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Limited operators and differentiability.

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Abstract. We characterize the limited operators by differentiability of convex continuous functions. Given Banach spaces $Y$ and $X$ and a linear continuous operator $T : Y \rightarrow X$, we prove that $T$ is a limited operator if and only if, for every convex continuous function $f : X \rightarrow \mathbb{R}$ and every point $y \in Y$, $f \circ T$ is Fréchet differentiable at $y \in Y$ whenever $f$ is Gâteaux differentiable at $T(y) \in X$.

Keyword, phrase: Limited operators, Gâteaux differentiability, Fréchet differentiability, convex functions, extreme points.

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1 Introduction.

A subset $A$ of a Banach space $X$ is called limited, if every weak* null sequence $(p_n)_n$ in $X^*$ converges uniformly on $A$, that is, $\lim_{n \to +\infty} \sup_{x \in A} |\langle p_n, x \rangle| = 0$.

We know that every relatively compact subset of $X$ is limited, but the converse is false in general. A bounded linear operator $T : Y \rightarrow X$ between Banach spaces $Y$ and $X$ is called limited, if $T$ takes the closed unit ball $B_Y$ of $Y$ to a limited subset of $X$. It is easy to see that $T : Y \rightarrow X$ is limited if and only if, the adjoint operator $T^* : X^* \rightarrow Y^*$ takes weak* null sequence to norm null sequence. For useful properties of limited sets and limited operators we refer to [11], [4], [6] and [1].

We know that in a finite dimensional Banach space, the notions of Gâteaux and Fréchet differentiability coincide for convex continuous functions. In [5], Borwein and Fabian proved that a Banach space $Y$ is infinite dimensional if and only if, there exists on $Y$ functions $f$ having points at which $f$ is Gâteaux but not Fréchet differentiable. They also pointed in the introduction of [5] the observation that if the sup-norm $\| \cdot \|_\infty$ on $c_0$ is Gâteaux differentiable at some point, then it is Fréchet differentiable there. In this article we observe that this phenomenon is not just related to the sup-norm but more generally, for each convex lower semicontinuous function $g : l^\infty \rightarrow \mathbb{R} \cup \{+\infty\}$, if $g$ is Gâteaux differentiable at some point $a \in c_0$ which is in the interior of its domain, then the restriction of $g$ to $c_0$ is Fréchet differentiable at $a$. This hold in particular when $g = (f^*)^*$ is the Fenchel biconjugate of a convex continuous function $f : c_0 \rightarrow \mathbb{R}$. In fact, this phenomenon is due, (see Corollary 1 in the Appendix and the comment just before), to the fact that the canonical embedding $i : c_0 \rightarrow l^\infty$ is a limited operator (see the reference [6]).
The goal of this paper is to prove the following characterization of limited operators in terms of the coincidence of Gâteaux and Fréchet differentiability of convex continuous functions.

**Theorem 1.** Let \( Y \) and \( X \) be two Banach spaces and \( T : Y \to X \) be a continuous linear operator. Then, \( T \) is a limited operator if and only if, for every convex continuous function \( f : X \to \mathbb{R} \) and every \( y \in Y \), the function \( f \circ T \) is Fréchet differentiable at \( y \in Y \) whenever \( f \) is Gâteaux differentiable at \( T(y) \in X \).

As consequence we give, in Theorem 2 below, new characterizations of infinite dimensional Banach spaces, complementing a result of Borwein and Fabian in [[5], Theorem 1.].

A real valued function \( f \) on a Banach space will be called a PGNF-function (see [5]) if there exists a point at which \( f \) is Gâteaux but not Fréchet differentiable. A JN-sequence (due to Josefson-Nissenzweig theorem, see [[7], Chapter XII]) is a sequence \( (p_n) \) in a dual space \( Y^* \) that is weak* null and \( \inf_n \|p_n\| > 0 \). We say that a function \( g \) on \( X^* \) has a norm-strong minimum (resp. weak*-strong minimum) at \( p \in X^* \) if \( g(p) = \inf_{q \in X^*} g(q) \) and \( (p_n) \) norm converges (resp. weak* converges) to \( p \) whenever \( g(p_n) \to g(p) \). A norm-strong minimum and weak*-strong minimum are in particular unique.

**Theorem 2.** Let \( Y \) be a Banach space. Then the following assertions are equivalent.

1. \( Y \) is infinite dimensional.
2. There exists a JN-sequence in \( Y^* \).
3. There exists a convex norm separable and weak* compact metrizable subset \( K \) of \( Y^* \) containing 0 and a continuous seminorm \( h \) on \( X^* \) which is weak* lower semicontinuous and weak* sequentially continuous, such that the restriction \( h|_K \) has a weak* strong minimum but not norm-strong minimum at 0.
4. There exists a Banach space \( X \) and a linear continuous non-limited operator \( T : Y \to X \).
5. There exists on \( Y \) a convex continuous PGNF-function.

In Section 2 we give some preliminary results, specially the key Lemma 2. In Section 3, we give the proof of Theorem 1 (divided into two part, Theorem 3 and Theorem 4) and the proof of Theorem 2. In Section 4 we give some complementary remarks.

## 2 Preliminaries.

We recall the following classical result.

**Lemma 1.** Let \( T_1 \) and \( T_2 \) be topologies on a set \( K \) such that

1. \( K \) is Hausdorff with respect \( T_1 \),
2. \( K \) is compact with respect to \( T_2 \),
3. \( T_1 \subset T_2 \),

Then \( T_1 = T_2 \).

**Proof.** Let \( F \subset K \) be a \( T_2 \)-closed set. It follows that \( F \) is \( T_2 \)-compact, since \( K \) is \( T_2 \)-compact. Let \( \{O_i : i \in I \} \) be any cover of \( F \) by \( T_1 \)-open sets. Since \( T_1 \subset T_2 \), then each of these sets is also \( T_2 \)-open. Hence, there exist a finite subcollection that covers \( F \). It follows that \( F \) is \( T_1 \)-compact and therefore is \( T_1 \)-closed since \( T_1 \) is Hausdorff. This implies that \( T_2 \subset T_1 \). Consequently, \( T_1 = T_2 \). 

Now, we establish the following useful lemma. If \( B \) is a subset of a dual Banach space \( X^* \), we denote by \( \overline{co}^{w^\ast}(B) \) the weak* closed convex hull of \( B \).
Lemma 2. Let $X$ be a Banach space and $K$ be a subset of $X^*$.

(1) Suppose that $K$ is norm separable, then there exists a sequence $(x_n)_n$ in the unit sphere $S_X$ of $X$ which separate the points of $K$ i.e. for all $p, p' \in K$, if $(p, x_n) = (p, x_n)$ for all $n \in \mathbb{N}$, then $p = p'$. Consequently, if $K$ is a weak* compact and norm separable set of $X^*$, then the weak* topology of $X^*$ restricted to $K$ is metrizable.

(2) Let $(p_n)_n$ be a weak* null sequence in $X^*$. Then, the set $\overline{co}^w \{p_n : n \in \mathbb{N}\}$ is convex weak* compact and norm separable.

Proof. (1) Since $K$ is norm separable, then $K \cap K := \{a - b/ (a, b) \in K \times K\}$ is also norm separable and so there exists a sequence $(q_n)_n$ of $K - K$ which is dense in $K - K$. According to the Bishop-Phelps theorem [3], the set

$$D = \{r \in X^* \mid r \text{ attains its supremum on the sphere } S_X\}$$

is norm-dense in the dual $X^*$. Thus, for each $n \in \mathbb{N}$, there exists $r_n \in D$ such that $\|q_n - r_n\| < \frac{1}{1 + n_k}$. For each $n \in \mathbb{N}$, let $x_n \in S_X$ be such that $\|r_n\| = \langle r_n, x_n \rangle$. We claim that the sequence $(x_n)_n$ separates the points of $K$. Indeed, let $q \in K - K$ and suppose that $\langle q, x_n \rangle = 0$, for all $n \in \mathbb{N}$. There exists a subsequence $(q_{n_k})_k \subset K - K$ such that $\langle q_{n_k} - q \rangle < \frac{1}{k}$ for all $k \in \mathbb{N}^*$ and so we have $\|r_{n_k} - q\| < \frac{1}{1 + n_k} + \frac{1}{k}$. It follows that

$$\|r_{n_k}\| = \langle r_{n_k}, x_{n_k} \rangle = \langle r_{n_k}, x_{n_k} \rangle - \langle q, x_{n_k} \rangle \leq \|r_{n_k} - q\| < \frac{1}{1 + n_k} + \frac{1}{k}.$$

Hence, for all $k \in \mathbb{N}^*$, $\|q\| \leq \|q - r_{n_k}\| + \|r_{n_k}\| < 2(\frac{1}{1 + n_k} + \frac{1}{k})$, which implies that $q = 0$, and so that $(x_n)_n$ separate the points of $K$. Now, suppose that $K$ is weak* compact subset of $X^*$. We show that the weak* topology of $X^*$ restricted to $K$ is metrizable. Indeed, each $x \in X$ determines a seminorm $\nu_x$ on $X^*$ given by

$$\nu_x(p) = \langle p, x \rangle, \quad p \in X^*.$$

The family of seminorms $(\nu_x)_{x \in X}$ induces the weak* topology $\sigma(X^*, X)$ on $X^*$. The subfamily $(\nu_{x_n})_n$ also induces a topology on $X^*$, which we will call $\mathcal{T}$. Since this is a smaller family of seminorms, we have $\mathcal{T} \subseteq \sigma(X^*, X)$. Suppose that $p, p' \in K$ and $\nu_{x_n}(p - p') = 0$ for all $n \in \mathbb{N}$. Then we have $\langle p, x_n \rangle = \langle p', x_n \rangle$ for all $n \in \mathbb{N}$ and so we have that $p = p'$ since $(x_n)_n$ separates the points of $K$. Consequently, $K$ is Hausdorff with respect to the topology $\mathcal{T}_K$ (the restriction of $\mathcal{T}$ to $K$). Thus $\mathcal{T}_K$ is a Hausdorff topology on $K$ induced from a countable family of seminorms, so this topology is metrizable. More precisely, $\mathcal{T}_K$ is induced from the metric

$$d(p, p') := \sum_{n=0}^{+\infty} 2^{-n} \frac{\nu_{x_n}(p - p')}{1 + \nu_{x_n}(p - p')}.$$

Then we have that $K$ is Hausdorff with respect to $\mathcal{T}_K$, and is compact with respect to $\sigma(X^*, X)_{|K}$. Lemma 1 implies that $\mathcal{T}_K = \sigma(X^*, X)_{|K}$. Hence $\sigma(X^*, X)_{|K}$ is metrizable.

(2) Let $(p_n)_n$ be a weak* null sequence in $X^*$ and set $K = \overline{co}^w \{p_n : n \in \mathbb{N}\}$. Clearly $K$ is a convex and weak* compact subset of $X^*$. According to Haydon’s theorem [8, Theorem 3.3] the weak* compact convex set $K$ is the norm closed convex hull of its extreme points whenever $ex(K)$ (the set of extreme points of $K$) is norm separable. By the Milman theorem [10], p.9 $ex(K) \subset \overline{co}^w \{p_n : n \in \mathbb{N}\} = \{p_n : n \in \mathbb{N}\} \cup \{0\}$ so that $ex(K)$ is norm separable and, hence, by Haydon’s theorem, $K$ itself is weak* compact, convex, and norm separable.

The following proposition will be used in the proof of Theorem 3.
Proposition 1. Let $X$ be a Banach space and $K$ be a weak* compact and norm separable subset of $X^*$ containing 0. Then, there exists a continuous seminorm $h$ on $X^*$ satisfying

1. $h$ is weak* lower semicontinuous and sequentially weak* continuous,
2. the restriction $h|_K$ of $h$ to $K$ has a weak* -strong minimum at 0.

Proof. Using Lemma 2, there exists a sequence $(x_k)_k \subset S_X$ which separate the points of $K$. Define the function $h : X^* \to \mathbb{R}$ as follows:

$$h(x^*) = \left( \sum_{k \geq 0} 2^{-k} \langle x^*, x_k \rangle^2 \right)^{\frac{1}{2}}, \quad \forall x^* \in X^*.$$ 

It is clear that $h$ is a seminorm, and since $h(x^*) \leq \|x^*\|$ for all $x^* \in X^*$, it is also continuous. Since $h$ is the supremum of a sequence of weak* continuous functions, it is weak* lower semicontinuous. On the other hand, since the series $\sum_{k \geq 0} 2^{-k} \langle x^*, x_k \rangle^2$ uniformly converges on bounded sets of $X^*$ and since the maps $x^* \mapsto \langle x^*, x_k \rangle$ are weak* continuous for all $k \in \mathbb{N}$, then $h$ is sequentially weak* continuous. If $p \in K$ and $h(p) = 0$, then $\langle p, x_k \rangle = 0$ for all $k \in \mathbb{N}$ which implies that $p = 0$, since the sequence $(x_k)_k$ separate the points of $K$. Hence, the restriction of $h$ to $K$ has a unique minimum at 0. This minimum is necessarily a weak* -strong minimum since $K$ is weak* metrizable by Lemma 2, this follows from a general fact which say that for every lower semicontinuous function on a compact metric space $(K, d)$, a unique minimum is necessarily a strong minimum for the metric $d$ in question. \qed

3 Limited operators and differentiability.

Recall that the domain of a function $f : X \to \mathbb{R} \cup \{+\infty\}$, is the set

$$\text{dom}(f) := \{x \in X / f(x) < +\infty\}.$$ 

For a function $f$ with $\text{dom}(f) \neq \emptyset$, the Fenchel transform of $f$ is defined on the dual space for all $p \in X^*$ by

$$f^*(p) := \sup_{x \in X} \{ \langle p, x \rangle - f(x) \}.$$ 

The second transform $(f^*)^*$ is defined on the bidual $X^{**}$ by the same formula. We denote by $f^{**}$, the restriction of $(f^*)^*$ to $X$, where $X$ is identified to a subspace of $X^{**}$ by the canonical embedding. Recall that the Fenchel theorem state that $f = f^{**}$ if and only if $f$ is convex lower semicontinuous on $X$.

The "if" part of Theorem 1 is given by the following theorem.

Theorem 3. Let $Y$ and $X$ be Banach spaces and let $T : Y \to X$ be a linear continuous operator. Suppose that $f \circ T$ is Fréchet differentiable at $y \in Y$ whenever $f : X \to \mathbb{R}$ is convex continuous and Gâteaux differentiable at $T(y) \in Y$. Then $T$ is a limited operator.

Proof. Let $(p_n)_n$ be a weak* null sequence in $X^*$. We want to prove that $\| T^*(p_n) \|_{Y^*} \to 0$. Set

$$K = \overline{\text{co}}^w \{ p_n : n \in \mathbb{N} \}.$$ 

According to Lemma 2, $K$ is convex weak* compact and norm separable. Using Proposition 1, there exists a continuous seminorm which is weak* lower semicontinuous and sequentially weak* continuous $h : X^* \to \mathbb{R}$ such that the restriction $h|_K$ of $h$ to $K$ has a weak* -strong minimum at 0 and in particular $\min_K h = h(0) = 0$. Since the sequence $(p_n)_n$ weak* converges to 0, it follows that $\lim_n h(p_n) = h(0) = \min_K h$. Thus, $(p_n)_n$ is a minimizing sequence for $h|_K$. Set $g = h + \delta_K$, where $\delta_K$ denotes the indicator function, which is equal to 0 on $K$ and equal to $+\infty$ otherwise. Since $K$ is convex, weak* -closed and norm bounded, then $g$ is a convex and
Proof. It is well known that there exists a convex -Lipschitz continuous function on with a norm bounded domain \( \text{dom}(g) = K \). Moreover we have,

1. \( g(p) > 0 = g(0) = \min_{X^*}(g) \) for all \( p \in X^* \setminus \{0\} \).
2. \( \lim_{n \to +\infty} g(p_n) = \min_{X^*}(g) \).

Hence, there exists a convex and Lipschitz continuous function \( f : X \to \mathbb{R} \) such that \( g = f^* \) (we can take \( f = g|_{X^*}^\circ \)). The function \( f \) is Gâteaux differentiable at 0 with Gâteaux derivative \( \nabla f(0) = 0 \), this is due to the fact that \( f^* = g \) has a weak*-strong minimum at 0 (we can see [Corollary 1. [2]]). Thus, from our hypothesis, \( f \circ T \) is Fréchet differentiable at 0 with Fréchet derivative equal to 0. It follows that \( (f \circ T)^* \) has a norm-strong minimum at 0 (see [Corollary 2. [2]]). Now, we prove that \( (T^*(p_n))_n \) is a minimizing sequence for \( (f \circ T)^* \), which will implies that \( \|T^*(p_n)\|_{Y^*} \to 0 \). Indeed, on one hand, we have \( 0 = \min_{X^*}(g) = -g^*(0) = -f(0) \). On the other hand we have

\[
0 = -f(0) \leq \sup_{y \in Y} \{-f \circ T(y)\} = (f \circ T)^*(0) \leq \sup_{x \in X} \{-f(x)\} = f^*(0) = g(0) = 0.
\]

It follows that \( (f \circ T)^*(0) = 0 \). Hence, since \((f \circ T)^* \) has a minimum at 0, we obtain

\[
0 = (f \circ T)^*(0) \leq (f \circ T)^*(T^*(p_n)) = \sup_{y \in Y} \{\langle T^*(p_n), y \rangle - f \circ T(y)\} = \sup_{y \in Y} \{\langle p_n, T(y) \rangle - f(T(y))\} \leq \sup_{x \in X} \{\langle p_n, x \rangle - f(x)\} = f^*(p_n) = g(p_n).
\]

Since, \( g(p_n) \to 0 \), it follows that \( (f \circ T)^*(T^*(p_n)) \to 0 = (f \circ T)^*(0) \). In other words, \((T^*(p_n))_n \) is a minimizing sequence for \((f \circ T)^* \). Since \((f \circ T)^* \) has a norm-strong minimum at 0, we obtain that \( \|T^*(p_n)\|_{Y^*} \to 0 \), which implies that \( T \) is a limited operator.

The "only if" part of Theorem 1 is given by the following theorem.

**Theorem 4.** Let \( Y \) and \( X \) be two Banach spaces and \( T : Y \to X \) be a limited operator. Let \( f : X \to \mathbb{R} \cup \{+\infty\} \) be a convex lower semicontinuous function and let \( a \in Y \) such that \( T(a) \) belongs to the interior of \( \text{dom}(f) \). Then, \( f \circ T \) is Fréchet differentiable at \( a \in Y \) with Fréchet-derivative \( T^*(Q) \in Y^* \), whenever \( f \) is Gâteaux differentiable at \( T(a) \in X \) with Gâteaux-derivative \( Q \in X^* \).

**Proof.** Since \( f \) is convex lower semicontinuous and \( T(a) \) is in the interior of \( \text{dom}(f) \), there exists \( r_a > 0 \) and \( L_a > 0 \) such that \( f \) is \( L_a \)-Lipschitz continuous on the closed ball \( B_X(T(a), r_a) \). It is well known that there exists a convex \( L_a \)-Lipschitz continuous function \( \tilde{f}_a \) on \( X \) such that \( f_a = f \) on \( B_X(T(a), r_a) \) (See for instance Lemma 2.31 [9]). It follows that \( f_a \circ T = f \circ T \) on \( B_Y(a, \frac{r_a}{L_a}) \), since \( T(B_X(a, \frac{r_a}{L_a})) \) is a subset of \( B_X(T(a), r_a) \) (we can assume that \( T \neq 0 \)). Replacing \( f \) by \( \frac{1}{L_a} f_a \), we can assume without loss of generality that \( f \) is convexe 1-Lipschitz continuous on \( X \). It follows that \( \text{dom}(f^*) \subset B_X \). (the closed unit ball of \( X^* \)).
Claim. Suppose that \( f \) is Gâteaux differentiable at \( T(a) \in X \) with Gâteaux-derivative \( Q \in X^* \), then the function \( q \mapsto f^*(q) - \langle q, T(a) \rangle \) has a weak*-strong minimum on \( B_{X^*} \) at \( Q \).

Proof of the claim. See [Corollary 1. [2]].

Now, suppose by contradiction that \( T^*(Q) \) is not the the Fréchet derivative of \( f \circ T \) at \( a \). There exist \( \varepsilon > 0 \), \( t_n \to 0^+ \) and \( h_n \in Y, \|h_n\|_Y = 1 \) such that for all \( n \in \mathbb{N}^* \),

\[
f \circ T(a + t_n h_n) - f \circ T(a) - (T^*(Q), t_n h_n) > \varepsilon t_n.
\]

Let \( r_n = t_n/n \) for all \( n \in \mathbb{N}^* \) and choose \( p_n \in B_{X^*} \) such that

\[
f^*(p_n) - \langle p_n, T(a + t_n h_n) \rangle < \inf_{p \in B_{X^*}} \{ f^*(p) - \langle p, T(a + t_n h_n) \rangle \} + r_n.
\]

From (2) we get

\[
f^*(p_n) - \langle p_n, T(a) \rangle < \inf_{p \in B_{X^*}} \{ f^*(p) - \langle p, T(a) \rangle \} + 2t_n\|T\| + r_n.
\]

This implies that the sequence \( (p_n)_n \) minimize the function \( q \mapsto f^*(q) - \langle q, T(a) \rangle \) on \( B_{X^*} \). Using the claim, the function \( q \mapsto f^*(q) - \langle q, T(a) \rangle \) has a weak*-strong minimum on \( B_{X^*} \) at \( Q \), it follows that \( (p_n)_n \) weak* converges to \( Q \) and so (since \( T \) is limited) we have

\[
\|T^*(p_n - Q)\|_{Y^*} \to 0.
\]

On the other hand, since \( f(T(a + t_n h_n)) = f^**(T(a + t_n h_n)) = -\inf_{p \in B_{X^*}} \{ f^*(p) - \langle p, T(a + t_n h_n) \rangle \} \), using (2) we obtain for all \( y \in Y \)

\[
f \circ T(a + t_n h_n) - \langle p_n, T(a + t_n h_n) \rangle < -f^*(p_n) + r_n \leq f \circ T(y) - \langle p_n, T(y) \rangle + r_n.
\]

Replacing \( y \) by \( a \) in the above inequality we obtain

\[
f \circ T(a + t_n h_n) - \langle p_n, T(t_n h_n) \rangle \leq f \circ T(a) + r_n.
\]

Combining (1) and (4) we get

\[
\varepsilon < \langle p_n, T(h_n) \rangle - \langle T^*(Q), h_n \rangle + r_n/t_n
\]

\[
= \langle T^*(p_n), h_n \rangle - \langle T^*(Q), h_n \rangle + \frac{1}{n}
\]

\[
\leq \|T^*(p_n - Q)\|_{Y^*} + \frac{1}{n}
\]

which is a contradiction with (3). Thus \( f \circ T \) is Fréchet differentiable at \( a \) with Fréchet derivative \( T^*(Q) \).

Now, we give the proof of Theorem 2.

Proof of Theorem 2. (1) \( \implies \) (2) is the deeper Josefson-Nissenzweig theorem [[7], Chapter XII].

(2) \( \implies \) (1) is well known.

(2) \( \implies \) (3) Let \( (p_n)_n \) be a weak* null sequence in \( Y^* \) such that \( \inf_n \|p_n\| > 0 \) and set \( K = \overline{co}^{\ast*} \{ p_n : n \in \mathbb{N} \} \). By Lemma 2, the set \( K \) is convex norm separable and weak* compact.
metrizable. On the other hand, from Proposition 1, there exists a continuous seminorm \( h \) which is weak* lower semicontinuous and weak* sequentially continuous on \( Y^* \) such that the restriction of \( h \) to \( K \) has a weak*-strong minimum at 0. It remains to show that 0 is not a norm-strong minimum for \( h|_K \). Indeed, since \( (p_n)_n \) is weak* null and \( h \) is weak* sequentially continuous, then \( \lim_n h(p_n) = h(0) = \min_K h \). So \( (p_n)_n \) is a minimizing sequence for \( h|_K \) which does not converge to 0 since \( \inf_n \| p_n \| > 0 \). Hence, 0 is not a norm-strong minimum for \( h|_K \).

(3) \implies (2) Since 0 is not a norm-strong minimum for the restriction \( h|_K \), there exists a sequence \( (p_n)_n \) that minimize \( h \) on \( K \) and \( \| p_n \| \to 0 \). Since \( h|_K \) has a weak*-strong minimum at 0, it follows that \( (p_n)_n \) weak* converges to 0. Hence, \( (p_n)_n \) weak* converges to 0 but \( \| p_n \| \to 0 \). Thus, there exists a JN-sequence in \( Y^* \).

(2) \implies (4) This part is given by taking \( X = Y \) and \( T = I \) the identity map. Indeed, there exists a sequence \( (p_n)_n \) which weak* converges to 0 but \( \inf_n \| I(p_n) \| = \inf_n \| p_n \| > 0 \). So I cannot be a limited operator.

(4) \implies (5). Indeed, if there exists a Banach space \( X \) and a non-limited operator \( T : Y \to X \), by using Theorem 1, there exists a convex continuous function \( f : X \to \mathbb{R} \) and a point \( y \in Y \) such that \( f \) is Gâteaux differentiable at \( T(y) \in X \) but \( f \circ T \) is not Fréchet differentiable at \( y \). So \( f \circ T \) is Gâteaux but not Fréchet differentiable at \( y \). Hence, \( f \circ T \) is a convex continuous PGNF-function on \( Y \).

(5) \implies (2) Let \( f \) be a PGNF-function on \( Y \). We can assume without loss of generality that \( f \) is Gâteaux differentiable at 0 with Gâteaux-derivative equal to 0, but \( f \) is not Fréchet differentiable at 0. It follows from classical duality result (see Corollary 1. and Corollary 2. in [2]) that \( f^* \) has a weak*-strong minimum but not norm-strong minimum at 0. Since 0 is not a norm-strong minimum for \( f^* \), there exists a sequence \( (p_n)_n \subset X^* \) minimizing \( f^* \) such that \( \| p_n \| \to 0 \). On the other hand, since \( f^* \) has a weak*-strong minimum at 0, and \( (p_n)_n \) minimize \( f^* \), we have that \( (p_n)_n \) weak* converges to 0. Thus, \( (p_n)_n \) weak* converges to 0 but \( \| p_n \| \to 0 \). Hence, there exists a JN-sequence.

Canonical construction of PGNF-function. There exist different way to build a PGNF-function in infinite dimensional Banach spaces. We can find examples of such constructions in [5]. We present below a different method for constructing a PGNF-function on a Banach space \( X \) canonically from a JN-sequence. Given a JN-sequence \( (p_n)_n \subset X^* \), we set \( K = \overline{\operatorname{co}}(\{p_n : n \in \mathbb{N}\}) \). Using Lemma 2, there exists a sequence \( (x_n)_n \subset S_X \) which separates the points of \( K \), and as in the proof of Proposition 1, there exist a continuous seminorm \( h \) which is weak* lower semicontinuous and weak* sequentially continuous such that \( h|_K \) has a weak*-strong minimum at 0. The function \( h \) is given explicitly as follows

\[
h(x^*) = (\sum_{n \geq 0} 2^{-n} (\langle x^*, x_n \rangle)^2)^{\frac{1}{2}}, \quad \forall x^* \in X^*.
\]

Since \( (p_n)_n \) weak* converges to 0, it follows that \( (p_n) \) is a minimizing sequence for \( h|_K \). Since \( (p_n)_n \) is a JN-sequence, it follows that 0 is not a norm-strong minimum for \( h|_K \). Define the function \( f \) by

\[
f(x) = (h + \delta_K)^*(\hat{x}), \quad \forall x \in X,
\]

where \( \delta_K \) denotes the indicator function, which is equal to 0 on \( K \) and equal to +\( \infty \) otherwise and where for each \( x \in X \), we denote by \( \hat{x} \in X^* \) the linear map \( x^* \mapsto (x^*, x) \) for all \( x^* \in X^* \). Then \( f \) is convex Lipschitz continuous, Gâteaux differentiable at 0 (since \( h + \delta_K \) has a weak*-strong minimum) but not Fréchet differentiable at 0 (because 0 is not a norm-strong minimum for \( h + \delta_K \)).

4 Appendix.

There exists a class of Banach spaces \((E, \| \cdot \|_E)\) such that the canonical embedding \( i : E \to E^{**} \) is a limited operator. This class contains in particular the space \( c_0 \) and any closed subspace
$F$ of $c_0$ (This class is also stable by product and quotient. For more information see [6]). In this setting, Theorem 4 gives immediately the following corollary.

**Corollary 1.** Suppose that the canonical embedding $i : E \rightarrow E^{**}$ is a limited operator. Let $g : E^{**} \rightarrow \mathbb{R} \cup \{+\infty\}$ be a convex lower semicontinuous function. Suppose that $x \in E$ belongs to the interior of $\text{dom}(g)$ and that $g$ is Gâteaux differentiable at $x \in E$ (we use the identification $i(x) = x$), then the restriction of $g$ to $E$ is Fréchet differentiable at $x$. In particular, if $f : E \rightarrow \mathbb{R} \cup \{+\infty\}$ is convex lower semicontinuous function, $x \in E$ belongs to the interior of $\text{dom}((f^*)^*)$ and $(f^*)^*$ is Gâteaux differentiable at $x$, then $f$ is Fréchet differentiable at $x$.

We obtain the following corollary by combining Proposition 2 and a delicate result due to Zajíček (see [Theorem 2; [12]]), which say that in a separable Banach space, the set of the points where a convex continuous function is not Gâteaux differentiable, can be covered by countably many $d.c$ (that is, delta-convex) hypersurface. Recall that in a separable Banach space $Y$, each set $A$ which can be covered by countably many $d.c$ hypersurface is $\sigma$-lower porous, also $\sigma$-directionally porous; in particular it is both Aronszajn (equivalent to Gauss) null and $\Gamma$-null. For details about this notions of small sets we refer to [13] and references therein. Note that a limited set in a separable Banach space is relatively compact [4].

**Proposition 2.** Let $Y$ and $X$ be Banach spaces and $T : Y \rightarrow X$ be a limited operator with a dense range. Let $f : X \rightarrow \mathbb{R}$ be a convex continuous function. Then $f \circ T$ is Gâteaux differentiable at $a \in Y$ if and only if, $f \circ T$ is Fréchet differentiable at $a \in Y$.

**Proof.** Suppose that $f \circ T$ is Gâteaux differentiable at $a \in Y$. It follows that $f$ is Gâteaux differentiable at $T(a)$ with respect to the direction $T(Y)$ which is dense in $X$. It follows (from a classical fact on locally Lipschitz continuous functions) that $f$ is Gâteaux differentiable at $T(a)$ on $X$. So by Theorem 4, $f \circ T$ is Fréchet differentiable at $a \in Y$. The converse is always true. \qed

**Corollary 2.** Let $Y$ be a separable Banach space, $X$ be a Banach spaces and $T : Y \rightarrow X$ be a compact operator with a dense range. Let $f : X \rightarrow \mathbb{R}$, be a convex and continuous function. Then, the set of all points at which $f \circ T$ is not Fréchet differentiable can be covered by countably many $d.c$ hypersurface.

**References**


