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*Research Article*

# Some Slater's Type Inequalities for Convex Functions Defined on Linear Spaces and Applications

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Some inequalities of the Slater type for convex functions defined on general linear spaces are given. Applications for norm inequalities and $f$-divergence measures are also provided.

## 1. Introduction

Suppose that $I$ is an interval of real numbers with interior $\mathring{I}$, and $f : I \to \mathbb{R}$ is a convex function on $I$. Then $f$ is continuous on $\mathring{I}$ and has finite left and right derivatives at each point of $\mathring{I}$. Moreover, if $x, y \in \mathring{I}$ and $x < y$, then $f'_-(x) \le f'_+(x) \le f'_-(y) \le f'_+(y)$ which shows that both $f'_-$ and $f'_+$ are nondecreasing functions on $\mathring{I}$. It is also known that a convex function must be differentiable except for at most countably many points.

For a convex function $f : I \to \mathbb{R}$, the subdifferential of $f$ denoted by $\partial f$ is the set of all functions $\varphi : I \to [-\infty, \infty]$ such that $\varphi(\mathring{I}) \subset \mathbb{R}$ and

$$f(x) \ge f(a) + (x-a)\varphi(a), \quad \text{for any } x, a \in I. \tag{1.1}$$

It is also well known that if $f$ is convex on $I$, then $\partial f$ is nonempty, $f'_-$, $f'_+ \in \partial f$ and if $\varphi \in \partial f$, then

$$f'_-(x) \leq \varphi(x) \leq f'_+(x), \quad \text{for any } x \in \mathring{I}. \tag{1.2}$$

In particular, $\varphi$ is a nondecreasing function.

If $f$ is differentiable and convex on $\mathring{I}$, then $\partial f = \{f'\}$.

The following result is well known in the literature as *the Slater inequality.*

**Theorem 1.1** (Slater, 1981, [1]). *If $f : I \to \mathbb{R}$ is a nonincreasing (nondecreasing) convex function, $x_i \in I$, $p_i \geq 0$ with $P_n := \sum_{i=1}^n p_i > 0$ and $\sum_{i=1}^n p_i\varphi(x_i) \neq 0$, where $\varphi \in \partial f$, then*

$$\frac{1}{P_n}\sum_{i=1}^n p_i f(x_i) \leq f\left(\frac{\sum_{i=1}^n p_i x_i \varphi(x_i)}{\sum_{i=1}^n p_i \varphi(x_i)}\right). \tag{1.3}$$

As pointed out in [2] (see also [3, p. 64] and [4, p. 208]), the monotonicity assumption for the derivative $\varphi$ can be replaced with the condition

$$\frac{\sum_{i=1}^n p_i x_i \varphi(x_i)}{\sum_{i=1}^n p_i \varphi(x_i)} \in I, \tag{1.4}$$

which is more general and can hold for suitable points in $I$ and for not necessarily monotonic functions.

For recent works on Slater's inequality, see [5–7].

The main aim of the present paper is to extend Slater's inequality for convex functions defined on general linear spaces. A reverse of the Slater's inequality is also obtained. Natural applications for norm inequalities and $f$-divergence measures are provided as well.

## 2. Slater's Inequality for Functions Defined on Linear Spaces

Assume that $f : X \to \mathbb{R}$ is a *convex function* on the real linear space $X$. Since for any vectors $x, y \in X$ the function $g_{x,y} : \mathbb{R} \to \mathbb{R}$, $g_{x,y}(t) := f(x + ty)$ is convex, it follows that the following limits exist

$$\nabla_{+(-)} f(x)(y) := \lim_{t \to 0+(-)} \frac{f(x+ty) - f(x)}{t}, \tag{2.1}$$

and they are called the *right (left) Gâteaux derivatives* of the function $f$ in the point $x$ over the direction $y$.

It is obvious that for any $t > 0 > s$ we have

$$\frac{f(x+ty)-f(x)}{t} \geq \nabla_+ f(x)(y) = \inf_{t>0}\left[\frac{f(x+ty)-f(x)}{t}\right] \geq \sup_{s<0}\left[\frac{f(x+sy)-f(x)}{s}\right] = \nabla_- f(x)(y) \geq \frac{f(x+sy)-f(x)}{s}, \tag{2.2}$$

for any $x, y \in X$ and, in particular,

$$\nabla_- f(u)(u-v) \geq f(u) - f(v) \geq \nabla_+ f(v)(u-v), \tag{2.3}$$

for any $u, v \in X$. We call this *the gradient inequality* for the convex function $f$. It will be used frequently in the sequel in order to obtain various results related to Slater's inequality.

The following properties are also of importance:

$$\nabla_+ f(x)(-y) = -\nabla_- f(x)(y), \tag{2.4}$$

$$\nabla_{+(-)} f(x)(\alpha y) = \alpha \nabla_{+(-)} f(x)(y), \tag{2.5}$$

for any $x, y \in X$ and $\alpha \geq 0$.

The right Gâteaux derivative is *subadditive* while the left one is *superadditive*, that is,

$$\nabla_+ f(x)(y+z) \leq \nabla_+ f(x)(y) + \nabla_+ f(x)(z),$$
$$\nabla_- f(x)(y+z) \geq \nabla_- f(x)(y) + \nabla_- f(x)(z), \tag{2.6}$$

for any $x, y, z \in X$.

Some natural examples can be provided by the use of normed spaces.

Assume that $(X, \|\cdot\|)$ is a real normed linear space. The function $f : X \to \mathbb{R}$, $f(x) := (1/2)\|x\|^2$ is a convex function which generates *the superior* and *the inferior semi-inner products*

$$\langle y, x\rangle_{s(i)} := \lim_{t\to 0+(-)} \frac{\|x+ty\|^2 - \|x\|^2}{2t}. \tag{2.7}$$

For a comprehensive study of the properties of these mappings in the Geometry of Banach Spaces, see the monograph [8].

For the convex function $f_p : X \to \mathbb{R}$, $f_p(x) := \|x\|^p$ with $p > 1$, we have

$$\nabla_{+(-)} f_p(x)(y) = \begin{cases} p\|x\|^{p-2}\langle y, x\rangle_{s(i)} & \text{if } x \neq 0, \\ 0 & \text{if } x = 0, \end{cases} \tag{2.8}$$

for any $y \in X$.

If $p = 1$, then we have

$$\nabla_{+(-)} f_1(x)(y) = \begin{cases} \|x\|^{-1} \langle y, x \rangle_{s(i)} & \text{if } x \neq 0, \\ +(-)\|y\| & \text{if } x = 0, \end{cases} \tag{2.9}$$

for any $y \in X$.

For a given convex function $f : X \to \mathbb{R}$ and a given $n$-tuple of vectors $\mathbf{x} = (x_1, \ldots, x_n) \in X^n$, we consider the sets

$$\begin{aligned} \mathrm{Sla}_{+(-)}(f, \mathbf{x}) &:= \{ v \in X \mid \nabla_{+(-)} f(x_i)(v - x_i) \geq 0 \ \forall i \in \{1, \ldots, n\} \}, \\ \mathrm{Sla}_{+(-)}(f, \mathbf{x}, \mathbf{p}) &:= \left\{ v \in X \mid \sum_{i=1}^{n} p_i \nabla_{+(-)} f(x_i)(v - x_i) \geq 0 \right\}, \end{aligned} \tag{2.10}$$

where $\mathbf{p} = (p_1, \ldots, p_n) \in \mathbb{P}^n$ is a given probability distribution, that is, $p_i \geq 0$ for $i \in \{1, \ldots, n\}$ and $\sum_{i=1}^{n} p_i = 1$.

The following properties of these sets hold.

**Lemma 2.1.** *For a given convex function $f : X \to \mathbb{R}$, a given $n$-tuple of vectors $\mathbf{x} = (x_1, \ldots, x_n) \in X^n$, and a given probability distribution $\mathbf{p} = (p_1, \ldots, p_n) \in \mathbb{P}^n$, one has*

(i) $\mathrm{Sla}_{-}(f, \mathbf{x}) \subset \mathrm{Sla}_{+}(f, \mathbf{x})$ *and* $\mathrm{Sla}_{-}(f, \mathbf{x}, \mathbf{p}) \subset \mathrm{Sla}_{+}(f, \mathbf{x}, \mathbf{p})$;

(ii) $\mathrm{Sla}_{-}(f, \mathbf{x}) \subset \mathrm{Sla}_{-}(f, \mathbf{x}, \mathbf{p})$ *and* $\mathrm{Sla}_{+}(f, \mathbf{x}) \subset \mathrm{Sla}_{+}(f, \mathbf{x}, \mathbf{p})$ *for all* $\mathbf{p} = (p_1, \ldots, p_n) \in \mathbb{P}^n$;

(iii) *the sets* $\mathrm{Sla}_{-}(f, \mathbf{x})$ *and* $\mathrm{Sla}_{-}(f, \mathbf{x}, \mathbf{p})$ *are convex.*

*Proof.* The properties (i) and (ii) follow from the definition and the fact that $\nabla_{+} f(x)(y) \geq \nabla_{-} f(x)(y)$ for any $x, y$.

(iii) Let us only prove that $\mathrm{Sla}_{-}(f, \mathbf{x})$ is convex.

If we assume that $y_1, y_2 \in \mathrm{Sla}_{-}(f, \mathbf{x})$ and $\alpha, \beta \in [0, 1]$ with $\alpha + \beta = 1$, then by the superadditivity and positive homogeneity of the Gâteaux derivative $\nabla_{-} f(\cdot)(\cdot)$ in the second variable we have

$$\begin{aligned} \nabla_{-} f(x_i)(\alpha y_1 + \beta y_2 - x_i) &= \nabla_{-} f(x_i)[\alpha(y_1 - x_i) + \beta(y_2 - x_i)] \\ &\geq \alpha \nabla_{-} f(x_i)(y_1 - x_i) + \beta \nabla_{-} f(x_i)(y_2 - x_i) \geq 0, \end{aligned} \tag{2.11}$$

for all $i \in \{1, \ldots, n\}$, which shows that $\alpha y_1 + \beta y_2 \in \mathrm{Sla}_{-}(f, \mathbf{x})$

The proof for the convexity of $\mathrm{Sla}_{-}(f, \mathbf{x}, \mathbf{p})$ is similar and the details are omitted. □

For the convex function $f_p : X \to \mathbb{R}$, $f_p(x) := \|x\|^p$ with $p \geq 1$, defined on the normed linear space $(X, \|\cdot\|)$ and for the $n$-tuple of vectors $\mathbf{x} = (x_1, \ldots, x_n) \in X^n \setminus \{(0, \ldots, 0)\}$ we have, by the well-known property of the semi-inner products,

$$\langle y + \alpha x, x \rangle_{s(i)} = \langle y, x \rangle_{s(i)} + \alpha \|x\|^2, \quad \text{for any } x, y \in X, \ \alpha \in \mathbb{R}, \tag{2.12}$$

that

$$\mathrm{Sla}_{+(-)}\left(\|\cdot\|^{p},\mathbf{x}\right)=\mathrm{Sla}_{+(-)}(\|\cdot\|,\mathbf{x}):=\left\{v\in X\mid\langle v,x_j\rangle_{s(i)}\geq\|x_j\|^2\ \forall j\in\{1,\ldots,n\}\right\}\tag{2.13}$$

which, as can be seen, does not depend on $p$. We observe, by the continuity of the semi-inner products in the first variable, that $\mathrm{Sla}_{+(-)}(\|\cdot\|,\mathbf{x})$ is closed in $(X,\|\cdot\|)$. Also, we should remark that if $v\in\mathrm{Sla}_{+(-)}(\|\cdot\|,\mathbf{x})$, then for any $\gamma\geq 1$ we also have that $\gamma v\in\mathrm{Sla}_{+(-)}(\|\cdot\|,\mathbf{x})$.

The larger classes, which are dependent on the probability distribution $\mathbf{p}\in\mathbb{P}^n$, are described by

$$\mathrm{Sla}_{+(-)}\left(\|\cdot\|^{p},\mathbf{x},\mathbf{p}\right):=\left\{v\in X\mid\sum_{j=1}^{n}p_j\|x_j\|^{p-2}\langle v,x_j\rangle_{s(i)}\geq\sum_{j=1}^{n}p_j\|x_j\|^{p}\right\}.\tag{2.14}$$

If the normed space is smooth, that is, the norm is Gâteaux differentiable in any nonzero point, then the superior and inferior semi-inner products coincide with the Lumer-Giles semi-inner product $[\cdot,\cdot]$ that generates the norm and is linear in the first variable (see for instance [8]). In this situation,

$$\begin{aligned}\mathrm{Sla}(\|\cdot\|,\mathbf{x})&=\left\{v\in X\mid[v,x_j]\geq\|x_j\|^2\ \forall j\in\{1,\ldots,n\}\right\},\\ \mathrm{Sla}\left(\|\cdot\|^{p},\mathbf{x},\mathbf{p}\right)&=\left\{v\in X\mid\sum_{j=1}^{n}p_j\|x_j\|^{p-2}[v,x_j]\geq\sum_{j=1}^{n}p_j\|x_j\|^{p}\right\}.\end{aligned}\tag{2.15}$$

If $(X,\langle\cdot,\cdot\rangle)$ is an inner product space, then $\mathrm{Sla}(\|\cdot\|^p,\mathbf{x},\mathbf{p})$ can be described by

$$\mathrm{Sla}\left(\|\cdot\|^{p},\mathbf{x},\mathbf{p}\right)=\left\{v\in X\mid\left\langle v,\sum_{j=1}^{n}p_j\|x_j\|^{p-2}x_j\right\rangle\geq\sum_{j=1}^{n}p_j\|x_j\|^{p}\right\},\tag{2.16}$$

and if the family $\{x_j\}_{j=1,\ldots,n}$ is orthogonal, then obviously, by the Pythagoras theorem, we have that the sum $\sum_{j=1}^{n}x_j$ belongs to $\mathrm{Sla}(\|\cdot\|,\mathbf{x})$ and therefore to $\mathrm{Sla}(\|\cdot\|^p,\mathbf{x},\mathbf{p})$ for any $p\geq 1$ and any probability distribution $\mathbf{p}=(p_1,\ldots,p_n)\in\mathbb{P}^n$.

We can state now the following results that provide a generalization of Slater's inequality as well as a counterpart for it.

**Theorem 2.2.** *Let $f:X\to\mathbb{R}$ be a convex function on the real linear space $X$, $\mathbf{x}=(x_1,\ldots,x_n)\in X^n$ an $n$-tuple of vectors, and $\mathbf{p}=(p_1,\ldots,p_n)\in\mathbb{P}^n$ a probability distribution. Then for any $v\in\mathrm{Sla}_{+}(f,\mathbf{x},\mathbf{p})$, one has the inequalities*

$$\nabla_{-}f(v)(v)-\sum_{i=1}^{n}p_i\nabla_{-}f(v)(x_i)\geq f(v)-\sum_{i=1}^{n}p_if(x_i)\geq 0.\tag{2.17}$$

*Proof.* If we write the gradient inequality for $v \in \mathrm{Sla}_+(f,\mathbf{x},\mathbf{p})$ and $x_i$, then we have that

$$\nabla_- f(v)(v-x_i) \geq f(v) - f(x_i) \geq \nabla_+ f(x_i)(v-x_i), \tag{2.18}$$

for any $i \in \{1,\ldots,n\}$.

By multiplying (2.18) with $p_i \geq 0$ and summing over $i$ from 1 to $n$, we get

$$\sum_{i=1}^{n} p_i \nabla_- f(v)(v-x_i) \geq f(v) - \sum_{i=1}^{n} p_i f(x_i) \geq \sum_{i=1}^{n} p_i \nabla_+ f(x_i)(v-x_i). \tag{2.19}$$

Now, since $v \in \mathrm{Sla}_+(f,\mathbf{x},\mathbf{p})$, then the right hand side of (2.19) is nonnegative, which proves the second inequality in (2.17).

By the superadditivity of the Gâteaux derivative $\nabla_- f(\cdot)(\cdot)$ in the second variable, we have

$$\nabla_- f(v)(v) - \nabla_- f(v)(x_i) \geq \nabla_- f(v)(v-x_i), \tag{2.20}$$

which, by multiplying with $p_i \geq 0$ and summing over $i$ from 1 to $n$, produces the inequality

$$\nabla_- f(v)(v) - \sum_{i=1}^{n} p_i \nabla_- f(v)(x_i) \geq \sum_{i=1}^{n} p_i \nabla_- f(v)(v-x_i). \tag{2.21}$$

Utilising (2.19) and (2.21), we deduce the desired result (2.17). □

*Remark 2.3.* The above result has the following form for normed linear spaces. Let $(X,\|\cdot\|)$ be a normed linear space, $\mathbf{x}=(x_1,\ldots,x_n) \in X^n$ an $n$-tuple of vectors from $X$, and $p=(p_1,\ldots,p_n) \in \mathbb{P}^n$ a probability distribution. Then for any vector $v \in X$ with the property

$$\sum_{j=1}^{n} p_j \|x_j\|^{p-2} \langle v, x_j\rangle_s \geq \sum_{j=1}^{n} p_j \|x_j\|^p, \quad p \geq 1, \tag{2.22}$$

we have the inequalities

$$p\left[\|v\|^p - \sum_{j=1}^{n} p_j \|x_j\|^{p-2} \langle v, x_j\rangle_i\right] \geq \|v\|^p - \sum_{j=1}^{n} p_j \|x_j\|^p \geq 0. \tag{2.23}$$

Rearranging the first inequality in (2.23), we also have that

$$(p-1)\|v\|^p + \sum_{j=1}^{n} p_j \|x_j\|^p \geq p \sum_{j=1}^{n} p_j \|x_j\|^{p-2} \langle v, x_j\rangle_i. \tag{2.24}$$

If the space is smooth, then the condition (2.22) becomes

$$\sum_{j=1}^{n} p_j \|x_j\|^{p-2} [v, x_j] \geq \sum_{j=1}^{n} p_j \|x_j\|^{p}, \quad p \geq 1, \tag{2.25}$$

implying the inequality

$$p\left[\|v\|^{p} - \sum_{j=1}^{n} p_j \|x_j\|^{p-2} [v, x_j]\right] \geq \|v\|^{p} - \sum_{j=1}^{n} p_j \|x_j\|^{p} \geq 0. \tag{2.26}$$

Notice also that the first inequality in (2.26) is equivalent with

$$(p-1)\|v\|^{p} + \sum_{j=1}^{n} p_j \|x_j\|^{p} \geq p \sum_{j=1}^{n} p_j \|x_j\|^{p-2} [v, x_j] \left( \geq p \sum_{j=1}^{n} p_j \|x_j\|^{p} \geq 0 \right). \tag{2.27}$$

**Corollary 2.4.** *Let $f : X \to \mathbb{R}$ be a convex function on the real linear space $X$, $x = (x_1, \ldots, x_n) \in X^n$ an $n$-tuple of vectors, and $p = (p_1, \ldots, p_n) \in \mathbb{P}^n$ a probability distribution. If*

$$\sum_{i=1}^{n} p_i \nabla_{+} f(x_i)(x_i) \geq (<) 0, \tag{2.28}$$

*and there exists a vector $s \in X$ with*

$$\sum_{i=1}^{n} p_i \nabla_{+(-)} f(x_i)(s) \geq (\leq) 1, \tag{2.29}$$

*then*

$$\begin{aligned} &\nabla_{-} f\left(\sum_{j=1}^{n} p_j \nabla_{+} f(x_j)(x_j) s\right)\left(\sum_{j=1}^{n} p_j \nabla_{+} f(x_j)(x_j) s\right) - \sum_{i=1}^{n} p_i \nabla_{-} f\left(\sum_{j=1}^{n} p_j \nabla_{+} f(x_j)(x_j) s\right)(x_i) \\ &\quad \geq f\left(\sum_{j=1}^{n} p_j \nabla_{+} f(x_j)(x_j) s\right) - \sum_{i=1}^{n} p_i f(x_i) \geq 0. \end{aligned} \tag{2.30}$$

*Proof.* Assume that $\sum_{i=1}^{n} p_i \nabla_{+} f(x_i)(x_i) \geq 0$ and $\sum_{i=1}^{n} p_i \nabla_{+} f(x_i)(s) \geq 1$ and define $v := \sum_{j=1}^{n} p_j \nabla_{+} f(x_j)(x_j) s$. We claim that $v \in \mathrm{Sla}_{+}(f, \mathbf{x}, \mathbf{p})$.

By the subadditivity and positive homogeneity of the mapping $\nabla_+ f(\cdot)(\cdot)$ in the second variable, we have

$$\begin{aligned}\sum_{i=1}^{n} p_i \nabla_+ f(x_i)(v - x_i) &\geq \sum_{i=1}^{n} p_i \nabla_+ f(x_i)(v) - \sum_{i=1}^{n} p_i \nabla_+ f(x_i)(x_i) \\ &= \sum_{i=1}^{n} p_i \nabla_+ f(x_i)\left(\sum_{j=1}^{n} p_j \nabla_+ f(x_j)(x_j) s\right) - \sum_{i=1}^{n} p_i \nabla_+ f(x_i)(x_i) \\ &= \sum_{j=1}^{n} p_j \nabla_+ f(x_j)(x_j) \sum_{i=1}^{n} p_i \nabla_+ f(x_i)(s) - \sum_{i=1}^{n} p_i \nabla_+ f(x_i)(x_i) \\ &= \sum_{j=1}^{n} p_j \nabla_+ f(x_j)(x_j)\left[\sum_{i=1}^{n} p_i \nabla_+ f(x_i)(s) - 1\right] \geq 0,\end{aligned} \tag{2.31}$$

as claimed. Applying Theorem 2.2 for this $v$, we get the desired result.

If $\sum_{i=1}^{n} p_i \nabla_+ f(x_i)(x_i) < 0$ and $\sum_{i=1}^{n} p_i \nabla_- f(x_i)(s) \leq 1$, then for

$$w := \sum_{j=1}^{n} p_j \nabla_+ f(x_j)(x_j) s, \tag{2.32}$$

we also have that

$$\begin{aligned}\sum_{i=1}^{n} p_i \nabla_+ f(x_i)(w - x_i) &\geq \sum_{i=1}^{n} p_i \nabla_+ f(x_i)\left(\sum_{j=1}^{n} p_j \nabla_+ f(x_j)(x_j) s\right) - \sum_{i=1}^{n} p_i \nabla_+ f(x_i)(x_i) \\ &= \sum_{i=1}^{n} p_i \nabla_+ f(x_i)\left(\left(-\sum_{j=1}^{n} p_j \nabla_+ f(x_j)(x_j)\right)(-s)\right) - \sum_{i=1}^{n} p_i \nabla_+ f(x_i)(x_i) \\ &= \left(-\sum_{j=1}^{n} p_j \nabla_+ f(x_j)(x_j)\right) \sum_{i=1}^{n} p_i \nabla_+ f(x_i)(-s) - \sum_{i=1}^{n} p_i \nabla_+ f(x_i)(x_i) \\ &= \left(-\sum_{j=1}^{n} p_j \nabla_+ f(x_j)(x_j)\right)\left(1 + \sum_{i=1}^{n} p_i \nabla_+ f(x_i)(-s)\right) \\ &= \left(-\sum_{j=1}^{n} p_j \nabla_+ f(x_j)(x_j)\right)\left(1 - \sum_{i=1}^{n} p_i \nabla_- f(x_i)(s)\right) \geq 0,\end{aligned} \tag{2.33}$$

where, for the last equality, we have used the property (2.4). Therefore, $w \in \mathrm{Sla}_+(f, \mathbf{x}, \mathbf{p})$ and by Theorem 2.2 we get the desired result. □

It is natural to consider the case of normed spaces.

*Remark 2.5.* Let $(X, \|\cdot\|)$ be a normed linear space, $\mathbf{x} = (x_1, \ldots, x_n) \in X^n$ an $n$-tuple of vectors from $X$, and $\mathbf{p} = (p_1, \ldots, p_n) \in \mathbb{P}^n$ a probability distribution. Then for any vector $s \in X$ with the property that

$$p \sum_{i=1}^{n} p_i \|x_i\|^{p-2} \langle s, x_i \rangle_s \geq 1, \tag{2.34}$$

we have the inequalities

$$\begin{aligned} & p^p \|s\|^{p-1} \left( \sum_{j=1}^{n} p_j \|x_j\|^p \right)^{p-1} \left( p\|s\| \sum_{j=1}^{n} p_j \|x_j\|^p - \sum_{j=1}^{n} p_j \langle x_j, s \rangle_i \right) \\ & \quad \geq p^p \|s\|^p \left( \sum_{j=1}^{n} p_j \|x_j\|^p \right)^p - \sum_{j=1}^{n} p_j \|x_j\|^p \geq 0. \end{aligned} \tag{2.35}$$

The case of smooth spaces can be easily derived from the above; however, the details are left to the interested reader.

## 3. The Case of Finite Dimensional Linear Spaces

Consider now the finite dimensional linear space $X = \mathbb{R}^m$ and assume that $C$ is an open convex subset of $\mathbb{R}^m$. Assume also that the function $f : C \to \mathbb{R}$ is differentiable and convex on $C$. Obviously, if $x = (x^1, \ldots, x^m) \in C$, then for any $y = (y^1, \ldots, y^m) \in \mathbb{R}^m$ we have

$$\nabla f(x)(y) = \sum_{k=1}^{m} \frac{\partial f(x^1, \ldots, x^m)}{\partial x^k} \cdot y^k. \tag{3.1}$$

For the convex function $f : C \to \mathbb{R}$ and a given $n$-tuple of vectors $\mathbf{x} = (x_1, \ldots, x_n) \in C^n$ with $x_i = (x_i^1, \ldots, x_i^m)$ with $i \in \{1, \ldots, n\}$, we consider the sets

$$\begin{aligned} \operatorname{Sla}(f, \mathbf{x}, C) &:= \left\{ v \in C \mid \sum_{k=1}^{m} \frac{\partial f(x_i^1, \ldots, x_i^m)}{\partial x_i^k} \cdot v^k \right. \\ & \qquad \left. \geq \sum_{k=1}^{m} \frac{\partial f(x_i^1, \ldots, x_i^m)}{\partial x_i^k} \cdot x_i^k \ \forall i \in \{1, \ldots, n\} \right\}, \\ \operatorname{Sla}(f, \mathbf{x}, \mathbf{p}, C) &:= \left\{ v \in C \mid \sum_{i=1}^{n} \sum_{k=1}^{m} p_i \frac{\partial f(x_i^1, \ldots, x_i^m)}{\partial x_i^k} \cdot v^k \right. \\ & \qquad \left. \geq \sum_{i=1}^{n} \sum_{k=1}^{m} p_i \frac{\partial f(x_i^1, \ldots, x_i^m)}{\partial x_i^k} \cdot x_i^k \right\}, \end{aligned} \tag{3.2}$$

where $\mathbf{p} = (p_1, \ldots, p_n) \in \mathbb{P}^n$ is a given probability distribution.

As in the previous section the sets, $\mathrm{Sla}(f, \mathbf{x}, C)$ and $\mathrm{Sla}(f, \mathbf{x}, \mathbf{p}, C)$ are convex and closed subsets of $\mathrm{clo}(C)$, the closure of $C$. Also $\{x_1, \dots, x_n\} \subset \mathrm{Sla}(f, \mathbf{x}, C) \subset \mathrm{Sla}(f, \mathbf{x}, \mathbf{p}, C)$ for any $\mathbf{p} = (p_1, \dots, p_n) \in \mathbb{P}^n$ is a probability distribution.

**Proposition 3.1.** *Let $f : C \to \mathbb{R}$ be a convex function on the open convex set $C$ in the finite dimensional linear space $\mathbb{R}^m$, $(x_1, \dots, x_n) \in C^n$ an $n$-tuple of vectors and $(p_1, \dots, p_n) \in \mathbb{P}^n$ a probability distribution. Then for any $v = (v^1, \dots, v^m) \in \mathrm{Sla}(f, \mathbf{x}, \mathbf{p}, C)$, one has the inequalities*

$$\begin{aligned} &\sum_{k=1}^{m} \frac{\partial f(v^1, \dots, v^m)}{\partial x^k} \cdot v^k - \sum_{i=1}^{n} \sum_{k=1}^{m} p_i \frac{\partial f(x_i^1, \dots, x_i^m)}{\partial x_i^k} \cdot v^k \\ &\quad \geq f\left(v^1, \dots, v^n\right) - \sum_{i=1}^{n} p_i f\left(x_i^1, \dots, x_i^m\right) \geq 0. \end{aligned} \tag{3.3}$$

The unidimensional case, that is, $m = 1$ is of interest for applications. We will state this case with the general assumption that $f : I \to \mathbb{R}$ is a convex function on an *open* interval $I$. For a given $n$-tuple of vectors $\mathbf{x} = (x_1, \dots, x_n) \in I^n$, we have

$$\begin{aligned} \mathrm{Sla}_{+(-)}(f, \mathbf{x}, I) &:= \left\{ v \in I \mid f'_{+(-)}(x_i) \cdot (v - x_i) \geq 0 \ \forall i \in \{1, \dots, n\} \right\}, \\ \mathrm{Sla}_{+(-)}(f, \mathbf{x}, \mathbf{p}, \mathbf{I}) &:= \left\{ v \in I \mid \sum_{i=1}^{n} p_i f'_{+(-)}(x_i) \cdot (v - x_i) \geq 0 \right\}, \end{aligned} \tag{3.4}$$

where $(p_1, \dots, p_n) \in \mathbb{P}^n$ is a probability distribution. These sets inherit the general properties pointed out in Lemma 2.1. Moreover, if we make the assumption that $\sum_{i=1}^{n} p_i f'_+(x_i) \neq 0$, then for $\sum_{i=1}^{n} p_i f'_+(x_i) > 0$ we have

$$\mathrm{Sla}_{+}(f, \mathbf{x}, \mathbf{p}, \mathbf{I}) = \left\{ v \in I \mid v \geq \frac{\sum_{i=1}^{n} p_i f'_+(x_i) x_i}{\sum_{i=1}^{n} p_i f'_+(x_i)} \right\}, \tag{3.5}$$

while for $\sum_{i=1}^{n} p_i f'_+(x_i) < 0$ we have

$$\mathrm{Sla}_{+}(f, \mathbf{x}, \mathbf{p}, \mathbf{I}) = \left\{ v \in I \mid v \leq \frac{\sum_{i=1}^{n} p_i f'_+(x_i) x_i}{\sum_{i=1}^{n} p_i f'_+(x_i)} \right\}. \tag{3.6}$$

Also, if we assume that $f'_+(x_i) \geq 0$ for all $i \in \{1, \dots, n\}$ and $\sum_{i=1}^{n} p_i f'_+(x_i) > 0$, then

$$v_s := \frac{\sum_{i=1}^{n} p_i f'_+(x_i) x_i}{\sum_{i=1}^{n} p_i f'_+(x_i)} \in I, \tag{3.7}$$

due to the fact that $x_i \in I$ and $I$ is a convex set.

**Proposition 3.2.** *Let $f : I \to \mathbb{R}$ be a convex function on an open interval $I$. For a given $n$-tuple of vectors $\mathbf{x} = (x_1, \ldots, x_n) \in I^n$ and $(p_1, \ldots, p_n) \in \mathbb{P}^n$ a probability distribution, one has*

$$f'_-(v)\left(v - \sum_{i=1}^{n} p_i x_i\right) \geq f(v) - \sum_{i=1}^{n} p_i f(x_i) \geq 0, \tag{3.8}$$

*for any $v \in \mathrm{Sla}_+(f, \mathbf{x}, \mathbf{p}, \mathbf{I})$.*

*In particular, if one assumes that $\sum_{i=1}^{n} p_i f'_+(x_i) \neq 0$ and*

$$\frac{\sum_{i=1}^{n} p_i f'_+(x_i) x_i}{\sum_{i=1}^{n} p_i f'_+(x_i)} \in I, \tag{3.9}$$

*then*

$$\begin{aligned} &f'_-\left(\frac{\sum_{i=1}^{n} p_i f'_+(x_i) x_i}{\sum_{i=1}^{n} p_i f'_+(x_i)}\right)\left[\frac{\sum_{i=1}^{n} p_i f'_+(x_i) x_i}{\sum_{i=1}^{n} p_i f'_+(x_i)} - \sum_{i=1}^{n} p_i x_i\right] \\ &\quad \geq f\left(\frac{\sum_{i=1}^{n} p_i f'_+(x_i) x_i}{\sum_{i=1}^{n} p_i f'_+(x_i)}\right) - \sum_{i=1}^{n} p_i f(x_i) \geq 0. \end{aligned} \tag{3.10}$$

*Moreover, if $f'_+(x_i) \geq 0$ for all $i \in \{1, \ldots, n\}$ and $\sum_{i=1}^{n} p_i f'_+(x_i) > 0$, then* (3.10) *holds true as well.*

*Remark 3.3. We remark that the first inequality in* (3.10) *provides a reverse inequality for the classical result due to Slater.*

## 4. Some Applications for $f$-Divergences

Given a convex function $f : [0, \infty) \to \mathbb{R}$, the *$f$-divergence functional*

$$I_f(\mathbf{p}, \mathbf{q}) := \sum_{i=1}^{n} q_i f\left(\frac{p_i}{q_i}\right), \tag{4.1}$$

where $\mathbf{p} = (p_1, \ldots, p_n)$, $\mathbf{q} = (q_1, \ldots, q_n)$ are positive sequences, was introduced by Csiszár in [9], as a generalized measure of information, a "distance function" on the set of probability distributions $\mathbb{P}^n$. As in [9], we interpret undefined expressions by

$$\begin{aligned} f(0) &= \lim_{t \to 0+} f(t), \qquad 0 f\left(\frac{0}{0}\right) = 0, \\ 0 f\left(\frac{a}{0}\right) &= \lim_{q \to 0+} q f\left(\frac{a}{q}\right) = a \lim_{t \to \infty} \frac{f(t)}{t}, \qquad a > 0. \end{aligned} \tag{4.2}$$

The following results were essentially given by Csiszár and Körner [10]:

(i) *if* $f$ *is convex, then* $I_f(\mathbf{p},\mathbf{q})$ *is jointly convex in* $\mathbf{p}$ *and* $\mathbf{q}$;

(ii) *for every* $\mathbf{p},\mathbf{q}\in\mathbb{R}_+^n$, *we have*

$$I_f(\mathbf{p},\mathbf{q}) \geq \sum_{j=1}^{n} q_j f\left(\frac{\sum_{j=1}^{n} p_j}{\sum_{j=1}^{n} q_j}\right). \tag{4.3}$$

*If* $f$ *is strictly convex, equality holds in* (4.3) *if and only if*

$$\frac{p_1}{q_1} = \frac{p_2}{q_2} = \cdots = \frac{p_n}{q_n}. \tag{4.4}$$

*If* $f$ *is normalized, that is,* $f(1)=0$, *then for every* $\mathbf{p},\mathbf{q}\in\mathbb{R}_+^n$ *with* $\sum_{i=1}^{n} p_i = \sum_{i=1}^{n} q_i$, *we have the inequality*

$$I_f(\mathbf{p},\mathbf{q}) \geq 0. \tag{4.5}$$

In particular, if $\mathbf{p},\mathbf{q}\in\mathbb{P}^n$, then (4.5) holds. This is the well-known positivity property of the $f$-divergence.

It is obvious that the above definition of $I_f(\mathbf{p},\mathbf{q})$ can be extended to any function $f:[0,\infty)\to\mathbb{R}$; however, the positivity condition will not generally hold for normalized functions and $\mathbf{p},\mathbf{q}\in\mathbb{R}_+^n$ *with* $\sum_{i=1}^{n} p_i = \sum_{i=1}^{n} q_i$.

For a normalized convex function $f:[0,\infty)\to\mathbb{R}$ and two probability distributions $\mathbf{p},\mathbf{q}\in\mathbb{P}^n$, we define the set

$$\operatorname{Sla}_+(f,\mathbf{p},\mathbf{q}) := \left\{ v\in[0,\infty) \mid \sum_{i=1}^{n} q_i f'_+\left(\frac{p_i}{q_i}\right)\cdot\left(v-\frac{p_i}{q_i}\right) \geq 0 \right\}. \tag{4.6}$$

Now, observe that

$$\sum_{i=1}^{n} q_i f'_+\left(\frac{p_i}{q_i}\right)\cdot\left(v-\frac{p_i}{q_i}\right) \geq 0, \tag{4.7}$$

is equivalent with

$$v\sum_{i=1}^{n} q_i f'_+\left(\frac{p_i}{q_i}\right) \geq \sum_{i=1}^{n} p_i f'_+\left(\frac{p_i}{q_i}\right). \tag{4.8}$$

If $\sum_{i=1}^{n} q_i f'_+(p_i/q_i) > 0$, then (4.8) is equivalent with

$$v \geq \frac{\sum_{i=1}^{n} p_i f'_+(p_i/q_i)}{\sum_{i=1}^{n} q_i f'_+(p_i/q_i)}, \tag{4.9}$$

therefore in this case

$$\mathrm{Sla}_+(f,\mathbf{p},\mathbf{q}) = \begin{cases} [0,\infty) & \text{if } \sum_{i=1}^{n} p_i f'_+(p_i/q_i) < 0, \\ \left[\dfrac{\sum_{i=1}^{n} p_i f'_+(p_i/q_i)}{\sum_{i=1}^{n} q_i f'_+(p_i/q_i)}, \infty\right) & \text{if } \sum_{i=1}^{n} p_i f'_+(p_i/q_i) \geq 0. \end{cases} \tag{4.10}$$

If $\sum_{i=1}^{n} q_i f'_+(p_i/q_i) < 0$, then (4.8) is equivalent with

$$v \leq \frac{\sum_{i=1}^{n} p_i f'_+(p_i/q_i)}{\sum_{i=1}^{n} q_i f'_+(p_i/q_i)}, \tag{4.11}$$

therefore

$$\mathrm{Sla}_+(f,\mathbf{p},\mathbf{q}) = \begin{cases} \left[0, \dfrac{\sum_{i=1}^{n} p_i f'_+(p_i/q_i)}{\sum_{i=1}^{n} q_i f'_+(p_i/q_i)}\right] & \text{if } \sum_{i=1}^{n} p_i f'_+\left(\dfrac{p_i}{q_i}\right) \leq 0, \\ \emptyset & \text{if } \sum_{i=1}^{n} p_i f'_+\left(\dfrac{p_i}{q_i}\right) > 0. \end{cases} \tag{4.12}$$

Utilising the extended $f$-divergences notation, we can state the following result.

**Theorem 4.1.** *Let $f : [0,\infty) \to \mathbb{R}$ be a normalized convex function and $\mathbf{p},\mathbf{q} \in \mathbb{P}^n$ two probability distributions. If $v \in \mathrm{Sla}_+(f,\mathbf{p},\mathbf{q})$, then one has*

$$f'_-(v)(v-1) \geq f(v) - I_f(\mathbf{p},\mathbf{q}) \geq 0. \tag{4.13}$$

*In particular, if one assumes that $I_{f'_+}(\mathbf{p},\mathbf{q}) \neq 0$ and*

$$\frac{I_{f'_+(\cdot)(\cdot)}(\mathbf{p},\mathbf{q})}{I_{f'_+}(\mathbf{p},\mathbf{q})} \in [0,\infty), \tag{4.14}$$

*then*

$$f'_-\left(\frac{I_{f'_+(\cdot)(\cdot)}(\mathbf{p},\mathbf{q})}{I_{f'_+}(\mathbf{p},\mathbf{q})}\right)\left[\frac{I_{f'_+(\cdot)(\cdot)}(\mathbf{p},\mathbf{q})}{I_{f'_+}(\mathbf{p},\mathbf{q})} - 1\right] \geq f\left(\frac{I_{f'_+(\cdot)(\cdot)}(\mathbf{p},\mathbf{q})}{I_{f'_+}(\mathbf{p},\mathbf{q})}\right) - I_f(\mathbf{p},\mathbf{q}) \geq 0. \tag{4.15}$$

*Moreover, if $f'_+(p_i/q_i) \geq 0$ for all $i \in \{1,\ldots,n\}$ and $I_{f'_+}(\mathbf{p},\mathbf{q}) > 0$, then* (4.15) *holds true as well.*

The proof follows immediately from Proposition 3.2 and the details are omitted.

The K. Pearson $\chi^2$-*divergence* is obtained for the convex function $f(t) = (1-t)^2$, $t \in \mathbb{R}$ and given by

$$\chi^2(\mathbf{p},\mathbf{q}) := \sum_{j=1}^{n} q_j \left(\frac{p_j}{q_j} - 1\right)^2 = \sum_{j=1}^{n} \frac{(p_j - q_j)^2}{q_j} = \sum_{j=1}^{n} \frac{p_i^2}{q_i} - 1. \tag{4.16}$$

The *Kullback-Leibler divergence* can be obtained for the convex function $f : (0,\infty) \to \mathbb{R}$, $f(t) = t\ln t$ and is defined by

$$\mathrm{KL}(\mathbf{p},\mathbf{q}) := \sum_{j=1}^{n} q_j \cdot \frac{p_j}{q_j} \ln\left(\frac{p_j}{q_j}\right) = \sum_{j=1}^{n} p_j \ln\left(\frac{p_j}{q_j}\right). \tag{4.17}$$

If we consider the convex function $f : (0,\infty) \to \mathbb{R}$, $f(t) = -\ln t$, then we observe that

$$I_f(\mathbf{p},\mathbf{q}) := \sum_{i=1}^{n} q_i f\left(\frac{p_i}{q_i}\right) = -\sum_{i=1}^{n} q_i \ln\left(\frac{p_i}{q_i}\right) = \sum_{i=1}^{n} q_i \ln\left(\frac{q_i}{p_i}\right) = \mathrm{KL}(\mathbf{q},\mathbf{p}). \tag{4.18}$$

For the function $f(t) = -\ln t$, we will obviously have that

$$\begin{aligned} \mathrm{Sla}(-\ln,\mathbf{p},\mathbf{q}) &:= \left\{ v \in [0,\infty) \mid -\sum_{i=1}^{n} q_i \left(\frac{p_i}{q_i}\right)^{-1} \cdot \left(v - \frac{p_i}{q_i}\right) \ge 0 \right\} \\ &= \left\{ v \in [0,\infty) \mid v \sum_{i=1}^{n} \frac{q_i^2}{p_i} - 1 \le 0 \right\} \\ &= \left[0, \frac{1}{\chi^2(\mathbf{q},\mathbf{p}) + 1}\right]. \end{aligned} \tag{4.19}$$

Utilising the first part of Theorem 4.1, we can state the following.

**Proposition 4.2.** *Let* $\mathbf{p},\mathbf{q} \in \mathbb{P}^n$ *be two probability distributions. If* $v \in [0, (1/(\chi^2(\mathbf{q},\mathbf{p}) + 1))]$, *then one has*

$$\frac{1-v}{v} \ge -\ln(v) - \mathrm{KL}(\mathbf{q},\mathbf{p}) \ge 0. \tag{4.20}$$

*In particular, for* $v = 1/(\chi^2(\mathbf{q},\mathbf{p}) + 1)$, *one gets*

$$\chi^2(\mathbf{q},\mathbf{p}) \ge \ln\left[\chi^2(\mathbf{q},\mathbf{p}) + 1\right] - \mathrm{KL}(\mathbf{q},\mathbf{p}) \ge 0. \tag{4.21}$$

If we consider now the function $f : (0,\infty) \to \mathbb{R}$, $f(t) = t\ln t$, then $f'(t) = \ln t + 1$ and

$$\begin{aligned}\operatorname{Sla}((\cdot)\ln(\cdot),\mathbf{p},\mathbf{q}) &:= \left\{ v \in [0,\infty) \mid \sum_{i=1}^{n} q_i\left(\ln\left(\frac{p_i}{q_i}\right)+1\right)\cdot\left(v-\frac{p_i}{q_i}\right) \geq 0 \right\} \\ &= \left\{ v \in [0,\infty) \mid v\sum_{i=1}^{n} q_i\left(\ln\left(\frac{p_i}{q_i}\right)+1\right) - \sum_{i=1}^{n} p_i\cdot\left(\ln\left(\frac{p_i}{q_i}\right)+1\right) \geq 0 \right\} \\ &= \{ v \in [0,\infty) \mid v(1-\operatorname{KL}(\mathbf{q},\mathbf{p})) \geq 1+\operatorname{KL}(\mathbf{p},\mathbf{q}) \}.\end{aligned} \tag{4.22}$$

We observe that if $\mathbf{p},\mathbf{q} \in \mathbb{P}^n$ are two probability distributions such that $0 < \operatorname{KL}(\mathbf{q},\mathbf{p}) < 1$, then

$$\operatorname{Sla}((\cdot)\ln(\cdot),\mathbf{p},\mathbf{q}) = \left[\frac{1+\operatorname{KL}(\mathbf{p},\mathbf{q})}{1-\operatorname{KL}(\mathbf{q},\mathbf{p})},\infty\right). \tag{4.23}$$

If $\operatorname{KL}(\mathbf{q},\mathbf{p}) \geq 1$, then $\operatorname{Sla}((\cdot)\ln(\cdot),\mathbf{p},\mathbf{q}) = \emptyset$.

By the use of Theorem 4.1, we can state now the following.

**Proposition 4.3.** *Let* $\mathbf{p},\mathbf{q} \in \mathbb{P}^n$ *be two probability distributions such that* $0 < \operatorname{KL}(\mathbf{q},\mathbf{p}) < 1$. *If* $v \in [(1+\operatorname{KL}(\mathbf{p},\mathbf{q}))/(1-\operatorname{KL}(\mathbf{q},\mathbf{p})),\infty)$, *then one has*

$$(\ln v + 1)(v-1) \geq v\ln(v) - \operatorname{KL}(\mathbf{p},\mathbf{q}) \geq 0. \tag{4.24}$$

*In particular, for* $v = (1+\operatorname{KL}(\mathbf{p},\mathbf{q}))/(1-\operatorname{KL}(\mathbf{q},\mathbf{p}))$, *one gets*

$$\begin{aligned}&\left(\ln\left[\frac{1+\operatorname{KL}(\mathbf{p},\mathbf{q})}{1-\operatorname{KL}(\mathbf{q},\mathbf{p})}\right]+1\right)\left(\frac{1+\operatorname{KL}(\mathbf{p},\mathbf{q})}{1-\operatorname{KL}(\mathbf{q},\mathbf{p})}-1\right) \\ &\quad\geq \frac{1+\operatorname{KL}(\mathbf{p},\mathbf{q})}{1-\operatorname{KL}(\mathbf{q},\mathbf{p})}\ln\left[\frac{1+\operatorname{KL}(\mathbf{p},\mathbf{q})}{1-\operatorname{KL}(\mathbf{q},\mathbf{p})}\right] - \operatorname{KL}(\mathbf{p},\mathbf{q}) \geq 0.\end{aligned} \tag{4.25}$$

Similar results can be obtained for other divergence measures of interest such as the *Jeffreys divergence and Hellinger discrimination.* However, the details are left to the interested reader.

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