is set out as follows. In Section 2 we state and prove the main result. In Section 3 we provide an application of our result to internal functions, also called Cauchy means, which can be classified according to their location within the range of the variables. A similar application to conjunctive and disjunctive functions is also investigated. In Section 4 we show

how the direct generalization of our result to Riemann-Stieltjes integrals enables us to consider the evaluation of certain expected values from various distributions.

We will use the following notation throughout. For any n -tuple \mathbf{x} , we denote by $(\mathbf{x} \mid x_j = u)$ the n -tuple whose i th coordinate is u if $i = j$, and x_i otherwise. Also, for any integer $n \geq 1$, we set $[n] := \{1, \dots, n\}$.

2 Main result

In this section we present our main result which consists of an alternative expression of integral (1). We start with a preliminary lemma, which concerns the particular cases of functions involving either the minimum or the maximum of the variables.

Lemma 2.1. *Let $f :]a, b[^{n+1} \rightarrow \mathbb{R}$ be an integrable function. Then we have*

$$\begin{aligned} & \int_{]a, b[^n} f(\mathbf{x}, \min x_i) d\mathbf{x} \\ &= \sum_{j=1}^n \int_a^b du \int_{]u, b[^{n-1}} f(\mathbf{x}, u \mid x_j = u) \prod_{i \in [n] \setminus \{j\}} dx_i, \\ & \int_{]a, b[^n} f(\mathbf{x}, \max x_i) d\mathbf{x} \\ &= \sum_{j=1}^n \int_a^b dv \int_{]a, v[^{n-1}} f(\mathbf{x}, v \mid x_j = v) \prod_{i \in [n] \setminus \{j\}} dx_i. \end{aligned}$$

Proof. Consider the following n -dimensional open polyhedra

$$P_j := \{\mathbf{x} \in]a, b[^n : x_i > x_j \forall i \neq j\} \quad (j \in [n]).$$

They are pairwise disjoint. Indeed, if $\mathbf{x} \in P_j \cap P_k$, with $j \neq k$, then $x_k > x_j$ and $x_j > x_k$, which is a contradiction. Moreover, the union of their set closures covers $]a, b[^n$. Indeed, for any $\mathbf{x} \in]a, b[^n$ there is always $j \in [n]$ such that $x_i \geq x_j$ for all $i \neq j$.

Therefore, for any integrable function $f :]a, b[^{n+1} \rightarrow \mathbb{R}$, we have

$$\begin{aligned} & \int_{]a, b[^n} f(\mathbf{x}, \min x_i) d\mathbf{x} \\ &= \sum_{j=1}^n \int_{P_j} f(\mathbf{x}, \min x_i) d\mathbf{x} \\ &= \sum_{j=1}^n \int_a^b dx_j \int_{]x_j, b[^{n-1}} f(\mathbf{x}, x_j) \prod_{i \in [n] \setminus \{j\}} dx_i, \end{aligned}$$

which proves the first formula. The second formula can be established similarly by considering the polyhedra

$$Q_j := \{\mathbf{x} \in]a, b[^n : x_i < x_j \forall i \neq j\} \quad (j \in [n]). \quad \square$$

Lemma 2.1 is interesting in its own right since it provides special cases of the main result. For instance, by applying the first formula, we immediately obtain the following identity, which will be used in the next section (see Example 3.2). For any $S \subseteq [n]$, we have

$$\begin{aligned} & \int_{]a, b[^n} f(\min_{i \in S} x_i) d\mathbf{x} \\ &= (b-a)^{n-|S|} |S| \int_a^b f(u)(b-u)^{|S|-1} du. \quad (4) \end{aligned}$$

Let us now state our main result, which follows immediately from two applications of Lemma 2.1.

Theorem 2.1. *Let $n \geq 2$ and let $f :]a, b[^{n+2} \rightarrow \mathbb{R}$ be an integrable function. Then we have*

$$\begin{aligned} & \int_{]a, b[^n} f(\mathbf{x}, \min x_i, \max x_i) d\mathbf{x} \\ &= \sum_{\substack{j, k=1 \\ j \neq k}}^n \int_a^b dv \int_a^v du \times \\ & \quad \int_{]u, v[^{n-2}} f(\mathbf{x}, u, v \mid x_j = u, x_k = v) \prod_{i \in [n] \setminus \{j, k\}} dx_i. \end{aligned}$$

A direct use of this result leads to formula (3). Indeed, as the integrand is symmetric in its variables, we simply need to consider

$$\begin{aligned} & f(\mathbf{x}, u, v \mid x_j = u, x_k = v) \\ &= \frac{1}{v-u} s^2(x_1, \dots, x_{n-2}, u, v), \quad (5) \end{aligned}$$

where, for any fixed $a < u < v < b$, the right-hand side is a quadratic polynomial in x_1, \dots, x_{n-2} .

3 Application to aggregation function theory

We now apply our main result to the computation of orness and andness average values of internal functions and to the computation of idempotency average values of conjunctive and disjunctive functions.

3.1 Internal functions

We recall the concept of internal functions, which was introduced in the theory of means and aggregation functions.

Definition 3.1. *A function $F :]a, b[^n \rightarrow \mathbb{R}$ is said to be *internal* if*

$$\min x_i \leq F(\mathbf{x}) \leq \max x_i \quad (\mathbf{x} \in]a, b[^n).$$

Internality is a property introduced by Cauchy [3] who considered in 1821 the *mean* of n independent variables x_1, \dots, x_n as a function $F(x_1, \dots, x_n)$ which should be internal to the set of x_i values. Internal functions, also called Cauchy means, are very often encountered in the literature on aggregation functions. Most of the classical means, such as the arithmetic mean, the geometric mean, and their weighted versions, are Cauchy means. For an overview on means and aggregation functions, see the edited book [2].

It is straightforward to see that a function $F :]a, b[^n \rightarrow \mathbb{R}$ is internal if and only if there is a function f from $]a, b[^n \setminus \text{diag}(]a, b[^n)$ to $[0, 1]$ such that

$$F(\mathbf{x}) = \min x_i + f(\mathbf{x}) (\max x_i - \min x_i),$$

where $\text{diag}(]a, b[^n) := \{(x, \dots, x) \in]a, b[^n : x \in]a, b[\}$.

Starting from this observation, Dujmović [4] (see also [6]) introduced the following concepts of local orness and andness functions, rediscovered independently by Fernández Salido and Murakami [8] as orness and andness distribution functions.

Definition 3.2. The *orness distribution function* (resp. *andness distribution function*) associated with an internal function $F :]a, b[^n \rightarrow \mathbb{R}$ is a function odf_F (resp. adf_F), from $]a, b[^n \setminus \text{diag}(]a, b[^n)$ to $[0, 1]$, defined as

$$\begin{aligned} odf_F(\mathbf{x}) &= \frac{F(\mathbf{x}) - \min x_i}{\max x_i - \min x_i} \\ (\text{resp. } adf_F(\mathbf{x})) &= \frac{\max x_i - F(\mathbf{x})}{\max x_i - \min x_i}. \end{aligned}$$

Thus defined, the orness distribution function (resp. andness distribution function) associated with an internal function $F :]a, b[^n \rightarrow \mathbb{R}$ measures, at each $\mathbf{x} \in]a, b[^n$, the extent to which $F(\mathbf{x})$ is close to $\max x_i$ (resp. $\min x_i$), that is, the extent to which $F(\mathbf{x})$ has a disjunctive (resp. conjunctive) or orlike (resp. andlike) behavior.

To measure the average orness or andness quality of an internal function over its domain, Dujmović [4] also introduced the concepts of mean local orness and andness, later called orness and andness average values by Fernández Salido and Murakami [8].

Definition 3.3. The *orness average value* (resp. *andness average value*) of an internal and integrable function $F :]a, b[^n \rightarrow \mathbb{R}$ is defined as

$$\begin{aligned} \overline{odf}_F &= \frac{1}{(b-a)^n} \int_{]a,b[^n} odf_F(\mathbf{x}) d\mathbf{x} \\ (\text{resp. } \overline{adf}_F) &= \frac{1}{(b-a)^n} \int_{]a,b[^n} adf_F(\mathbf{x}) d\mathbf{x}. \end{aligned}$$

As an immediate property, we note that

$$\overline{odf}_F(\mathbf{x}) + \overline{adf}_F(\mathbf{x}) = 1,$$

which entails $\overline{odf}_F + \overline{adf}_F = 1$. Thus, as expected, both \overline{odf}_F and \overline{adf}_F render the same information and hence we can restrict ourselves to the computation of \overline{odf}_F .

Even though the computation of \overline{odf}_F remains very difficult in most of the cases, Theorem 2.1 enables us to rewrite this integral in a more practical form, namely

$$\begin{aligned} \overline{odf}_F &= \frac{1}{(b-a)^n} \sum_{j,k=1}^n \int_a^b dv \int_a^v du \times \\ &\quad \int_{]u,v[^{n-2}} \frac{F(\mathbf{x} \mid x_j = u, x_k = v) - u}{v - u} \prod_{i \in [n] \setminus \{j,k\}} dx_i. \end{aligned}$$

The following two examples demonstrate the power of this formula:

Example 3.1. The orness average value over $[0, 1]^n$ of the geometric mean

$$G^{(n)}(\mathbf{x}) = \prod_{i=1}^n x_i^{1/n}$$

is given for $n = 2$ by

$$\overline{odf}_{G^{(2)}} = \ln 4 - 1$$

and for $n > 2$ by

$$\begin{aligned} \overline{odf}_{G^{(n)}} &= n(n-1) \left(\frac{n}{n+1} \right)^{n-2} \int_0^1 \frac{x^n (1-x^{n+1})^{n-2}}{1-x^n} dx \\ &\quad - \frac{1}{n-2}. \end{aligned}$$

Example 3.2. Consider a function of the form

$$C_a^{(n)}(\mathbf{x}) = \sum_{S \subseteq [n]} a(S) \min_{i \in S} x_i,$$

where the set function $a : 2^{[n]} \rightarrow \mathbb{R}$ fulfills

$$a(\emptyset) = 0 \quad \text{and} \quad \sum_{S \subseteq [n]} a(S) = 1$$

and is chosen so that the function $C_a^{(n)}$ is nondecreasing in each variable. Such a function is known in aggregation function theory as a *Lovász extension* or a *discrete Choquet integral* (see for instance [9, 11]). As particular cases, we can consider weighted means

$\sum_i w_i x_i$ and convex combinations $\sum_i w_i x_{(i)}$ of order statistics, also known as “ordered weighted averaging” functions (see [13]).

The orness average value over $[0, 1]^n$ of $C_a^{(n)}$ is given by

$$\overline{odf}_{C_a^{(n)}} = \frac{1}{n-1} \sum_{S \subseteq [n]} a(S) \frac{n-|S|}{|S|+1}.$$

To overcome the difficulty of calculating intractable orness average values, Dujmović [5] introduced the next concept of global orness and andness measures (see also [6, 8]). Denote by \overline{F} the average value of any internal and integrable function $F :]a, b[^n \rightarrow \mathbb{R}$ over its domain, that is,

$$\overline{F} := \frac{1}{(b-a)^n} \int_{]a, b[^n} F(\mathbf{x}) d\mathbf{x}.$$

Definition 3.4. The *global orness value* (resp. *global andness value*) of an internal and integrable function $F :]a, b[^n \rightarrow \mathbb{R}$ is defined as

$$\begin{aligned} \text{orness}_F &= \frac{\overline{F} - \overline{\text{Min}}}{\overline{\text{Max}} - \overline{\text{Min}}} \\ (\text{resp. andness}_F) &= \frac{\overline{\text{Max}} - \overline{F}}{\overline{\text{Max}} - \overline{\text{Min}}}, \end{aligned}$$

where Min and Max are, respectively, the minimum and maximum functions defined in $]a, b[^n$.

For example, considering the geometric mean $G^{(n)}(\mathbf{x}) = \prod_{i=1}^n x_i^{1/n}$ in $[0, 1]^n$, we simply obtain

$$\text{orness}_{G^{(n)}} = -\frac{1}{n-1} + \frac{n+1}{n-1} \left(\frac{n}{n+1} \right)^n.$$

Considering the discrete Choquet integral $C_a^{(n)}$ in $[0, 1]^n$, as defined in Example 3.2, we get

$$\text{orness}_{C_a^{(n)}} = \frac{1}{n-1} \sum_{S \subseteq [n]} a(S) \frac{n-|S|}{|S|+1}.$$

Surprisingly enough, in $[0, 1]^n$ we have

$$\text{orness}_{C_a^{(n)}} = \overline{odf}_{C_a^{(n)}},$$

that is, for any discrete Choquet integral, the global orness value identifies with the orness average value, a result already reached by Fernández Salido and Murakami [8] for the special case of symmetric Choquet integrals, that is, convex combinations of order statistics.

The interesting question of determining those internal functions $F :]a, b[^n \rightarrow \mathbb{R}$ fulfilling the equation $\text{orness}_F = \overline{odf}_F$ remains open.

3.2 Conjunctive and disjunctive functions

Let us now consider conjunctive and disjunctive functions.

Definition 3.5. A function $F :]a, b[^n \rightarrow \mathbb{R}$ is said to be *conjunctive* (resp. *disjunctive*) if

$$a \leq F(\mathbf{x}) \leq \min x_i \quad (\text{resp. } \max x_i \leq F(\mathbf{x}) \leq b).$$

Prominent examples of conjunctive (resp. disjunctive) functions in the literature are *t-norms* (resp. *t-conorms*), which are symmetric, associative, and non-decreasing functions, from $[0, 1]^2$ to $[0, 1]$, with 0 (resp. 1) as the neutral element. For an account on t-norms and t-conorms, see for instance the book by Alsina et al. [1].

Clearly, a function $F :]a, b[^n \rightarrow \mathbb{R}$ is conjunctive (resp. disjunctive) if and only if there is a function $f :]a, b[^n \rightarrow [0, 1]$ such that

$$\begin{aligned} F(\mathbf{x}) &= a + f(\mathbf{x})(\min x_i - a) \\ (\text{resp. } F(\mathbf{x}) &= b - f(\mathbf{x})(b - \max x_i)). \end{aligned}$$

Just as for the orness and andness distribution functions, we can naturally define the concept of idempotency distribution function associated with a conjunctive (resp. disjunctive) function $F :]a, b[^n \rightarrow \mathbb{R}$ as a measure, at each $\mathbf{x} \in]a, b[^n$, of the extent to which F is idempotent (i.e., such that $F(x, \dots, x) = x$), that is, the extent to which F is close to $\min x_i$ (resp. $\max x_i$).

Definition 3.6. The *idempotency distribution function* associated with a conjunctive (resp. disjunctive) function $F :]a, b[^n \rightarrow \mathbb{R}$ is a function $idf_F :]a, b[^n \rightarrow [0, 1]$, defined as

$$\begin{aligned} idf_F(\mathbf{x}) &= \frac{F(\mathbf{x}) - a}{\min x_i - a} \\ (\text{resp. } idf_F(\mathbf{x}) &= \frac{b - F(\mathbf{x})}{b - \max x_i}). \end{aligned}$$

We can now introduce the concept of idempotency average value as follows.

Definition 3.7. The *idempotency average value* of a conjunctive or disjunctive function $F :]a, b[^n \rightarrow \mathbb{R}$ is defined as

$$\overline{idf}_F = \frac{1}{(b-a)^n} \int_{]a, b[^n} idf_F(\mathbf{x}) d\mathbf{x}.$$

According to Lemma 2.1, for any conjunctive function

$F :]a, b[^n \rightarrow \mathbb{R}$ for instance, we can write

$$\overline{idf}_F = \frac{1}{(b-a)^n} \sum_{j=1}^n \int_a^b du \times \int_{]u, b[^{n-1}} \frac{F(\mathbf{x} | x_j = u) - a}{u - a} \prod_{i \in [n] \setminus \{j\}} dx_i.$$

The following concept of global idempotency value was introduced by Kolesárová [10] for t-norms as an idempotency measure:

Definition 3.8. The *global idempotency value* of a conjunctive (resp. disjunctive) function $F :]a, b[^n \rightarrow \mathbb{R}$ is defined by

$$\text{idemp}_F = \frac{\overline{F} - a}{\text{Min} - a} \quad (\text{resp. } \text{idemp}_F = \frac{b - \overline{F}}{b - \text{Max}}).$$

Example 3.3. The idempotency average value and the global idempotency value over $[0, 1]^n$ of the product

$$P^{(n)}(\mathbf{x}) = \prod_{i=1}^n x_i,$$

which is a conjunctive function, is given by

$$\overline{idf}_{P^{(n)}} = \frac{2^{n-1}}{\binom{2n-1}{n}}$$

while its global idempotency value is given by

$$\text{idemp}_{P^{(n)}} = \frac{n+1}{2^n}.$$

4 Application to probability theory

Since the idea behind our results merely consists in breaking the integration domain into smaller regions, Lemma 2.1 and Theorem 2.1 can be straightforwardly extended to Riemann-Stieltjes integrals, thus making it possible to consider average values from various probability distributions.

Consider a measurable function $g : \mathbb{R}^{n+2} \rightarrow \mathbb{R}$ and n independent random variables X_1, \dots, X_n , X_i ($i \in [n]$) having distribution function $F_i(x)$. Define the random variable Y_g as

$$Y_g := g(\mathbf{X}, \min X_i, \max X_i),$$

where \mathbf{X} denotes the vector (X_1, \dots, X_n) .

The direct generalization of Theorem 2.1 to Riemann-Stieltjes integrals can be used to evaluate the expected value of Y_g , namely

$$\mathbf{E}[Y_g] = \int_{\mathbb{R}^n} g(\mathbf{x}, \min x_i, \max x_i) dF_1(x_1) \cdots dF_n(x_n).$$

It can also be used in the evaluation of the distribution function of Y_g , which is defined as

$$\begin{aligned} F_g(z) &= \mathbf{E}[H(z - Y_g)] \\ &= \int_{\mathbb{R}^n} H(z - g(\mathbf{x}, \min x_i, \max x_i)) \times dF_1(x_1) \cdots dF_n(x_n), \end{aligned}$$

where $H : \mathbb{R} \rightarrow \{0, 1\}$ is the Heaviside step function, defined by $H(x) = 1$ if $x \geq 0$, and 0 otherwise. Note that the case where Y_g is a lattice polynomial (max-min combination) of the variables X_1, \dots, X_n has been thoroughly investigated by the author in [12].

To keep our exposition simple, let us examine the special case where Y_g depends only on $\min X_i$ and $\max X_i$, that is,

$$Y_g := g(\min X_i, \max X_i),$$

where $g : \mathbb{R}^2 \rightarrow \mathbb{R}$ is a measurable function. In this case, our method immediately leads to

$$\begin{aligned} \mathbf{E}[Y_g] &= \sum_{j,k=1}^n \int_{-\infty}^{\infty} dF_k(v) \times \\ &\quad \int_{-\infty}^v g(u, v) dF_j(u) \int_{]u, v[^{n-2}} \prod_{i \in [n] \setminus \{j, k\}} dF_i(x_i) \\ &= \sum_{j,k=1}^n \int_{-\infty}^{\infty} dF_k(v) \times \\ &\quad \int_{-\infty}^v g(u, v) \prod_{i \in [n] \setminus \{j, k\}} (F_i(v) - F_i(u)) dF_j(u). \end{aligned}$$

In the particular case where the random variables X_1, \dots, X_n are independent and identically distributed, each with distribution function $F(x)$, the expected value clearly reduces to

$$\begin{aligned} \mathbf{E}[Y_g] &= n(n-1) \int_{-\infty}^{\infty} dF(v) \times \\ &\quad \int_{-\infty}^v g(u, v) (F(v) - F(u))^{n-2} dF(u), \quad (6) \end{aligned}$$

which generalizes formula (2).

Example 4.1. For exponential variables X_1, \dots, X_n , each with distribution function $F(x) = 1 - e^{-\lambda x}$ ($x > 0$), we simply have

$$\begin{aligned} \mathbf{E}[Y_g] &= n(n-1) \int_0^{\infty} \lambda e^{-\lambda v} dv \times \\ &\quad \int_0^v g(u, v) (e^{-\lambda u} - e^{-\lambda v})^{n-2} \lambda e^{-\lambda u} du. \end{aligned}$$

Using the change of variables $x = e^{-\lambda u}$ and $y = e^{-\lambda u} - e^{-\lambda v}$, this integral can be easily rewritten as

$$\mathbf{E}[Y_g] = n(n-1) \int_0^1 dx \times \int_0^x y^{n-2} g\left(-\frac{1}{\lambda} \ln(x), -\frac{1}{\lambda} \ln(x-y)\right) dy.$$

Example 4.2. Let us calculate the distribution function and the raw moments of the random variable

$$Y = \frac{\max X_i - \min X_i}{\max X_i}$$

from the uniform distribution over $]0, 1]^n$.

The raw moments can be calculated very easily from (6). For any integer $r \geq 0$, we have

$$\mathbf{E}[Y^r] = n(n-1) \int_0^1 dv \times \int_0^v \left(\frac{v-u}{v}\right)^r (v-u)^{n-2} du = \frac{n-1}{n+r-1}.$$

On the other hand, the distribution of Y is simply given by

$$F(z) = n(n-1) \int_0^1 dv \int_0^v H\left(z - \frac{v-u}{v}\right) (v-u)^{n-2} du,$$

that is,

$$F(z) = \begin{cases} 0, & \text{if } z \leq 0, \\ z^{n-1}, & \text{if } 0 \leq z \leq 1, \\ 1, & \text{if } 1 \leq z. \end{cases}$$

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