LIPSCHITZ BEHAVIOR OF THE ROBUST REGULARIZATION

ADRIAN S. LEWIS AND C.H. JEFFREY PANG

Abstract. To minimize or upper-bound the value of a function “robustly”, we might instead minimize or upper-bound the “$\epsilon$-robust regularization”, defined as the map from a point to the maximum value of the function within an $\epsilon$-radius. This regularization may be easy to compute: convex quadratics lead to semidefinite-representable regularizations, for example, and the spectral radius of a matrix leads to pseudospectral computations. For favorable classes of functions, we show that the robust regularization is Lipschitz around any given point, for all small $\epsilon > 0$, even if the original function is nonlipschitz (like the spectral radius). One such favorable class consists of the semi-algebraic functions. Such functions have graphs that are finite unions of sets defined by finitely-many polynomial inequalities, and are commonly encountered in applications.

Contents

1. Introduction 2
2. Calmness as an extension to Lipschitzness 4
3. Calmness and robust regularization 7
4. Robust regularization in general 9
5. Semi-algebraic robust regularization 13
6. Quadratic examples 21
7. 1-peaceful sets 22
8. Nearly radial sets 27
References 31

Key words: robust optimization, nonsmooth analysis, locally Lipschitz, regularization, semi-algebraic, pseudospectrum, robust control, semidefinite-representable, prox-regularity.


Date: 30th September 2008.
1. Introduction

In the implementation of the optimal solution of an optimization model, one is not only concerned with the minimizer of the optimization model, but how numerical errors and perturbations in the problem description and implementation can affect the solution. We might therefore try to solve an optimization model in a robust manner. The issues of robust optimization, particularly in the case of linear and quadratic programming, are documented in [1].

A formal way to address robustness is to consider the “robust regularization” [15]. The notation “$\Rightarrow$” denotes a set-valued map. That is, if $F : X \Rightarrow Y$ and $x \in X$, then $F(x)$ is a subset of $Y$.

Definition 1.1. For $\epsilon > 0$ and $F : X \rightarrow \mathbb{R}^m$, where $X \subset \mathbb{R}^n$, the set-valued robust regularization $F_\epsilon : X \Rightarrow \mathbb{R}^m$ is defined as

$$F_\epsilon(x) := \{ F(x + e) \mid |e| \leq \epsilon, x + e \in X \}.$$

For the particular case of a real-valued function $f : X \rightarrow \mathbb{R}$, we define the robust regularization $\bar{f}_\epsilon : X \rightarrow \mathbb{R}$ of $f$ by

$$\bar{f}_\epsilon(x) := \sup \{ y \in f_\epsilon(x) \} = \sup \{ y \mid \exists x' \in X \text{ such that } f(x') = y \text{ and } |x' - x| \leq \epsilon \}.$$

In this paper, we restrict our attention to the real-valued robust regularization $\bar{f}_\epsilon : X \rightarrow \mathbb{R}$. The use of set-valued analysis is restricted to Section 4.

The minimizer of the robust regularization protects against small perturbations better, and might be a better solution to implement. We illustrate with the example

$$f(x) = \begin{cases} -x & \text{if } x < 0 \\ \sqrt{x} & \text{if } x \geq 0. \end{cases}$$

The robust regularization can be quickly calculated to be

$$\bar{f}_\epsilon(x) = \begin{cases} \epsilon - x & \text{if } x < \alpha(\epsilon) \\ \sqrt{\epsilon + x} & \text{if } x \geq \alpha(\epsilon), \end{cases}$$

where $\alpha(\epsilon) = \frac{1+2\epsilon-\sqrt{1+8\epsilon}}{2} > -\epsilon$. The minimizer of $f$ is $\alpha(0)$, and $f$ is not Lipschitz there. To see this, observe that $\frac{f(\delta) - f(0)}{\delta} \rightarrow \infty$ as $\delta \rightarrow 0$. But the robust regularization $\bar{f}_\epsilon$ is Lipschitz at its minimizer $\alpha(\epsilon)$; its left and right derivatives there are $-1$ and $\frac{1}{2\sqrt{\epsilon+\alpha(\epsilon)}}$, which are both finite.

The sensitivity of $f$ at 0 can be attributed to the lack of Lipschitz continuity there. Lipschitz continuity is important in variational analysis, and is well studied in the recent books [23, 20]. The existence of a finite Lipschitz
constant on $f$ close to the optimizer can be important in the problems from which the optimization problem was derived.

There are two main aims in this paper. The first aim is to show that robust regularization has a regularizing property: Even if the original function $f$ is not Lipschitz at a point $x$, the robust regularization can be Lipschitz there under various conditions. For example, in Corollary 4.6, we prove that if the set of points at which $f$ is not Lipschitz is isolated, then the robust regularization $\bar{f}_\epsilon$ is Lipschitz at these points for all small $\epsilon > 0$. The second aim is to highlight the relationship between calmness and Lipschitz continuity, a topic important in the study of metric regularity, and studied in some generality for set-valued mappings (for example, in [17, Theorem 2.1], [21, Theorem 1.5]) but exploited less for single-valued mappings.

In Theorem 5.3, we prove that if $f : \mathbb{R}^n \to \mathbb{R}$ is semi-algebraic and continuous, then given any point in $\mathbb{R}^n$, the robust regularization $\bar{f}_\epsilon$ is Lipschitz there for all small $\epsilon > 0$. Semi-algebraic functions are functions whose graph can be defined by a finite union of sets defined by finitely many polynomial equalities and inequalities, and is a broad class of functions in applications. (For example, piecewise polynomial functions, rational functions and the mapping from a matrix to its eigenvalues are all semi-algebraic functions.) Moreover, the Lipschitz modulus of $\bar{f}_\epsilon$ at $\bar{x}$ is of order $o\left(\frac{1}{\epsilon}\right)$. This estimate of the Lipschitz modulus can be helpful for robust design.

Several interesting examples of robust regularization are tractable to compute and optimize. For example, the robust regularization of any strictly convex quadratic is a semidefinite -representable function, tractable via semidefinite programming: see Section 6. The robust regularizations of the spectral abscissa and radius of a nonsymmetric square matrix, which are the largest real part and the largest norm respectively of the eigenvalues of a matrix, are two more interesting examples. The robust regularization of the spectral abscissa and spectral radius are also known as the pseudospectral abscissa and the pseudospectral radius. The pseudospectral abscissa is important in the study of the system $\frac{d}{dt} u(t) = Au(t)$, and is easily calculated using the algorithm in [4], while the pseudospectral radius is important in the study of the system $u_{t+1} = Au_t$, and is easily calculated using the algorithm in [18]. We refer the reader to [27] for more details on the importance of the pseudospectral abscissa and radius in applications. The spectral abscissa is nonlipschitz whenever the eigenvalue with the largest real part has a nontrivial Jordan block. But for a fixed matrix, the pseudospectral abscissa is Lipschitz there for all $\epsilon \in (0, \bar{\epsilon})$ if $\bar{\epsilon} > 0$ is small enough [16]. We rederive this result here, using a much more general approach.
2. CALMNESS AS AN EXTENSION TO LIPSCHITZNESS

We begin by discussing the relation between calmness and Lipschitz continuity, which will be important in the proofs in Section 5 later. Throughout the paper, we will limit ourselves to the single-valued case. For more on these topics and their set-valued extensions, we refer the reader to [23].

**Definition 2.1.** Let \( F : X \to \mathbb{R}^m \) be a single-valued map, where \( X \subset \mathbb{R}^n \).

(a) [23, Section 8F] Define the calmness modulus of \( F \) at \( \bar{x} \) with respect to \( X \) to be

\[
\text{calm } F(\bar{x}) := \inf \{ \kappa \mid \text{There is a neighbourhood } V \text{ of } \bar{x} \text{ such that } |F(x) - F(\bar{x})| \leq \kappa |x - \bar{x}| \text{ for all } x \in V \cap X \} = \limsup_{x \to \bar{x}} \frac{|F(x) - F(\bar{x})|}{|x - \bar{x}|}.
\]

Here, \( x \to x \bar{x} \) means that \( x \in X \) and \( x \to \bar{x} \). The function \( F \) is calm at \( \bar{x} \) with respect to \( X \) if calm \( F(\bar{x}) < \infty \).

(b)[23, Definition 9.1] Define the Lipschitz modulus of \( F \) at \( \bar{x} \) with respect to \( X \) to be

\[
\text{lip } F(\bar{x}) := \inf \{ \kappa \mid \text{There is a neighbourhood } V \text{ of } \bar{x} \text{ such that } |F(x) - F(x')| \leq \kappa |x - x'| \text{ for all } x, x' \in V \cap X \} = \limsup_{x, x' \to \bar{x}} \frac{|F(x) - F(x')|}{|x - x'|}.
\]

The function \( F \) is Lipschitz at \( \bar{x} \) with respect to \( X \) if lip \( F(\bar{x}) < \infty \).

The definitions differ slightly from that of [23]. As can be seen in the definitions, Lipschitz continuity is a more stringent form of continuity than calmness. In fact, they are related in the following manner.

**Proposition 2.2.** Suppose that \( F : X \to \mathbb{R}^m \) where \( X \subset \mathbb{R}^n \).

(a) \( \limsup_{x \to \bar{x}} \text{calm } F(x) \leq \text{lip } F(\bar{x}) \).

(b) If there is an open set \( U \) containing \( \bar{x} \) such that \( U \cap X \) is convex, then \( \text{lip } F(\bar{x}) = \limsup_{x \to \bar{x}} \text{calm } F(x) \).

**Proof.** To simplify notation, let \( \kappa := \limsup_{x \to \bar{x}} \text{calm } F(x) \).

(a) For any \( \epsilon > 0 \), we can find a point \( x_\epsilon \) such that \( |\bar{x} - x_\epsilon| < \epsilon \) and calm \( F(x_\epsilon) > \kappa - \epsilon \). Then we can find a point \( \tilde{x}_\epsilon \) such that \( |x_\epsilon - \tilde{x}_\epsilon| < \epsilon \) and \( |F(x_\epsilon) - F(\tilde{x}_\epsilon)| > (\kappa - \epsilon)|x_\epsilon - \tilde{x}_\epsilon| \). As \( \epsilon \) can be made arbitrarily small, we have \( \kappa \leq \text{lip } F(\bar{x}) \) as needed.
(b) For every \( \epsilon > 0 \), there is some neighborhood of \( \bar{x} \), say \( B_{\epsilon}(\bar{x}) \), such that
\[
\text{calm } F(x) \leq \kappa + \epsilon \text{ if } x \in B_{\epsilon}(\bar{x}) \cap X.
\]
For any \( y, z \in B_{\epsilon}(\bar{x}) \cap X \), consider the line segment joining \( y \) and \( z \), which we denote \([y, z]\). As calm \( F(\bar{x}) \leq \kappa + \epsilon \) for all \( \bar{x} \in [y, z] \), there is a neighborhood around \( \bar{x} \), say \( V_{\bar{x}} \), such that \( |F(\bar{x}) - F(\tilde{x})| \leq (\kappa + 2\epsilon) |\bar{x} - \tilde{x}| \) for all \( \tilde{x} \in V_{\bar{x}} \cap X \).

As \([y, z]\) is compact, choose finitely many \( \tilde{x}_1, \ldots, \tilde{x}_k \) such that the union of \( V_{\tilde{x}_i} \) covers \([y, z]\). We can add \( y \) and \( z \) into our choice of points and rename them as \( \tilde{x}_1, \ldots, \tilde{x}_k \) in their order on the line segment \([y, z]\), with \( \tilde{x}_1 = y \) and \( \tilde{x}_k = z \). Also, we can find a point \( \hat{x}_i \) between \( \tilde{x}_i \) and \( \tilde{x}_{i+1} \) such that \( \hat{x}_i \in V_{\tilde{x}_i} \cap V_{\tilde{x}_{i+1}} \). Therefore, we add these \( \hat{x}_i \) into \( \tilde{x}_1, \ldots, \tilde{x}_k \) and get a new set \( x_1, \ldots, x_K \), again in their order on the line segment and \( x_1 = y, x_K = z \).

We have:
\[
|F(y) - F(z)| \leq \sum_{i=1}^{K-1} |F(x_i) - F(x_{i+1})| \\
\leq \sum_{i=1}^{K-1} (\kappa + 2\epsilon) |x_i - x_{i+1}| \\
\leq (\kappa + 2\epsilon) |y - z|,
\]
and as \( \epsilon \) is arbitrary, \( \text{lip } F(\bar{x}) \leq \kappa \) as claimed. \( \square \)

Convexity is a strong assumption here, but some analogous condition is needed, as the following examples show.

**Example 2.3.** (a) Consider the set \( X \subset \mathbb{R} \) defined by
\[
X = \left( \bigcup_{i=1}^{\infty} \left[ \frac{1}{3^i}, \frac{2}{3^i} \right] \right) \cup \{0\},
\]
and define the function \( F : X \to \mathbb{R} \) by
\[
F(x) = \begin{cases} 
\frac{1}{3^i} & \text{if } \frac{1}{3^i} \leq x \leq \frac{2}{3^i}, \\
0 & \text{if } x = 0.
\end{cases}
\]
It is clear that calm \( F(x) = 0 \) for all \( x \in X \setminus \{0\} \) since \( F \) is constant on each component of \( X \), and calm \( F(0) = 1 \). But
\[
\text{lip } F(0) = \lim_{i \to \infty} \frac{F\left(\frac{1}{3^i}\right) - F\left(\frac{2}{3^{i+1}}\right)}{\frac{1}{3^i} - \frac{2}{3^{i+1}}} \\
= \lim_{i \to \infty} \frac{\frac{1}{3^i} - \frac{1}{3^{i+1}}}{\frac{1}{3^i} - \frac{2}{3^{i+1}}} \\
= 2.
\]
Thus, \( \limsup_{x \to 0} \text{calm} F(x) < \text{lip} F(0) \).

(b) Consider \( X \subset \mathbb{R}^2 \) defined by \( X := \{(x_1, x_2) \mid x_2^2 = x_1^4\} \) and the function \( F : \mathbb{R}^2 \to \mathbb{R} \) defined by \( F(x_1, x_2) = x_2 \). One can easily check that \( \limsup_{x \to 0} \text{calm} F(x) = 0 \) and \( \text{lip} F(0, 0) = 1 \). This is an example of a semi-algebraic function where inequality holds.

Note that \( \text{calm} F(\overline{x}) \) can be strictly smaller than \( \text{lip} F(\overline{x}) \) even if \( X \) is convex, as demonstrated below.

**Example 2.4.** (a) Consider \( F : \mathbb{R} \to \mathbb{R} \) defined by

\[
F(x) = \begin{cases} 
0 & \text{if } x = 0, \\
x^2 \sin \left( \frac{1}{x^2} \right) & \text{otherwise}.
\end{cases}
\]

Here, \( \text{calm} F(0) = 0 \), but \( \text{lip} F(0) = \infty \).

(b) Consider \( F : \mathbb{R}^2 \to \mathbb{R} \) defined by:

\[
F(x_1, x_2) = \begin{cases} 
0 & \text{if } x_1 \leq 0 \\
x_1 & \text{if } 0 \leq x_1 \leq x_2/2 \\
-x_1 & \text{if } 0 \leq x_1 \leq -x_2/2 \\
2x_2 & \text{if } x_1 \geq |x_2|/2.
\end{cases}
\]

We can calculate \( \text{calm} F(0, 0) = 2/\sqrt{5} \), and \( \text{lip} F(0, 0) = 2 \), so this gives \( \text{calm} F(0, 0) \lessdot \text{lip} F(0, 0) \). This is an example of a semi-algebraic function where inequality holds.

At this point, we make a remark about subdifferentially regular functions. We recall the definition of subdifferential regularity.

**Definition 2.5.** [23, Definition 8.3] Consider a function \( f : \mathbb{R}^n \to \mathbb{R} \cup \{\infty\} \) and a point \( \overline{x} \) with \( f(\overline{x}) \) finite. For a vector \( v \in \mathbb{R}^n \), one says that

(a) \( v \) is a regular subgradient of \( f \) at \( \overline{x} \), written \( v \in \hat{\partial} f(\overline{x}) \), if

\[
f(x) \geq f(\overline{x}) + \langle v, x - \overline{x} \rangle + o(|x - \overline{x}|);
\]

(b) \( v \) is a (general) subgradient of \( f \) at \( \overline{x} \), written \( v \in \partial f(\overline{x}) \), if there are sequences \( x^n \to \overline{x} \) and \( v^n \in \hat{\partial} f(x^n) \) with \( v^n \to v \) and \( f(x^n) \to f(\overline{x}) \).

(c) If \( f \) is Lipschitz continuous at \( \overline{x} \), then \( f \) is subdifferentially regular if \( \hat{\partial} f(\overline{x}) = \partial f(\overline{x}) \).

Though the definition of subdifferential regularity differs from that given in [23, Definition 7.25], it can be deduced from [23, Corollary 8.11, Theorem 9.13 and Theorem 8.6] when \( f \) is Lipschitz, and is simple enough for our purposes. Subdifferentially regular functions are important and well-studied in variational analysis. The class of subdifferentially regular functions is closed under sums and pointwise maxima, and includes smooth functions and convex functions. It turns out that the calmness and Lipschitz moduli are equal for subdifferentially regular functions.
Proposition 2.6. If \( f : \mathbb{R}^n \to \mathbb{R} \cup \{\infty\} \) is Lipschitz continuous at \( \bar{x} \) and subdifferentially regular there, then calm \( f (\bar{x}) = \text{lip } f (\bar{x}) \).

Proof. By [23, Theorem 9.13], \( \text{lip } f (\bar{x}) = \max \{ |v| \mid v \in \partial f (\bar{x}) \} \). If \( v \in \partial f (\bar{x}) \), then \( v \in \partial f (\bar{x}) \), and we observe that calm \( f (\bar{x}) \geq |v| \) because
\[
f (\bar{x} + tv) \geq f (\bar{x}) + \langle v, tv \rangle + o (|t|)
= f (\bar{x}) + |v| |tv| + o (|t|).
\]
Therefore calm \( f (\bar{x}) \leq \text{lip } f (\bar{x}) = \max \{ |v| \mid v \in \partial f (\bar{x}) \} \leq \text{calm } f (\bar{x}) \), which implies that all three terms are equal. \( \square \)

3. CALMNESS AND ROBUST REGULARIZATION

Recall the definition of robust regularization in Definition 1.1. To study robust regularization, it is useful to study the dependence of \( \bar{f}_\epsilon (x) \) on \( \epsilon \) instead of on \( x \). For a point \( x \in X \), define \( g_x : \mathbb{R}_+ \to \mathbb{R} \) by
\[
g_x (\epsilon) = \bar{f}_\epsilon (x).
\]
To simplify notation, we write \( g \equiv g_x \) if it is clear from context. Here are a few basic properties of \( g_x \).

Proposition 3.1. For \( f : X \to \mathbb{R} \) and \( g_x \) as defined above, we have the following:

(a) \( g_x \) is monotonically nondecreasing.

(b) If \( f \) is continuous in a neighborhood of \( x \), then \( g_x \) is continuous in a neighborhood of \( 0 \).

Proof. Part (a) is obvious. For part (b), we prove the left and right limits separately. Suppose that \( \epsilon_i \downarrow \epsilon \). There is a sequence of \( x_i \) such that \( f (x_i) = \bar{f}_{\epsilon_i} (x) \), and \( |x_i - x| \leq \epsilon_i \). We assume, by choosing a subsequence if needed, that \( \lim_{i \to \infty} x_i = \hat{x} \). We have \( |\hat{x} - x| \leq \epsilon \), and since \( f \) is continuous, \( f (x_i) \to f (\hat{x}) \). This means that
\[
\bar{f}_\epsilon (x) \geq f (\hat{x}) = \lim_{i \to \infty} \bar{f}_{\epsilon_i} (x),
\]
which implies \( g (\epsilon) \geq \lim \sup_{\epsilon \downarrow \epsilon} g (\epsilon) \). The monotonicity of \( g \) tells us that \( g (\epsilon) = \lim_{\epsilon \downarrow \epsilon} g (\epsilon) \).

Next, suppose that \( \epsilon_i \) increases monotonically to \( \epsilon \). Let \( \hat{x} \) be such that \( f (\hat{x}) = \bar{f}_\epsilon (x) \), with \( |\hat{x} - x| \leq \epsilon \). Since \( f \) is continuous, for every \( \delta_1 > 0 \), there is a \( \delta_2 > 0 \) such that \( |f (x') - f (\hat{x})| < \delta_1 \) if \( |x' - \hat{x}| < \delta_2 \). This means that if \( \epsilon - \epsilon_i < \delta_2 \), then
\[
\bar{f}_{\epsilon_i} (x) \geq f (\hat{x}) - \delta_1 = \bar{f}_\epsilon (x) - \delta_1.
\]
As \( \delta_1 \) can be made arbitrarily small, we conclude that \( \lim_{\epsilon \downarrow \epsilon} \bar{f}_\epsilon (x) = \bar{f}_\epsilon (x) \), or \( \lim_{\epsilon \downarrow \epsilon} g (\epsilon) = g (\epsilon) \). \( \square \)
It turns out that calmness of the robust regularization is related to the derivative of \( g_x \).

**Proposition 3.2.** If \( f : X \to \mathbb{R} \) and \( \epsilon > 0 \), then calm \( \bar{f}_\epsilon (x) \leq \text{calm } g_x (\epsilon) \).

If in addition \( X = \mathbb{R}^n \) and \( g_x \) is differentiable at \( \epsilon \), then

\[
\text{calm } \bar{f}_\epsilon (x) = \text{calm } g_x (\epsilon) = g'_x (\epsilon).
\]

**Proof.** For the first part, we proceed to show that if \( \kappa \geq \text{calm } g_x (\epsilon) \), then \( \kappa \geq \text{calm } \bar{f}_\epsilon (x) \).

If \( |\tilde{x} - x| < \epsilon \), we have

\[
\mathbb{B}_{\epsilon - |\tilde{x} - x|} (x) \subseteq \mathbb{B}_\epsilon (\tilde{x}) \subseteq \mathbb{B}_{\epsilon + |\tilde{x} - x|} (x),
\]

which implies

\[
\bar{f}_{\epsilon - |\tilde{x} - x|} (x) \leq \bar{f}_\epsilon (\tilde{x}) \leq \bar{f}_{\epsilon + |\tilde{x} - x|} (x).
\]

Then note that if \( \tilde{x} \) is close enough to \( x \), we have

\[
\bar{f}_\epsilon (\tilde{x}) \leq \bar{f}_{\epsilon + |\tilde{x} - x|} (x) = g_x (\epsilon + |\tilde{x} - x|) \leq g_x (\epsilon) + \kappa |\tilde{x} - x|,
\]

and similarly

\[
\bar{f}_\epsilon (\tilde{x}) \geq \bar{f}_{\epsilon - |\tilde{x} - x|} (x) = g_x (\epsilon - |\tilde{x} - x|) \geq g_x (\epsilon) - \kappa |\tilde{x} - x|,
\]

which tells us that \( |\bar{f}_\epsilon (x) - \bar{f}_\epsilon (\tilde{x})| \leq \kappa |\tilde{x} - x| \), which is what we need.

For the second part, it is clear from the definition of the derivative that \( g'_x (\epsilon) = \text{calm } g_x (\epsilon) \). We prove that if \( \kappa < g'_x (\epsilon) \), then \( \kappa \leq \text{calm } \bar{f}_\epsilon (x) \). By the differentiability of \( g_x \), there is some \( \delta > 0 \) such that for any \( 0 \leq \delta \leq \delta \), we have

\[
\bar{f}_{\epsilon + \delta} (x) = g_x (\epsilon + \delta) > g_x (\epsilon) + \kappa \delta = \bar{f}_\epsilon (x) + \kappa \delta.
\]

For any \( 0 \leq \delta \leq \delta \), there is some \( \tilde{x}_\delta \in \mathbb{B}_{\epsilon + \delta} (x) \) such that \( f (\tilde{x}_\delta) = \bar{f}_{\epsilon + \delta} (x) \).

Let \( \tilde{x}_\delta = \frac{\delta}{|\tilde{x}_\delta - x|} (\tilde{x}_\delta - x) + x \). We have \( \bar{f}_\epsilon (\tilde{x}_\delta) = \bar{f}_{\epsilon + \delta} (x) \), which gives \( \bar{f}_\epsilon (\tilde{x}_\delta) - \bar{f}_\epsilon (x) > \kappa \delta \). Since \( \tilde{x}_\delta \) was chosen such that \( \delta = |\tilde{x}_\delta - x| \), we have \( \bar{f}_\epsilon (\tilde{x}_\delta) - \bar{f}_\epsilon (x) > \kappa |\tilde{x}_\delta - x| \), which implies \( \kappa \leq \text{calm } \bar{f}_\epsilon (x) \) as needed. \( \square \)

**Remark 3.3.** A similar statement can be made for \( \epsilon = 0 \), except that we change calmness to “calm from above” as defined in [23, Section 8F] in both parts.

We have the following corollary. The subdifferential “\( \partial \)” was defined in Definition 2.5.

**Corollary 3.4.** If \( f : \mathbb{R}^n \to \mathbb{R}, \epsilon > 0 \) and \( g_x \) is Lipschitz at \( \epsilon \), then

\[
\text{calm } \bar{f}_\epsilon (x) \leq \text{lip } g_x (\epsilon) = \sup \{|y| \mid y \in \partial g_x (\epsilon)\}.
\]
In general, the robust regularization is calm.

**Theorem 3.5.** For a continuous function \( f : X \to \mathbb{R} \), there is an \( \bar{\epsilon} > 0 \) such that \( \bar{f}_\epsilon \) is calm at \( \bar{x} \) for all \( 0 < \epsilon \leq \bar{\epsilon} \) except on a subset of \((0, \bar{\epsilon}]\) of measure zero.

**Proof.** By Proposition 3.1(b), since \( f \) is continuous at \( \bar{x} \), \( g_{\bar{x}} \) is continuous in \([0, \bar{\epsilon}]\) for some \( \bar{\epsilon} > 0 \). Since \( g_{\bar{x}} \) is monotonically nondecreasing, it is differentiable in all \([0, \bar{\epsilon}]\) except for a set of measure zero. The derivative \( g'_{\bar{x}}(\epsilon) \) equals calm \( \bar{f}_\epsilon(\bar{x}) \) by Proposition 3.2.

**Remark 3.6.** In general, the above result cannot be improved. For an example, let \( c : [0, 1] \to [0, 1] \) denote the Cantor function, commonly used in real analysis texts as an example of a function that is not absolutely continuous and not satisfying the Fundamental Theorem of Calculus. Then calm \( \bar{c}_\epsilon(0) = \infty \) for all \( \epsilon \) lying in the Cantor set.

### 4. Robust Regularization in General

In this section, in Corollary 4.6, we prove that if \( \text{lip } f(x) < \infty \) for \( x \) close to but not equal to \( \bar{x} \), then \( \text{lip } \bar{f}_\epsilon(\bar{x}) < \infty \) for all small \( \epsilon > 0 \), even when \( \text{lip } f(\bar{x}) = \infty \). To present the details of the proof, we need a short foray into set-valued analysis.

**Definition 4.1.** [23, Example 4.13] For two sets \( C, D \subset \mathbb{R}^m \), the Pompeiu-Hausdorff distance between \( C \) and \( D \), denoted by \( d(C, D) \), is defined by

\[
d(C, D) := \inf \{ \eta \geq 0 \mid C \subset D + \eta \mathbb{B}, D \subset C + \eta \mathbb{B} \}.
\]

**Definition 4.2.** [23, Definitions 9.26, 9.28] A mapping \( S : X \Rightarrow \mathbb{R}^m \) is Lipschitz continuous on its domain \( X \subset \mathbb{R}^n \), if it is nonempty-closed-valued on \( X \) and there exists \( \kappa \geq 0 \), a Lipschitz constant, such that

\[
d(S(x'), S(x)) \leq \kappa |x' - x| \quad \text{for all } x, x' \in X,
\]

or equivalently, \( S(x') \subset S(x) + \kappa |x' - x| \mathbb{B} \) for all \( x, x' \in X \). The Lipschitz modulus is defined as

\[
\text{lip } S(\bar{x}) := \limsup_{x,x' \to \bar{x}} \frac{d(S(x'), S(x))}{|x' - x|},
\]

and is the infimum of all \( \kappa \) such that there exists a neighborhood \( U \) of \( \bar{x} \) such that \( S \) is Lipschitz continuous with constant \( \kappa \) in \( U \cap X \).
For $F : X \to \mathbb{R}^m$, we may write the robust regularization $F_\epsilon : X \to \mathbb{R}^m$ by $F_\epsilon = F \circ \Phi_\epsilon$, where $\Phi_\epsilon : X \to X$ is defined by $\Phi_\epsilon (x) = \mathbb{B}_\epsilon (x) \cap X$. For reasons that will be clear later in Section 7, we consider the extension $\tilde{\Phi}_\epsilon : \mathbb{R}^n \to X$ defined by $\tilde{\Phi}_\epsilon (x) = \mathbb{B}_\epsilon (x) \cap X$. It is clear that $\Phi_\epsilon |_X = \Phi_\epsilon$ using our previous notation, and it follows straight from the definitions that $\text{lip} \Phi_\epsilon (x) \leq \text{lip} \tilde{\Phi}_\epsilon (x)$ for $x \in X$.

**Definition 4.3.** We say that $X \subset \mathbb{R}^n$ is *peaceful* at $\bar{x} \in X$ if $\text{lip} \tilde{\Phi}_\epsilon (\bar{x})$ is finite for all small $\epsilon > 0$. If in addition $\limsup_{\epsilon \downarrow 0} \text{lip} \tilde{\Phi}_\epsilon (\bar{x}) \leq \kappa$ for all small $\epsilon > 0$, we say that $X$ is peaceful with modulus $\kappa$ at $\bar{x}$, or $\kappa$-*peaceful* at $\bar{x}$.

When $\bar{x}$ lies in the interior of $X$ and $\epsilon$ is small enough, then $\tilde{\Phi}_\epsilon$ is Lipschitz with constant 1. In section 7, we will find weaker conditions on $X$ for the Lipschitz continuity of $\tilde{\Phi}_\epsilon$. We will see that convex sets are 1-peaceful, but for now, we remark that if $X$ is convex, then $\tilde{\Phi}_\epsilon$ is globally Lipschitz in $X$.

**Proposition 4.4.** If $X$ is a convex set, then $\Phi_\epsilon (x) \subset \Phi (x') + |x - x'| \mathbb{B}$ for all $x, x' \in X$.

**Proof.** The condition we are required to prove is equivalent to

$$\mathbb{B}_\epsilon (x) \cap X \subset \mathbb{B}_\epsilon (x') \cap X \cap \mathbb{B}$$

for all $x, x' \in X$. For any point $\hat{x} \in \mathbb{B}_\epsilon (x) \cap X$, the line segment $[x', \hat{x}]$ lies in $X$, and is of length at most $|\hat{x} - x| + |x - x'|$. The ball $\mathbb{B}_\epsilon (x')$ can contain the line segment $[x', \hat{x}]$, in which case $\hat{x} \in \mathbb{B}_\epsilon (x') \cap X$, or the boundary of $\mathbb{B}_\epsilon (x')$ may intersect $[x', \hat{x}]$ at a point, say $\hat{\hat{x}}$. Since $X$ is a convex set, we have $\hat{\hat{x}} \in \mathbb{B}_\epsilon (x') \cap X$. Furthermore

$$|\hat{x} - \hat{\hat{x}}| = |\hat{x} - x'| - \epsilon \leq |\hat{x} - x| + |x - x'| - \epsilon \leq |x - x'|,$$

so $\hat{\hat{x}} \in (\mathbb{B}_\epsilon (x') \cap X) + |x - x'| \mathbb{B}$. □

We remark that if $X$ is nearly radial at $\bar{x}$ as introduced in [15], then $X$ is 1-peaceful: see Section 7. The set $X$ is *nearly radial* at $\bar{x}$ if

$$\text{dist} (\bar{x}, x + T_X (x)) \to 0 \text{ as } x \to \bar{x} \text{ in } X.$$

The set $X$ is *nearly radial* if it is nearly radial at all points in $X$. The notation $T_X (x)$ refers to the (Bouligand) tangent cone (or “contingent cone”) to $X$ at $x \in X$, formally defined as

$$T_X (\bar{x}) = \{ \lim t_r^{-1} (x_r - \bar{x}) : t_r \downarrow 0, \ x_r \to \bar{x}, \ x_r \in X \}$$
is finite, say \( \Phi \). Open balls \( B \) lie in \( \mathcal{C} \) on \( \mathcal{B} \).

We now present a result on the regularizing property of robust regularization. In Proposition 4.5 below, condition (i) allows us to evaluate the Lipschitz modulus of functions whose domains are not necessarily convex. One situation where (i) is interesting is when \( X \) is a smooth manifold.

**Proposition 4.5.** For \( F : X \to \mathbb{R}^m \), suppose that either (i) or (ii) holds.

(i) \( X \) is peaceful and \( \text{lip} \ F (x) < \infty \) for all \( x \) close to but not equal to \( \bar{x} \).

Here, \( \tilde{F} : \mathbb{R}^n \to \mathbb{R}^m \) is an extension of \( F \) on \( \mathbb{R}^n \) such that \( \tilde{F}|_X = F \).

(ii) \( X \) is convex and \( \text{lip} \ F (x) < \infty \) for all \( x \in X \) close to but not equal to \( \bar{x} \).

Then \( \text{lip} \ F_\epsilon (\bar{x}) \) is finite for all small \( \epsilon > 0 \).

**Proof.** The proof for both conditions are similar, so they will be treated together. One notes that \( \text{lip} \ F (x) \leq \text{lip} \tilde{F} (x) \) always by the definition of these Lipschitz moduli, so we assume \( \text{lip} \ F (x) < \infty \) for all \( x \in X \) close to but not equal to \( \bar{x} \) until we have to distinguish these cases.

First, we prove that \( \text{lip} \ F : X \to \mathbb{R}_+ \) is upper semicontinuous. This result is just a slight modification of the first part of [23, Theorem 9.2], but we include the proof for completeness. Suppose that \( x_i \to x \). By the definition of \( \text{lip} \ F \), we can find \( x_{i,1}, x_{i,2} \in X \) such that

\[
\frac{|F (x_{i,1}) - F (x_{i,2})|}{|x_{i,1} - x_{i,2}|} > \text{lip} \ F (x_i) \quad \text{is upper semicontinuous}.
\]

Taking limits as \( i \to \infty \), we see that \( x_{i,1}, x_{i,2} \to x \), and it follows that

\[
\text{lip} \ F (x) \geq \limsup_{i \to \infty} \frac{|F (x_{i,1}) - F (x_{i,2})|}{|x_{i,1} - x_{i,2}|} = \limsup_{i \to \infty} \text{lip} \ F (x_i).
\]

Thus \( \text{lip} \ F : X \to \mathbb{R}_+ \) is upper semicontinuous.

So for \( \epsilon_1 \) small enough, choose \( \epsilon_2 < \epsilon_1 \) such that \( \text{lip} \ F \) is bounded above in \( C_1 = (B_{\epsilon_1+\epsilon_2} (\bar{x}) \setminus B_{\epsilon_1-\epsilon_2} (\bar{x})) \cap X \), say by the constant \( \kappa_1 \). Then for any \( \kappa_2 > \kappa_1 \) and any \( x \in C_1 \), there is an \( \epsilon_x \) such that \( F \) is Lipschitz continuous on \( B_{\epsilon_x} (x) \cap X \) with constant \( \kappa_2 \) with respect to \( X \). Thus \( \cup_{x \in C_1} \{ B_{\epsilon_x} (x) \} \) is an open cover of \( C_1 \).

By the Lebesgue Number Lemma, there is a constant \( \delta \) such that if \( x_1, x_2 \) lie in \( C_1 \) and \( |x_1 - x_2| \leq \delta \), then the line segment \( [x_1, x_2] \) lies in one of the open balls \( B_{\epsilon_x} (x) \) for some \( x \in C_1 \). We may assume that \( \delta < \epsilon_2 \).

Also, since \( X \) is peaceful at \( \bar{x} \), choose \( \epsilon_1 \) small enough so that \( \text{lip} \Phi_{\epsilon_1} (\bar{x}) \) is finite, say \( \text{lip} \Phi_{\epsilon_1} (\bar{x}) < K \). If \( X \) is convex, then this is possible due to
Proposition 4.4. We can assume that $K > 2$. Therefore, there is an open set $U$ about $\bar{x}$ such that $\Phi_{e_1}$ is Lipschitz in $U \cap X$ with constant $K$, that is $\Phi_{e_1}(x) \subset \Phi_{e_1}(x') + K |x - x'| \mathbb{B}$ for all $x, x' \in U \cap X$.

So, for $x, x' \in U \cap B_{\frac{\delta}{2K}}(\bar{x}) \cap X$, we want to show that 

$$F_{e_1}(x) \subset F_{e_1}(x') + K \kappa_2 |x - x'| \mathbb{B}.$$ 

Suppose that $y \in F_{e_1}(x)$. So $y = F(\bar{x})$ for some $\bar{x} \in B_{e_1}(x) \cap X$. If $\bar{x} \in B_{\frac{\delta}{2K}}(\bar{x})$, then $\bar{x} \in B_{e_1}(x') \cap X$ because $|x' - \bar{x}| \leq \frac{\delta}{2K}$. So $y \in F_{e_1}(x')$. Otherwise $\bar{x} \in \left( B_{e_1 + \frac{\delta}{2K}}(\bar{x}) \setminus B_{\frac{\delta}{2K}}(\bar{x}) \right) \cap X$.

We have $\Phi_{e_1}(x) \subset \Phi_{e_1}(x') + K |x - x'| \mathbb{B}$. So there is some $\bar{x} \in \Phi_{e_1}(x')$ such that 

$$|\hat{x} - \bar{x}| \leq K |x - x'| \leq K \frac{\delta}{2K} = \frac{\delta}{2}.$$ 

Furthermore, 

$$|\hat{x} - \bar{x}| \leq |\hat{x} - x| + |x - \bar{x}| + |\hat{x} - \hat{x}| \leq \epsilon_1 + \frac{\delta}{2K} + \frac{\delta}{2} \leq \epsilon_1 + \frac{3\delta}{4} < \epsilon_1 + \epsilon_2,$$

and 

$$|\hat{x} - \bar{x}| \geq |\hat{x} - x| - |x - \bar{x}| - |\hat{x} - \hat{x}| \geq \epsilon_1 - \frac{\delta}{2K} - \frac{\delta}{2} \geq \epsilon_1 - \frac{3\delta}{4} > \epsilon_1 - \epsilon_2.$$ 

Hence $\hat{x} \in (B_{e_1 + \epsilon_2}(\bar{x}) \setminus B_{e_1 - \epsilon_2}(\bar{x})) \cap X$. We now proceed to prove the inequality $|F(\hat{x}) - F(\bar{x})| < \kappa_2 |\hat{x} - \bar{x}|$ for the two cases.

Condition (i): Since $|\hat{x} - \bar{x}| < \delta$, the line segment $[\hat{x}, \bar{x}]$ lies in $B_{\epsilon_2}(x)$ for some $x \in X$. Since the line segment $[\hat{x}, \bar{x}]$ is convex and $\hat{F}$ is bounded from above by $\kappa_2$ there, we have 

$$|F(\hat{x}) - F(\bar{x})| = \left| \hat{F}(\hat{x}) - \hat{F}(\bar{x}) \right| < \kappa_2 |\hat{x} - \bar{x}|$$

by [23, Theorem 9.2].

Condition (ii): The proof is similar, except that $[\hat{x}, \bar{x}] \subset X$, and $\hat{F}$ is bounded above by $\kappa_2$.

On establishing $|F(\hat{x}) - F(\bar{x})| < \kappa_2 |\hat{x} - \bar{x}|$, we note that 

$$F(\hat{x}) \in F(\bar{x}) + \kappa_2 |\hat{x} - \bar{x}| \mathbb{B}$$ 

$$\subset F_{e_1}(x') + \kappa_2 |\hat{x} - \bar{x}| \mathbb{B}$$ 

$$\subset F_{e_1}(x') + K \kappa_2 |x - x'| \mathbb{B},$$

and we are done. \hfill \square

We are now ready to relate $\text{lip} \ f_{\epsilon}(\bar{x})$ to $\text{lip} \ f(\bar{x})$. We remind the reader that in the proof of Corollary 4.6 below, $f_{\epsilon} : X \Rightarrow \mathbb{R}$ is a set-valued map as
introduced in Definition 1.1, which is similar to $\bar{f}$, but maps to intervals in $\mathbb{R}$.

**Corollary 4.6.** For $f : X \to \mathbb{R}$, if either condition (i) or condition (ii) in Proposition 4.5 for $F : X \to \mathbb{R}$ taken to be $f$ holds, then $\text{lip } \bar{f}_\epsilon (\bar{x}) < \infty$ for all small $\epsilon > 0$.

**Proof.** By Proposition 4.5, we have $\text{lip } f_\epsilon (\bar{x}) < \infty$ with the given conditions. It remains to prove that $\text{lip } \bar{f}_\epsilon (\bar{x}) \leq \text{lip } f_\epsilon (\bar{x})$. We can do this by proving that $\text{lip } \bar{S}(\bar{x}) \leq \text{lip } S(\bar{x})$, where $\bar{S} : X \to \mathbb{R}$ is a set-valued map, and $\bar{S} : X \to \mathbb{R}$ is defined by $\bar{S}(x) = \sup \{ y \mid y \in S(x) \}$. Note that if $S = f_\epsilon$, then $\bar{S} = (\bar{f}_\epsilon) = \bar{f}_\epsilon$.

For any $\kappa > \text{lip } S(x)$, we have $d(S(\hat{x}), S(\hat{x})) \leq \kappa |\hat{x} - \hat{x}|$ for $\hat{x}, \hat{x} \in X$ close enough to $x$ by [23, Definition 9.26]. The definition of the Pompeiu-Hausdorff distance tells us that $\bar{S}(\hat{x}) \subset S(\hat{x}) + \kappa |\hat{x} - \hat{x}|$, which implies $\bar{S}(\hat{x}) \leq \bar{S}(\hat{x}) + \kappa |\hat{x} - \hat{x}|$. By reversing the roles of $\hat{x}$ and $\hat{x}$, we obtain $|\bar{S}(\hat{x}) - \bar{S}(\hat{x})| \leq \kappa |\hat{x} - \hat{x}|$. So $\kappa > \text{lip } \bar{S}(x)$, and since $\kappa$ is arbitrary, we have $\text{lip } \bar{S}(x) \leq \text{lip } S(x)$ as needed. \[\square\]

### 5. Semi-algebraic Robust Regularization

In this section, in Theorem 5.3, we prove that if $f : \mathbb{R}^n \to \mathbb{R}$ is continuous and semi-algebraic, then at any given point, the robust regularization is locally Lipschitz there for all sufficiently small $\epsilon > 0$. This theorem is more appealing than Corollary 4.6 because the required condition is weaker. The condition $\text{lip } f(x) < \infty$ for all $x$ close to but not equal to $\bar{x}$ in Corollary 4.6 is a strong condition because if a function is not Lipschitz at a point $\bar{x}$, it is likely that it is not Lipschitz at some points close to $\bar{x}$ as well. For example, in $f : \mathbb{R}^2 \to \mathbb{R}$ defined by $f(x_1, x_2) = |\sqrt{x_1}|$, $f$ is not Lipschitz at all points where $x_1 = 0$.

We proceed to prove the main theorem of this section in the steps outlined below.

**Proposition 5.1.** For $f : X \to \mathbb{R}$, where $X \subset \mathbb{R}^n$ is convex, define $G : X \times \mathbb{R}_+ \to \mathbb{R}_+ \cup \{ \infty \}$ by $G(x, \epsilon) := \limsup_{\epsilon \to 0} \text{lip } \bar{f}_\epsilon (x)$.

If $f$ is semi-algebraic, then the maps $(x, \epsilon) \mapsto \text{calm } \bar{f}_\epsilon (x)$, $(x, \epsilon) \mapsto \text{lip } \bar{f}_\epsilon (x)$ and $G$ are semi-algebraic.

**Proof.** The semi-algebraic nature is a consequence of the Tarski-Seidenberg quantifier elimination. \[\square\]

The semi-algebraicity of $(x, \epsilon) \mapsto \text{calm } \bar{f}_\epsilon (x)$ gives us an indication of how the map $\epsilon \mapsto \text{calm } \bar{f}_\epsilon (x)$ behaves asymptotically.
Proposition 5.2. Suppose that \( f : X \to \mathbb{R} \) is continuous and semi-algebraic, where \( X \subset \mathbb{R}^n \). Fix \( x \in X \). Then \( \text{calm} \bar{f}_\epsilon (x) = o \left( \frac{1}{\epsilon} \right) \) as \( \epsilon \searrow 0 \). Hence \( \bar{f}_\epsilon \) is calm at \( x \) for all small \( \epsilon > 0 \).

Proof. The map \( g_x \) is semi-algebraic because it can be written as a composition of semi-algebraic maps \( \epsilon \mapsto (x, \epsilon) \mapsto \bar{f}_\epsilon (x) \). Thus \( g_x \) is differentiable on some open interval of the form \( (0, \bar{\epsilon}) \) for some \( \bar{\epsilon} > 0 \). Recall that \( \text{calm} g_x (\epsilon) = g'_x (\epsilon) \) by Proposition 3.2.

We show that for any \( K > 0 \), we can reduce \( \bar{\epsilon} \) if necessary so that the map \( \epsilon \mapsto \text{calm} \bar{f}_\epsilon (x) \) is bounded from above by \( K \epsilon \) on \( \epsilon \in (0, \bar{\epsilon}) \). For any \( K > 0 \), there exists a \( \bar{\epsilon} > 0 \) such that either \( g'_x (\epsilon) \leq K \epsilon \) for all \( 0 < \epsilon < \bar{\epsilon} \), or \( g'_x (\epsilon) \geq K \epsilon \) for all \( 0 < \epsilon < \bar{\epsilon} \). The latter cannot happen, otherwise for any \( 0 < \epsilon < \bar{\epsilon} \),

\[
\bar{f}_\epsilon (x) - f (x) = \int_0^\epsilon g'_x (s) \, ds \\
\geq \int_0^\epsilon K \frac{ds}{s} = \infty.
\]

This contradicts the continuity of \( g_x \). If \( \epsilon \) is small enough, the derivatives of \( g_x \) exist for all small \( \epsilon > 0 \) and \( g'_x (\epsilon) = \text{calm} \bar{f}_\epsilon (x) \) by Proposition 3.2. This gives us the required result. \( \square \)

Consider \( f : [0, 1] \to \mathbb{R} \) defined by \( f (x) = x^{1/k} \). Then \( g_0 (\epsilon) = \epsilon^{1/k} \), so \( \text{calm} \bar{f}_\epsilon (0) = g'_0 (\epsilon) = \frac{1}{k} \epsilon^{(1/k)-1} \). As \( k \to \infty \), we see that the bound above is tight.

We are now ready to state the main theorem of this paper. In the particular case of \( X = \mathbb{R}^n \), we have the following theorem.

Theorem 5.3. Consider any continuous semi-algebraic function \( f : \mathbb{R}^n \to \mathbb{R} \). At any fixed point \( \bar{x} \in \mathbb{R}^n \), the robust regularization \( \bar{f}_\epsilon \) is Lipschitz at \( \bar{x} \), and its calmness and Lipschitz moduli, \( \text{calm} \bar{f}_\epsilon (\bar{x}) \) and \( \text{lip} \bar{f}_\epsilon (\bar{x}) \), agree for sufficiently small \( \epsilon \) and behave like \( o \left( \frac{1}{\epsilon} \right) \) as \( \epsilon \searrow 0 \).

Proof. In view of Proposition 5.2, we only need to prove the there is some \( \bar{\epsilon} > 0 \) such that \( \text{lip} \bar{f}_\epsilon (\bar{x}) = \text{calm} \bar{f}_\epsilon (\bar{x}) \) for all \( \epsilon \in (0, \bar{\epsilon}) \). We can assume that \( g_x \) is twice continuously differentiable in \( (0, \bar{\epsilon}) \). The graph of \( G : \mathbb{R}^n \times \mathbb{R}_+ \to \mathbb{R}_+ \) as defined in Proposition 5.1 is semi-algebraic, so by the decomposition theorem [10, Theorem 6.7], there is a finite partition of definable \( C^2 \) manifolds \( C_1, \ldots, C_l \) such that \( G \mid_{C_i} \) is \( C^2 \).
If the segment \( \{ \bar{x} \} \times (0, \bar{c}] \) lies in the (relative) interior of one definable manifold, then
\[
\text{lip } \bar{f}_\epsilon (\bar{x}) = \limsup_{\bar{x} \to \bar{x}} \text{calm } \bar{f}_\epsilon (\bar{x}) \quad \text{(by Proposition 2.2)}
\]
\[
= \limsup_{\bar{x} \to \bar{x}} g'_\epsilon (\epsilon) \quad \text{(by Proposition 3.2)}
\]
\[
= g'_\epsilon (\epsilon)
\]
\[
= \text{calm } \bar{f}_\epsilon (\bar{x}),
\]
and we have nothing to do. Therefore, assume that the segment is on the boundary of two or more of the \( C_i \).

Since \( G \) is semi-algebraic, the map \( \epsilon \mapsto \limsup_{\alpha \to \epsilon} \text{lip } \bar{f}_\alpha (\bar{x}) \) is semi-algebraic, so we can reduce \( \epsilon > 0 \) as necessary such that either
\[
(1) \text{limsup}_{\alpha \to \epsilon} \text{lip } \bar{f}_\alpha (\bar{x}) < \text{calm } \bar{f}_\epsilon (\bar{x}) \quad \text{for all } \epsilon \in (0, \bar{c}], \text{ or}
\]
\[
(2) \text{limsup}_{\alpha \to \epsilon} \text{lip } \bar{f}_\alpha (\bar{x}) = \text{calm } \bar{f}_\epsilon (\bar{x}) \quad \text{for all } \epsilon \in (0, \bar{c}], \text{ or}
\]
\[
(3) \text{limsup}_{\alpha \to \epsilon} \text{lip } \bar{f}_\alpha (\bar{x}) > \text{calm } \bar{f}_\epsilon (\bar{x}) \quad \text{for all } \epsilon \in (0, \bar{c}].
\]
Case (1) cannot hold because \( \text{lip } \bar{f}_\epsilon (\bar{x}) \geq \text{calm } \bar{f}_\epsilon (\bar{x}) \). Case (2) is what we seek to prove, so we proceed to show that case (3) cannot happen by contradiction.

We can choose \( \bar{\epsilon}, M_1, M_2 > 0 \) such that \( 0 < \bar{\epsilon} < \bar{c} \) and
\[
\text{calm } \bar{f}_\epsilon (\bar{x}) < M_2 < M_1 < \limsup_{\alpha \to \epsilon} \text{lip } \bar{f}_\alpha (\bar{x}) \quad \text{for all } \epsilon \in [\bar{\epsilon}, \bar{c}].
\]
We state and prove a lemma important to the rest of the proof before continuing.

**Lemma 5.4.** There exists an interval \( (\epsilon_1, \epsilon_2) \) contained in \( (\bar{\epsilon}, \bar{c}] \) and a manifold \( T_1 \subset \mathbb{R}^n \times \mathbb{R}_+ \) such that
1. \( \{ \bar{x} \} \times (\epsilon_1, \epsilon_2) \subset \text{cl } (T_1) \).
2. \( T_1 \) is an open \( C^2 \) manifold.
3. \( H : \mathbb{R}^n \times \mathbb{R}_+ \to \mathbb{R} \), defined by \( H(x, \epsilon) = \bar{f}_\epsilon (x) \), is \( C^2 \) in \( T_1 \).
4. For all \((x, \epsilon) \in T_1\), we have \( M_1 \leq g'_\epsilon (\epsilon) < \infty \).
5. \((x, \epsilon) \mapsto g'_\epsilon (\epsilon) \) is continuous in \( T_1 \).

**Proof.** Consider the set
\[
T := \{(x, \epsilon) \mid M_1 \leq g'_\epsilon (\epsilon) < \infty \}.
\]
First, we prove that \( \{ \bar{x} \} \times [\bar{\epsilon}, \bar{c}] \subset \text{cl } T \). It suffices to show that for all \( \epsilon \in (\bar{\epsilon}, \bar{c}] \), \( (\bar{x}, \epsilon) \in \text{cl } T \). This can in turn be proven by showing that for all \( \delta > 0 \), we can find \( \bar{x}', \bar{\epsilon}' \) such that \( |\bar{x} - \bar{x}'| < \delta, |\epsilon - \bar{\epsilon}'| < \delta \) such that \( (\bar{x}', \bar{\epsilon}') \in T \), or equivalently, \( M_1 \leq g'_{\bar{\epsilon}'} (\bar{\epsilon}') < \infty \).

Since \( \limsup_{\alpha \to \epsilon} \text{lip } \bar{f}_\alpha (\bar{x}) > M_1 \), there is some \( \epsilon_0 \) such that \( |\epsilon_0 - \epsilon| < \frac{\delta}{2} \) and \( \text{lip } \bar{f}_{\epsilon_0} (\bar{x}) > M_1 \).
Next, since

$$\limsup_{x \to \bar{x}} |\partial g_x(e^o)| \geq \limsup_{x \to \bar{x}} \text{calm} \ f_{e^o}(x) = \text{lip} \ f_{e^o}(\bar{x}),$$

there is some $x'$ such that $|\bar{x} - x'| < \delta$ and $|\partial g_{x'}(e^o)| > \frac{1}{2} \text{lip} \ f_{e^o}(\bar{x}) + \frac{1}{2} M_1$.

Finally, since $g_{x'}(\cdot)$ is semi-algebraic, we can find some $e'$ such that $|e' - e^o| < \frac{\delta}{2}$, $g_{x'}(e')$ is well defined and finite, and

$$g'_{x'}(e') > |\partial g_{x'}(e^o)| - \frac{1}{2} (\text{lip} f_{e^o}(\bar{x}) - M_1) > M_1.$$

This choice of $x'$ and $e'$ are easily verified to satisfy the requirements stated.

By the decomposition theorem [10, Theorem 6.7], $T$ can be decomposed into a finite disjoint union of $C^2$ smooth manifolds $T_1, T_2, \ldots, T_p$ on which $H$ is $C^2$. Since $\{\bar{x}\} \times [\hat{\epsilon}, \hat{\epsilon}] \subset \text{cl} T$, there must be some $T_i$ and $(\epsilon_1, \epsilon_2)$ such that $\{\bar{x}\} \times (\epsilon_1, \epsilon_2) \subset \text{cl} T_i$. Without loss of generality, let one such $T_i$ be $T_1$.

Conditions (1), (2), (3) and (4) are automatically satisfied. Note that $g'_{x'}(e)$ is exactly the derivative of $H(\cdot, \cdot)$ with respect to the second coordinate, and so Property (5) is satisfied. This concludes the proof of the lemma. $\square$

We now continue with the rest of the proof of the theorem. If $T_1$ is of dimension one, then we have $T_1 \supset \{\bar{x}\} \times (\epsilon_1, \epsilon_2)$. Recall that if the derivative $g'_{x'}(e)$ exists, then $g'_{x'}(e) = \text{calm} \ f_{e}(\bar{x})$ by Proposition 3.2. This would mean that $\text{calm} \ f_{e}(\bar{x}) \geq M_2$, which contradicts our earlier assumption of $\text{calm} \ f_{e}(\bar{x}) < M_2$. Therefore, the manifold $T_1$ is of dimension at least two.

Using Lemma 5.7 which we will prove later, we can construct the map $\varphi : [0, \hat{\epsilon}) \times (\epsilon_1, \epsilon_2) \to \text{cl} T_1$, such that its derivative with respect to the second variable exists and is continuous, and $\varphi(0, \epsilon) = (\bar{x}, \epsilon)$ for all $\epsilon \in (\epsilon_1, \epsilon_2)$.

For each $0 < \delta < 1$, consider the path $\tilde{x}_\delta : [\epsilon_1, \epsilon_2] \to \mathbb{R}^n$ defined by $\tilde{x}_\delta(\epsilon) := \varphi(\delta, \epsilon)$. We have

$$\tilde{f}_{\epsilon_2}(\tilde{x}_\delta(\epsilon_2)) - \tilde{f}_{\epsilon_1}(\tilde{x}_\delta(\epsilon_1)) = \int_{\epsilon_1}^{\epsilon_2} \nabla H(\tilde{x}_\delta(s), s) \cdot (\tilde{x}_\delta'(s), 1) \, ds = \int_{\epsilon_1}^{\epsilon_2} \nabla H(\tilde{x}_\delta(s), s) \cdot \tilde{x}_\delta'(s) \, ds + \int_{\epsilon_1}^{\epsilon_2} \nabla_s H(\tilde{x}_\delta(s), s) \, ds,$$
where $H(x, \delta) = \tilde{f}_t(x)$. The second component of $\nabla H(\tilde{x}_\delta(s), s)$ is simply $g'_{\tilde{x}_\delta}(s)$. The first component can be analyzed as follows:

$$\nabla_x H(\tilde{x}_\delta(s), s) \cdot \tilde{x}'_\delta(s) = \lim_{t \to 0} \frac{1}{t} \left( H(\tilde{x}_\delta(s) + t\tilde{x}'_\delta(s), s) - H(\tilde{x}_\delta(s), s) \right)$$

$$= \lim_{t \to 0} \frac{1}{t} \left( \tilde{f}_s (\tilde{x}_\delta(s)) + t\tilde{x}'_\delta(s) - \tilde{f}_s (\tilde{x}_\delta(s)) \right).$$

Provided that $t |\tilde{x}'_\delta(s)| < s$, $B_{s-t|\tilde{x}'_\delta(s)|}(\tilde{x}_\delta(s)) \subset B_s (\tilde{x}_\delta(s) + t\tilde{x}'_\delta(s))$, and so

$$\nabla_x H(\tilde{x}_\delta(s), s) \cdot \tilde{x}'_\delta(s) \geq \lim_{t \to 0} \frac{1}{t} \left( \tilde{f}_{s-t|\tilde{x}'_\delta(s)|}(\tilde{x}_\delta(s)) - \tilde{f}_s (\tilde{x}_\delta(s)) \right)$$

$$= |\tilde{x}'_\delta(s)| \lim_{t \to 0} \frac{1}{t} \left( \tilde{f}_{s-t|\tilde{x}'_\delta(s)|}(\tilde{x}_\delta(s)) - \tilde{f}_s (\tilde{x}_\delta(s)) \right)$$

$$= -|\tilde{x}'_\delta(s)| g'_{\tilde{x}_\delta}(s) \cdot \tilde{x}'_\delta(s).$$

Hence,

$$\tilde{f}_{\tilde{x}_\delta}(\tilde{x}_\delta(\epsilon_2)) - \tilde{f}_{\tilde{x}_\delta}(\tilde{x}_\delta(\epsilon_1))$$

$$= \int_{\epsilon_1}^{\epsilon_2} \nabla_x H(\tilde{x}_\delta(s), s) \cdot \tilde{x}'_\delta(s) \, ds + \int_{\epsilon_1}^{\epsilon_2} \nabla_s H(\tilde{x}_\delta(s), s) \, ds$$

$$\geq \int_{\epsilon_1}^{\epsilon_2} (1 - |\tilde{x}'_\delta(s)|) g'_{\tilde{x}_\delta}(s) \, ds.$$

Since the derivatives of $\varphi$ are continuous, $\tilde{x}'_\delta(s) \to \tilde{x}'_0(s) = 0$ as $\delta \to 0$ for $\epsilon_1 < s < \epsilon_2$. In fact, the term $|\tilde{x}'_\delta(s)|$ converges to zero uniformly in $[\epsilon_1, \epsilon_2]$. To see this, recall that $\tilde{x}'_\delta(s)$ is a partial derivative of $\varphi$. Since $\varphi$ is $C^1$, $\tilde{x}'_\delta(s)$ is continuous with respect to $s$ and $\delta$. For any $\beta > 0$ and $s \in [\epsilon_1, \epsilon_2]$, there exists $\gamma_s$ such that

$$|\tilde{x}'_\delta(s)| < \beta \text{ if } \delta < \gamma_s \text{ and } |\tilde{s} - s| < \gamma_s.$$

The existence of $\gamma_s$ such that

$$|\tilde{x}'_\delta(s)| < \beta \text{ if } \delta < \gamma \text{ and } s \in [\epsilon_1, \epsilon_2]$$

follows by the compactness of $[\epsilon_1, \epsilon_2]$. So we may choose $\delta$ small enough so that

$$(1 - |\tilde{x}'_\delta(s)|) = \frac{M_1 + M_2}{2M_1} \text{ for all } s \in [\epsilon_1, \epsilon_2].$$

Now, for $\delta$ small enough and $i = 1, 2$, we have $g'_{\tilde{x}_\delta}(\epsilon_i) < M_2$, so this gives us calm $\tilde{f}_{\tilde{x}_\delta}(\tilde{x}) = g'_{\tilde{x}_\delta}(\epsilon_i) < M_2$ by Proposition 3.2. Therefore, if $\delta$ is
small enough,
\[
|\tilde{f}_{\tilde{e}_i}(x_{\delta}(\tilde{e}_i)) - \tilde{f}_{\tilde{e}_i}(\bar{x})| \leq M_2 |x_{\delta}(\tilde{e}_i) - \bar{x}|.
\]

Recall that if the derivative \(g_{x_{\delta}}'(\epsilon)\) exists, then \(g_{x_{\delta}}'(\epsilon) = \text{calm} \tilde{f}_x(\bar{x})\) by Proposition 3.2. On the one hand, we have
\[
\tilde{f}_{\tilde{e}_2}(\bar{x}) - \tilde{f}_{\tilde{e}_1}(\bar{x}) = \int_{\tilde{e}_1}^{\tilde{e}_2} g_{x_{\delta}}'(s) \, ds \leq \int_{\tilde{e}_1}^{\tilde{e}_2} M_2 \, ds = M_2 (\tilde{e}_2 - \tilde{e}_1).
\]
But on the other hand, \(x_{\delta}(s) \in T_1\) for \(0 < \delta < 1\), and so \(g_{x_{\delta}(s)}'(s) \geq M_1\) by Lemma 5.4. If \(\delta\) is small enough, we have
\[
\begin{align*}
|\tilde{f}_{\tilde{e}_2}(\bar{x}) - \tilde{f}_{\tilde{e}_1}(\bar{x})| &\geq |\tilde{f}_{\tilde{e}_2}(x_{\delta}(\tilde{e}_2)) - \tilde{f}_{\tilde{e}_1}(x_{\delta}(\tilde{e}_1))| \\
&\quad - (|\tilde{f}_{\tilde{e}_2}(x_{\delta}(\tilde{e}_2)) - \tilde{f}_{\tilde{e}_2}(\bar{x})| + |\tilde{f}_{\tilde{e}_1}(x_{\delta}(\tilde{e}_1)) - \tilde{f}_{\tilde{e}_1}(\bar{x})|) \\
&\geq \int_{\tilde{e}_1}^{\tilde{e}_2} (1 - |x_{\delta}'(s)|) g_{x_{\delta}(s)}'(s) \, ds \\
&\quad - M_2 (|x_{\delta}(\tilde{e}_2) - \bar{x}| + |x_{\delta}(\tilde{e}_1) - \bar{x}|) \\
&\geq \int_{\tilde{e}_1}^{\tilde{e}_2} (1 - |x_{\delta}'(s)|) M_1 \, ds - M_2 (|x_{\delta}(\tilde{e}_2) - \bar{x}| + |x_{\delta}(\tilde{e}_1) - \bar{x}|) \\
&\geq \int_{\tilde{e}_1}^{\tilde{e}_2} \left( \frac{M_1 + M_2}{2} \right) \, ds - M_2 (|x_{\delta}(\tilde{e}_2) - \bar{x}| + |x_{\delta}(\tilde{e}_1) - \bar{x}|) \\
&= \left( \frac{M_1 + M_2}{2} \right) (\tilde{e}_2 - \tilde{e}_1) - M_2 (|x_{\delta}(\tilde{e}_2) - \bar{x}| + |x_{\delta}(\tilde{e}_1) - \bar{x}|).
\end{align*}
\]
As \(\delta\) is arbitrarily small and the terms \(|x_{\delta}(\tilde{e}_i) - \bar{x}| \to 0\) as \(\delta \to 0\) for \(i = 1, 2\), we have \(|\tilde{f}_{\tilde{e}_2}(\bar{x}) - \tilde{f}_{\tilde{e}_1}(\bar{x})| \geq \left( \frac{M_1 + M_2}{2} \right) (\tilde{e}_2 - \tilde{e}_1)\). This is a contradiction, and thus we are done. \(\square\)

Before we prove Lemma 5.7 below, we need to recall the definition of simplicial complexes from \cite[Section 3.2.1]{11}. A simplex with vertices \(a_0, \ldots, a_d\) is
\[
[a_0, \ldots, a_d] = \{ x \in \mathbb{R}^n \mid \exists \lambda_0, \ldots, \lambda_d \in [0, 1], \sum_{i=0}^{d} \lambda_i = 1 \text{ and } x = \sum_{i=0}^{d} \lambda_i a_i \}.
\]
The corresponding open simplex is
\[
(a_0, \ldots, a_d) = \{ x \in \mathbb{R}^n \mid \exists \lambda_0, \ldots, \lambda_d \in (0, 1), \sum_{i=0}^{d} \lambda_i = 1 \text{ and } x = \sum_{i=0}^{d} \lambda_i a_i \}.
\]
We shall denote by int(σ) the open simplex corresponding to the simplex σ. A face of the simplex σ = [a₀, ..., aₖ] is a simplex τ = [b₀, ..., bₑ] such that

\[ \{b₀, ..., bₑ\} \subset \{a₀, ..., aₖ\}. \]

A finite simplicial complex in \( \mathbb{R}^n \) is a finite collection \( K = \{σ₁, ..., σ_p\} \) of simplices \( σ_i \subset \mathbb{R}^n \) such that, for every \( σ_i, σ_j \in K \), the intersection \( σ_i \cap σ_j \) is either empty or is a common face of \( σ_i \) and \( σ_j \). We set \( |K| = \cup_{σ_i \in K} σ_i \); this is a semi-algebraic subset of \( \mathbb{R}^n \). We recall a result on relating semi-algebraic sets to simplicial complexes.

**Theorem 5.5.** [11, Theorem 3.12] Let \( S \subset \mathbb{R}^n \) be a compact semi-algebraic set, and \( S_1, ..., S_p \), semi-algebraic subsets of \( S \). Then there exists a finite simplicial complex \( K \) in \( \mathbb{R}^n \) and a semi-algebraic homeomorphism \( h : |K| \to S \), such that each \( S_k \) is the image by \( h \) of a union of open simplices of \( K \).

We need yet another result for the proof of Lemma 5.7.

**Proposition 5.6.** Suppose that \( φ : (0, 1)^2 \to \mathbb{R} \), not necessarily semi-algebraic, is continuous in \((0, 1)^2\). Let \( \text{gph} \ φ \subset (0, 1)^2 \times \mathbb{R} \) be the graph of \( φ \). Then for any \( t \in (0, 1) \), \( \text{cl} (\text{gph} \ φ) \cap (0, t) \times \mathbb{R} \) is either a single point or a connected line segment.

**Proof.** Suppose that \((0, t), a₁\) and \((0, t), a₂\) lie in \( \text{cl} (\text{gph} \ φ) \). We need to show that for any \( α \in (a₁, a₂) \), \((0, t), α\) lies in \( \text{cl} (\text{gph} \ φ) \).

For any \( ε > 0 \), we can find points \( p₁, p₂ \in (0, 1)^2 \) such that the points \((p₁, a₁), (p₂, a₂)\) are such that \( |aᵢ - aᵢ| < ε \) and \( |pᵢ - (0, t)| < ε \) for \( i = 1, 2 \). Recall that by definition \( aᵢ = φ (pᵢ) \) for \( i = 1, 2 \). Choose \( ε \) such that \( a₁ + ε < a₂ - ε \). By the intermediate value theorem, for any \( α \in (a₁ + ε, a₂ - ε) \), there exists a point \( p \) in the line segment \([p₁, p₂]\) such that \( φ (p) = α \). Moreover, \( |p - (0, t)| < \max_{i=1,2} |pᵢ - (0, t)| \). Letting \( ε \to 0 \), we see that \((0, t), α\) lies in \( \text{cl} (\text{gph} \ φ) \) as needed. \( \Box \)

We now prove our last result important for the proof of Theorem 5.3. The proof of the lemma below is similar to the proof of the Curve Selection Lemma in [11, Theorem 3.13].

**Lemma 5.7.** Let \( S \subset \mathbb{R}^n \) be a semi-algebraic set, and \( τ : [ε₁, ε₂] \to \mathbb{R}^n \) be a semi-algebraic curve such that \( τ ([ε₁, ε₂]) \cap S = \emptyset \) and \( τ ([ε₁, ε₂]) \subset \text{cl} (S) \). Then there exists a function \( ϕ : [0, 1] \times [ε₁, ε₂] \to \mathbb{R}^n \), with \( [ε₁, ε₂] \neq \emptyset \) and \([ε₁, ε₂] \subset [ε₁, ε₂] \), such that

\( \varphi (0, ε) = τ (ε) \) for \( ε \in [ε₁, ε₂] \) and \( \varphi ((0, 1) \times [ε₁, ε₂]) \subset S \).

(1) The partial derivative of \( ϕ \) with respect to the second variable, which we denote by \( \frac{∂}{∂ε} \varphi \), exists and is continuous in \([0, 1] \times [ε₁, ε₂] \).
**Proof.** Replacing $S$ with its intersection with a closed bounded set containing $\tau([\varepsilon_1, \varepsilon_2])$, we can assume $S$ is bounded. Then $\text{cl}(S)$ is a compact semi-algebraic set. By Theorem 5.5, there is a finite simplicial complex $K$ and a semi-algebraic homeomorphism $h : |K| \to \text{cl}(S)$, such that $S$ and $\tau([\varepsilon_1, \varepsilon_2])$ are images by $h$ of a union of open simplices in $K$. In particular, this means that there is an open interval $(\hat{\varepsilon}_1, \hat{\varepsilon}_2) \subset [\varepsilon_1, \varepsilon_2]$ such that $\tau((\hat{\varepsilon}_1, \hat{\varepsilon}_2))$ is an image by $h$ of a 1-dimensional open simplex in $K$. Since $h^{-1} \circ \tau((\hat{\varepsilon}_1, \hat{\varepsilon}_2))$ is in $\text{cl}(S)$ but not in $S$, there is a simplex $\sigma$ of $K$ which has $h^{-1} \circ \tau((\hat{\varepsilon}_1, \hat{\varepsilon}_2))$ lying in the boundary of $\sigma$, and $h(\text{int}(|\sigma|)) \subset S$.

Let $\delta$ be the barycenter of $\sigma$. Define the map $\delta : [0, 1] \times [\hat{\varepsilon}_1, \hat{\varepsilon}_2] \to \mathbb{R}^n$ by

$$\delta(t, \varepsilon) = (1 - t) h^{-1} \circ \tau(\varepsilon) + t \delta.$$

The map above satisfies $\delta((0, 1] \times (\hat{\varepsilon}_1, \hat{\varepsilon}_2)) \subset \text{int}(\sigma)$. By contracting the interval $[\hat{\varepsilon}_1, \hat{\varepsilon}_2]$ slightly, $\varphi = h \circ \delta$ satisfies property (1).

By contracting the interval $[\hat{\varepsilon}_1, \hat{\varepsilon}_2]$ if necessary and applying the decomposition theorem [10, Theorem 6.7], we can assume that $\varphi$ is $C^1$ in the set $(0, \hat{\ell}] \times [\hat{\varepsilon}_1, \hat{\varepsilon}_2]$ for some $\hat{\ell} \in (0, 1)$.

Since $\tau$ is semi-algebraic, we contract the interval $[\hat{\varepsilon}_1, \hat{\varepsilon}_2]$ again if necessary so that $\tau$ is $C^1$ there. Therefore, $\frac{\partial}{\partial \varepsilon}\varphi$ exists in $[0, \hat{\ell}] \times [\hat{\varepsilon}_1, \hat{\varepsilon}_2]$. It remains to show that $\frac{\partial}{\partial \varepsilon}\varphi$ is continuous in $[0, \hat{\ell}] \times [\hat{\varepsilon}_1, \hat{\varepsilon}_2]$. We do this by showing that $\frac{\partial}{\partial \varepsilon}\varphi_i : [0, \hat{\ell}] \times [\hat{\varepsilon}_1, \hat{\varepsilon}_2] \to \mathbb{R}$, the $i$th component of the derivative with respect to the second variable, is continuous for each $i$.

Since $\frac{\partial}{\partial \varepsilon}\varphi_i$ is continuous in $[0, \hat{\ell}] \times [\hat{\varepsilon}_1, \hat{\varepsilon}_2]$, it remains to show that it is continuous at every point in $\{0\} \times [\hat{\varepsilon}_1, \hat{\varepsilon}_2]$. The graph of $\frac{\partial}{\partial \varepsilon}\varphi_i$ corresponding to the domain $(0, \hat{\ell}] \times [\hat{\varepsilon}_1, \hat{\varepsilon}_2]$, which we denote by $\text{gph}(\frac{\partial}{\partial \varepsilon}\varphi_i)$, is a subset of $(0, \hat{\ell}] \times [\hat{\varepsilon}_1, \hat{\varepsilon}_2] \times \mathbb{R}$. We show that $((0, \varepsilon), \frac{\partial}{\partial \varepsilon}\varphi_i(0, \varepsilon)) \in \text{cl}(\text{gph}(\frac{\partial}{\partial \varepsilon}\varphi_i))$.

For small $t_1, t_2 > 0$, consider $\varphi_i(t_1, \varepsilon - t_2)$ and $\varphi_i(t_1, \varepsilon + t_2)$. By the intermediate value theorem, there is some $\hat{\varepsilon} \in (\varepsilon - t_2, \varepsilon + t_2)$ such that

$$\frac{\partial}{\partial \varepsilon}\varphi_i(t_1, \hat{\varepsilon}) = \frac{1}{2t_2} (\varphi_i(t_1, \varepsilon + t_2) - \varphi_i(t_1, \varepsilon - t_2)).$$

If $t_2$ were chosen such that

$$\frac{1}{2t_2} (\varphi_i(0, \varepsilon + t_2) - \varphi_i(0, \varepsilon - t_2)) - \frac{\partial}{\partial \varepsilon}\varphi_i(0, \varepsilon)$$

is small and $t_1$ is chosen such that

$$\frac{1}{2t_2} (\varphi_i(t_1, \varepsilon + t_2) - \varphi_i(t_1, \varepsilon - t_2)) - \frac{1}{2t_2} (\varphi_i(0, \varepsilon + t_2) - \varphi_i(0, \varepsilon - t_2))$$

is small, then $|\frac{\partial}{\partial \varepsilon}\varphi_i(t_1, \hat{\varepsilon}) - \frac{\partial}{\partial \varepsilon}\varphi_i(0, \varepsilon)|$ is small. Taking $t_2 \to 0$ and $t_1 \to 0$, we have $((0, \varepsilon), \frac{\partial}{\partial \varepsilon}\varphi_i(0, \varepsilon)) \in \text{cl}(\text{gph}(\frac{\partial}{\partial \varepsilon}\varphi_i))$ as desired.
Recall that the graph $\text{gph} \left( \frac{\partial}{\partial \epsilon} \varphi_i \right)$ is taken corresponding to the domain $(0, \bar{t}] \times [\tilde{\epsilon}_1, \tilde{\epsilon}_2]$, and is a manifold of dimension 2 in $\mathbb{R}^3$. Its boundary is of dimension 1 [11, Proposition 3.16], so the intersection of $\text{cl} \left( \text{gph} \left( \frac{\partial}{\partial \epsilon} \varphi_i \right) \right)$ with $\{0\} \times [\tilde{\epsilon}_1, \tilde{\epsilon}_2] \times \mathbb{R}$ is of dimension 1 as well, and is homeomorphic to a closed line segment. There cannot be an interval $[\tilde{\epsilon}_1, \tilde{\epsilon}_2] \subset [\bar{t}, \bar{t}]$ on which $\text{cl} \left( \text{gph} \left( \frac{\partial}{\partial \epsilon} \varphi_i \right) \right) \cap \{0\} \times \{\epsilon\} \times \mathbb{R}$ has more than one value for all $\epsilon \in [\tilde{\epsilon}_1, \tilde{\epsilon}_2]$ because by appealing to Proposition 5.6, this implies that the dimension cannot be 1. We note however that it is possible that there exists an $\bar{\epsilon} \in [\tilde{\epsilon}_1, \tilde{\epsilon}_2]$ such that $\text{cl} \left( \text{gph} \left( \frac{\partial}{\partial \epsilon} \varphi_i \right) \right) \cap \{0\} \times \{\bar{\epsilon}\} \times \mathbb{R}$ is a 1-dimensional line segment. This can only happen for only finitely many $\bar{\epsilon} \in [\tilde{\epsilon}_1, \tilde{\epsilon}_2]$ due to semi-algebraicity.

In any case, we can contract the interval $[\tilde{\epsilon}_1, \tilde{\epsilon}_2]$ if necessary so that $\text{cl} \left( \text{gph} \left( \frac{\partial}{\partial \epsilon} \varphi_i \right) \right) \cap \{0\} \times \{\epsilon\} \times \mathbb{R}$ is a single point for all $\epsilon \in [\tilde{\epsilon}_1, \tilde{\epsilon}_2]$. This means that for any $(t, \tilde{\epsilon}) \to (0, \epsilon)$, we have $\frac{\partial}{\partial \epsilon} \varphi_i (t, \tilde{\epsilon}) \to \frac{\partial}{\partial \epsilon} \varphi_i (0, \epsilon)$, establishing the continuity of $\frac{\partial}{\partial \epsilon} \varphi_i (t, \cdot)$ on $[0, \bar{t}] \times [\tilde{\epsilon}_1, \tilde{\epsilon}_2]$. A reparametrization allows us to assume that $\bar{t} = 1$, and we are done.

6. Quadratic Examples

In this section, we show how the robust regularization can be calculated for quadratic examples, which are more-or-less standard in the spirit of [3, 1]. We write $A \succeq 0$ for a real symmetric matrix $A$ if $A$ is positive semidefinite.

**Theorem 6.1.** (Euclidean norm) For any real $m \times n$ matrix $A$ and vector $b \in \mathbb{R}^m$, consider the function $g : \mathbb{R}^n \to \mathbb{R}$ defined by

$$g(x) = \|Ax + b\|_2,$$

Then the following properties are equivalent for any point $(x, t) \in \mathbb{R}^n \times \mathbb{R}$:

(i) $t \geq \tilde{g}_t (x)$

(ii) there exists a real $\mu$ such that

$$\begin{bmatrix}
    tI_m & Ax + b & \epsilon A \\
    (Ax + b)^T & t - \mu & 0 \\
    \epsilon A^T & 0 & \mu I_n
  \end{bmatrix} \succeq 0.$$

**Proof.** Applying [1, Thm 4.5.60] shows $t \geq \tilde{g}_t (x)$ holds if and only if there exist real $s$ and $\mu$ satisfying

$$\begin{bmatrix}
    sI_m & Ax + b & \epsilon A \\
    (Ax + b)^T & s - \mu & 0 \\
    \epsilon A^T & 0 & \mu I_n
  \end{bmatrix} \succeq 0.$$

and the result now follows immediately. □
Since the matrix in property (ii) above is an affine function of the variables $x$, $t$ and $\mu$, it follows that the robust regularization $\tilde{g}_\epsilon$ is “semidefinite-representable”, in the language of [1]. This result allows us to use $\tilde{g}_\epsilon$ in building tractable representations of convex optimization problems as semidefinite programs.

An easy consequence of the above result is a representation for the robust regularization of any strictly convex quadratic function.

**Corollary 6.2.** (quadratics) For any real positive definite $n$-by-$n$ matrix $H$, vector $c \in \mathbb{R}^n$, and scalar $d$, consider the function $h : \mathbb{R}^n \to \mathbb{R}$ defined by
\[
h(x) = x^T H x + 2c^T x + d.
\]
Then the following properties are equivalent for any point $(x, t) \in \mathbb{R}^n \times \mathbb{R}$:
1. $t \geq \tilde{h}_\epsilon(x)$;
2. there exist reals $s$ and $\mu$ such that
\[
\begin{bmatrix}
s I_n & (H^{1/2} x + H^{-1/2} c)^T \\
(H^{1/2} x + H^{-1/2} c) & s - \mu
\end{bmatrix}
\begin{bmatrix}
- s^2 + c^T H^{-1} c - d \\
\epsilon H^{1/2}
\end{bmatrix}
\begin{bmatrix}
s I_n \\
\epsilon H^{1/2}
\end{bmatrix}
\begin{bmatrix}
0 \\
0
\end{bmatrix}
\begin{bmatrix}
\epsilon H^{1/2} \\
0
\end{bmatrix}
\begin{bmatrix}
0 \\
\mu I_n
\end{bmatrix}
\geq 0.
\]

**Proof.** Clearly $t \geq \tilde{h}_\epsilon(x)$ if and only if
\[
\|y - x\|_2 \leq \epsilon \quad \Rightarrow \quad \|H^{1/2} y + H^{-1/2} c\|_2^2 \leq t - d + c^T H^{-1} c.
\]
This property in turn is equivalent to the existence of a real $s$ satisfying
\[
s^2 \leq t - d + c^T H^{-1} c
\]
and the result now follows from the preceding theorem. $\square$

Since the quadratic inequality
\[
t - s^2 + c^T H^{-1} c - d \geq 0
\]
is semidefinite-representable, so is the robust regularization $\tilde{h}_\epsilon$.

**7. 1-PeACEFUL SETS**

In this section, we prove that $X \subset \mathbb{R}^n$ is nearly radial implies $X$ is 1-peaceful using the Mordukhovich Criterion [23, Theorem 9.40], which relates the Lipschitz modulus of set-valued maps to normal cones of its graph. The next section discusses further properties of nearly radial sets and how they are common in analysis.

The Mordukhovich Criterion requires the domain of the set-valued map to be $\mathbb{R}^n$, so we recall the map $\tilde{\Phi}_\epsilon : \mathbb{R}^n \rightrightarrows \mathbb{R}^n$ by $\tilde{\Phi}_\epsilon(x) = B_\epsilon(x) \cap X$. Recall that $\tilde{\Phi}_\epsilon|_X = \Phi_\epsilon$ and $\text{lip} \tilde{\Phi}_\epsilon(x) \leq \text{lip} \tilde{\Phi}_\epsilon(x)$ for all $x \in X$. Let us
recall the definitions of normal cones, the Aubin property and the graphical modulus.

**Definition 7.1.** [23, Definition 6.3] Let $X \subset \mathbb{R}^n$ and $\bar{x} \in X$. A vector $v$ is normal to $X$ at $\bar{x}$ in the regular sense, or a regular normal, written $v \in \hat{N}_X(\bar{x})$, if
\[
\langle v, x - \bar{x} \rangle \leq o(|x - \bar{x}|) \quad \text{for } x \in X.
\]
It is normal to $X$ at $\bar{x}$ in the general sense, or simply a normal vector, written $v \in N_X(\bar{x})$, if there are sequences $x^\nu \to \bar{x}$ and $v^\nu \to v$ with $v^\nu \in \hat{N}_X(x^\nu)$.

**Definition 7.2.** [23, Definition 9.36] For $X \subset \mathbb{R}^n$, a mapping $S : X \rightrightarrows \mathbb{R}^m$ has the Aubin property at $\bar{x}$ for $\bar{u}$, where $\bar{x} \in X$ and $\bar{u} \in S(\bar{x})$, if $\text{gph} \, S$ is locally closed at $(\bar{x}, \bar{u})$ and there are neighborhoods $V$ of $\bar{x}$ and $W$ of $\bar{u}$ such that
\[
S(x') \cap W \subset S(x) + \kappa |x' - x| \mathbb{B} \quad \text{for all } x, x' \in X \cap V.
\]

The graphical modulus of $S$ at $\bar{x}$ for $\bar{u}$ is
\[
\text{lip} S(\bar{x} \mid \bar{u}) := \inf \{ \kappa \mid \text{There are neighbourhoods } V \text{ of } \bar{x}, W \text{ of } \bar{u} \text{ such that } S(x') \cap W \subset S(x) + \kappa |x' - x| \mathbb{B} \quad \text{for all } x, x' \in X \cap V \}.
\]

If $S$ is single-valued at $\bar{x}$, then in keeping with the notation of lip in Definition 2.1, we write $\text{lip} S(\bar{x})$ instead of $\text{lip} S(\bar{x} \mid S(\bar{x}))$. Note that this equals $\text{lip} S(\bar{x})$ if $S$ is continuous at $\bar{x}$.

A set-valued map $S$ is locally compact around $\bar{x}$ if there exist a neighborhood $V$ of $\bar{x}$ and a compact set $C \subset Y$ such that $S(V) \subset C$. This is equivalent to $S(V)$ being a bounded set, which is the case when $S$ is outer semicontinuous and $S(\bar{x})$ is bounded. If $S$ is outer semicontinuous and locally compact at $\bar{x}$, then by [20, Theorem 1.42], the Lipschitz modulus and the Aubin property are related by
\[
\text{lip} S(\bar{x}) = \max_{\bar{u} \in S(\bar{x})} \{ \text{lip} S(\bar{x} \mid \bar{u}) \}.
\]

In finite dimensions, we need $S(\bar{x})$ to be bounded and $S$ to be outer semicontinuous for the formula above to hold.

Here is a lemma on convex cones.

**Lemma 7.3.** Given any two convex cones $C_1$ and $C_2$ polar to each other and any vector $x$, we have
\[
(d(x, C_1))^2 + (d(x, C_2))^2 = \|x\|^2
\]
Proof. This is a simple consequence of [23, Exercise 12.22] \(\square\)

We now present our result on the relation between 1-peaceful sets and nearly radial sets.

**Theorem 7.4.** If \(X\) is nearly radial at \(\bar{x}\), then \(X\) is 1-peaceful at \(\bar{x}\). The converse holds if \(X\) is subdifferentially regular for all points in a neighborhood around \(\bar{x}\).

**Proof.** The graph of \(\tilde{\Phi}_\epsilon\) is the intersection of \(\mathbb{R}^n \times X\) and the set \(D \subset \mathbb{R}^n \times \mathbb{R}^n\) defined by

\[
D := \{(x, y) \mid ||x - y|| \leq \epsilon\}.
\]

By applying a rule on the normal cones of products of sets [23, Proposition 6.41], we infer that \(N_{\mathbb{R}^n \times X} (x, y) = \{0\} \times N_X (y)\). Define the real valued function \(g_0 : \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}^+\) by \(g_0 (x, y) := \frac{1}{2} ||x - y||^2\). Then the gradient of \(g_0\) is \(\nabla g_0 (x, y) = (x - y, y - x)\).

>From this point, we assume that \(||x - y|| = \epsilon\). The normal cone of \(D\) at \((x, y)\) is \(N_D (x, y) = \mathbb{R}^+ \{(x - y, y - x)\}\) using [23, Exercise 6.7]. On applying a rule on the normal cones of intersections [23, Theorem 6.42], we get

\[
N_{\text{gph} \tilde{\Phi}_\epsilon} (x, y) \subset (\{0\} \times N_X (y)) + \mathbb{R}^+ \{(x - y, y - x)\}.
\]

Furthermore, if \(X\) is subdifferentially regular at \(y\), the above set inclusion is an equation. By the Mordukhovich criterion [23, Theorem 9.40], \(\tilde{\Phi}_\epsilon\) has the Aubin Property at \((x, y)\) if and only if the graphical modulus \(\text{lip} \tilde{\Phi}_\epsilon (x \mid y)\) is finite. It can be calculated by appealing to the formulas for the coderivative \(D^*\) [23, Definition 8.33] and outer norm \(|\cdot|^+\) [23, Section 9D] below.

\[
\text{lip} \tilde{\Phi}_\epsilon (x \mid y) = \left| D^* \tilde{\Phi}_\epsilon (x \mid y) \right|^+ \quad \text{(by [23, Theorem 9.40])}
\]

\[
= \sup_{w \in \mathbb{R}^n} \sup_{z \in D^* \tilde{\Phi}_\epsilon (w)} \|z\| \quad \text{(by [23, Section 9D])}
\]

\[
= \sup \left\{ ||z|| \mid (w, z) \in \text{gph} D^* \tilde{\Phi}_\epsilon, ||w|| \leq 1 \right\}
\]

\[
= \sup \left\{ ||z|| \mid (-z, w) \in N_{\text{gph} \tilde{\Phi}_\epsilon} (x, y), ||w|| \leq 1 \right\}
\]

\[
\quad \text{(by [23, Definition 8.33])}
\]

\[
\leq \sup \left\{ ||z|| \mid (-z, w) \in (\{0\} \times N_X (y)) + \mathbb{R}^+ \{(x - y, y - x)\}, ||w|| \leq 1 \right\}
\]

(7.2)

We can assume that \(z = y - x\) with a rescaling, and \(w = y - x + v\) for some \(v \in N_X (y)\). Since \((\{0\} \times N_X (y)) + \mathbb{R}^+ \{(x - y, y - x)\}\) is positively
homogeneous set, we could find the supremum of $\|z\|^{\|w\|}$ in the same set and the formula reduces to

$$\text{lip } \tilde{\Phi}_\epsilon (x \mid y) \leq \sup_{v \in N_X(y)} \frac{\|y - x\|}{\|y - x + v\|}$$

$$= \sup_{v \in N_X(y)} \frac{\|x - y\|}{\|(x - y) - v\|}$$

$$= \frac{\|x - y\|}{d(x - y, N_X(y))}. \quad (7.3)$$

For a fixed $x \neq y$, say $\bar{x}$, we have $1/\text{lip } \tilde{\Phi}_\epsilon (\bar{x} \mid y) \geq \frac{d(\bar{x} - y, N_X(y))}{\|\bar{x} - y\|}$. First, we prove that for any open set $W$ about $\bar{x}$, we have

$$\inf_{y \in W \cap X \setminus \bar{x}} \frac{d(\bar{x} - y, N_X(y))}{\|\bar{x} - y\|} = \inf_{y \in W \cap X \setminus \bar{x}} \frac{d(\bar{x} - y, \hat{N}_X(y))}{\|\bar{x} - y\|}. \quad (7.4)$$

It is clear that “$\leq$” holds because $\hat{N}_X(y) \subset N_X(y)$, so we proceed to prove the other inequality. Consider $d(\bar{x} - y, N_X(y))$. Let $v \in P_{N_X(y)}(\bar{x} - y)$, the projection of $(\bar{x} - y)$ onto $N_X(y)$. Then $v \in N_X(y)$, and so there exists $y_i \to y$, with $y_i \in W \cap X$, and $v_i \to v$ such that $v_i \in \hat{N}_X(y_i)$. So

$$d(\bar{x} - y, N_X(y)) = d(\bar{x} - y, \mathbb{R}_+(v))$$

$$= \lim_{i \to \infty} d(\bar{x} - y, \mathbb{R}_+(v_i))$$

$$= \lim_{i \to \infty} d(\bar{x} - y_i, \mathbb{R}_+(v_i))$$

$$\geq \limsup_{i \to \infty} d(\bar{x} - y_i, \hat{N}_X(y_i))$$

$$\Rightarrow \frac{d(\bar{x} - y, N_X(y))}{\|\bar{x} - y\|} \geq \limsup_{i \to \infty} \frac{d(\bar{x} - y_i, \hat{N}_X(y_i))}{\|\bar{x} - y_i\|}.$$}

Thus equation 7.4 holds. Therefore

$$\liminf_{y \to \bar{x}} \frac{d(\bar{x} - y, \hat{N}_X(y))}{\|\bar{x} - y\|} \geq 1 \text{ implies } \limsup_{y \to \bar{x}} \text{lip } \tilde{\Phi}_{\|x - y\|} (\bar{x} \mid y) \leq 1,$$

so we may now consider only regular normal cones.

By Lemma 7.3, we deduce the following:

$$d(\bar{x} - y, \hat{N}_X(y))^2 + d(\bar{x} - y, \hat{N}_X(y)^*)^2 = \|\bar{x} - y\|^2 \text{ for } y \in X.$$
Since $T_X(y)^* = \tilde{N}_X(y)$ always [23, Theorem 6.28(a)], we apply Lemma 7.3 and get
\[ d\left((\bar{x} - y, \tilde{N}_X(y))\right)^2 + d\left((\bar{x} - y, T_X(y)^*)\right)^2 = \|\bar{x} - y\|^2 \text{ for } y \in X. \]
As $T_X(y) \subset T_X(y)^*$ [23, Corollary 6.21], this implies that
\begin{equation}
(7.5) \quad d\left((\bar{x} - y, \tilde{N}_X(y))\right)^2 + d\left((\bar{x} - y, T_X(y))\right)^2 \geq \|\bar{x} - y\|^2 \text{ for } y \in X.
\end{equation}

Note that if $X$ is nearly radial at $\bar{x}$, then $1/\|\bar{x} - y\| \to 1$ as $\epsilon = \|\bar{x} - y\| \downarrow 0$, $y \in X$. This means that
\[ \limsup_{y \to \bar{x}, y \neq \bar{x}} \frac{1}{\|\bar{x} - y\|} d\left((\bar{x} - y, \tilde{N}_X(y))\right) \leq 1, \]
where $y \to \bar{x}$ means $y \in X$ and $y \to \bar{x}$. Consequently
\[ \limsup_{y \to \bar{x}, y \neq \bar{x}} \frac{1}{\|\bar{x} - y\|} d\left((\bar{x} - y, T_X(y))\right) \to 0 \text{ as } y \to \bar{x} \text{ and } y \neq \bar{x}, \]
which means that $X$ is nearly radial at $\bar{x}$. □

Finally, 1-peaceful sets are interesting in robust regularization for another reason. The Lipschitz modulus of the robust regularization over 1-peaceful sets have Lipschitz modulus bounded above by that of the original function, as the following result shows.

**Proposition 7.5.** If $X$ is 1-peaceful and $F : X \to \mathbb{R}^n$ is locally Lipschitz at $\bar{x}$, then
\[ \limsup_{\epsilon \to 0} \text{lip } F_{\epsilon}(\bar{x}) \leq \text{lip } F(\bar{x}). \]
Proof. We use a set-valued chain rule [23, Exercise 10.39]. Recall the formula \( F_\epsilon = (F \circ \tilde{\Phi}_\epsilon) \mid_X \). The mapping \((x, u) \mapsto \tilde{\Phi}_\epsilon(x) \cap F^{-1}(u)\) is locally bounded because the map \( x \mapsto \tilde{\Phi}_\epsilon(x) \) is locally bounded. Thus \[
\text{lip } F_\epsilon(\bar{x}) \leq \text{lip } \tilde{\Phi}_\epsilon(\bar{x}) \cdot \max_{x \in \tilde{\Phi}_\epsilon(\bar{x})} \text{lip } F(x).
\]
By Theorem 7.4, \( \lim_{\epsilon \to 0} \text{lip } \tilde{\Phi}_\epsilon(\bar{x}) \leq 1 \). Also, since \( \text{lip } F : \mathbb{R}^n \to \mathbb{R}^+ \) is upper semicontinuous, \( \limsup_{\epsilon \to 0} \max_{x \in \tilde{\Phi}_\epsilon(\bar{x})} \text{lip } F(x) \leq \text{lip } F(\bar{x}) \). Taking limits to both sides gives us what we need.

8. NEARLY RADIAL SETS

As highlighted in Section 7, nearly radial sets are 1-peaceful. In this section, we study the properties of nearly radial sets and give examples of nearly radial sets to illustrate their abundance in analysis.

We contrast the definition of nearly radial sets given before Proposition 4.5 with a stronger property introduced by [25], which is the uniform version of the same idea. This idea was called \( o(1) \)-convexity in [25].

**Definition 8.1.** (nearly convex sets) A set \( X \subset \mathbb{R}^n \) is nearly convex at a point \( \bar{x} \in X \) if
\[
\text{dist}(y, x + T_X(x)) = o(\|x - y\|) \quad \text{as} \quad x, y \to \bar{x} \quad \text{in} \quad X.
\]
The set \( X \) is nearly convex if it is nearly convex at every point \( X \).

Clearly if a set is nearly convex at a point, then it is nearly radial there, but the class of nearly radial sets is considerably broader. For example, the set
\[
X = \{x \in \mathbb{R}^2 : x_1x_2 = 0\}
\]
is nearly radial at the origin but not nearly convex there, since as \( n \to \infty \) the points \( x_n = (n^{-1}, 0) \) and \( y_n = (0, n^{-1}) \) approach the origin in \( X \) and yet
\[
\text{dist}(y_n, x_n + T_X(x_n)) = n^{-1} \neq o(\|x_n - y_n\|).
\]

It is immediate that convex sets are nearly convex, and hence nearly radial. A straightforward exercise shows that smooth manifolds are also nearly convex, and hence again nearly radial. These observations are both special cases of the following result, rather analogous to [25, Theorem 2.2].

A set \( X \subset \mathbb{R}^n \) is amenable [23, Section 10F] at a point \( \bar{x} \in X \) if there is an open neighborhood \( V \) of \( \bar{x} \), a \( C^1 \) mapping \( F : V \to \mathbb{R}^m \), and a closed convex set \( D \subset \mathbb{R}^m \), such that
\[
X \cap V = \{x \in V : F(x) \in D\}
\]
and
\[
N_D(F(\bar{x})) \cap N(\nabla F(\bar{x})^*) = \{0\}.
\]
where $N_D(\cdot)$ denotes the normal cone to $D$, and $N(\cdot)$ denotes null space. If in fact $F$ is $C^2$ then we call $X$ strongly amenable [23, Definition 10.23] at $\bar{x}$.

**Theorem 8.2.** (amenable implies nearly radial) Suppose the set $X \subset \mathbb{R}^n$ is amenable at the point $\bar{x} \in X$. Then $X$ is nearly convex (and hence nearly radial) at $\bar{x}$.

**Proof.** Since $X$ is amenable at $\bar{x}$, we can suppose property (8.6) holds. Suppose without loss of generality $\bar{x} = 0$, and consider a sequence of points $x_r, y_r \to 0$ in the set $X \cap V$. We want to show

$$\text{dist}(y_r, x_r + T_X(x_r)) = o(\|x_r - y_r\|).$$

Without loss of generality we can suppose $x_r \neq y_r$ for all $r$, and denote the unit vectors $\|x_r - y_r\|^{-1}(x_r - y_r)$ by $z_r$. We want to prove

$$d_r = \min\{\|w + z_r\| : w \in T_X(x_r)\} \to 0.$$

The unique minimizer $w_r \in T_X(x_r)$ in the above projection problem satisfies

$$d_r = \|w_r + z_r\|$$

$$w_r + z_r \in -N_X(x_r) = -\nabla F(x_r)^*N_D(F(x_r))$$

$$\langle w_r, w_r + z_r \rangle = 0,$$

by [23, Exercise 10.26(d)]. Choose vectors $u_r \in -N_D(F(x_r))$ such that

$$w_r + z_r = \nabla F(x_r)^*u_r.$$

We next observe that the sequence of vectors $\{u_r\}$ is bounded. Otherwise, we could choose a subsequence $\{u_r\}$ satisfying $\|u_r\| \to \infty$, and then any limit point of the sequence of unit vectors $\left\{\|u_r\|^{-1}u_r\right\}$ must lie in the set $-N_D(F(0)) \cap N(\nabla F(0)^*)$, contradicting property (8.6).

We now have

$$0 \leq d_r^2 = \langle z_r, \nabla F(x_r)^*u_r \rangle = \langle \nabla F(x_r)z_r, u_r \rangle$$

$$= \langle \nabla F(x_r)z_r - \|x_r - y_r\|^{-1}[F(x_r) - F(y_r)], u_r \rangle$$

$$+ \langle \|x_r - y_r\|^{-1}[F(x_r) - F(y_r)], u_r \rangle.$$

The first term converges to zero, using the smoothness of the mapping $F$ and the boundedness of the sequence $\{u_r\}$. On the other hand, since the set $D$ is convex, we have $F(y_r) - F(x_r) \in T_D(F(x_r))$, and $u_r \in -N_D(F(x_r))$ by assumption, so the second term is nonpositive, and the result follows. □

It is worth comparing these notions to a property that is slightly stronger still: prox-regularity (in the terminology of [23, Section 13F]), or $O(2)$-convexity [25].
Definition 8.3. (prox-regular sets) A set \( X \subset \mathbb{R}^n \) is **prox-regular** at a point \( \bar{x} \in X \) if
\[
\text{dist} \left( y, x + T_X(x) \right) = O \left( \| x - y \|^2 \right) \quad \text{as} \quad x, y \rightarrow \bar{x} \quad \text{in} \quad X.
\]

Theorem 8.2 (amenable implies nearly radial) is analogous to the fact that strong amenability implies prox-regularity [23, Proposition 13.32] (and also to [25, Proposition 2.3]).

The class of nearly radial sets is very broad, as the following easy result (which fails for nearly convex sets) emphasizes.

Proposition 8.4. (unions) If the sets \( X_1, X_2, \ldots, X_n \) are each nearly radial at the point \( \bar{x} \in \bigcap_j X_j \), then so is the union \( \bigcup_j X_j \).

**Proof.** If the result fails, there is a sequence of points \( x_r \rightarrow \bar{x} \) in \( \bigcup_j X_j \) and real \( \epsilon > 0 \) such that
\[
\text{dist} \left( \frac{\bar{x} - x_r}{\| \bar{x} - x_r \|}, T_{\bigcup_j X_j}(x_r) \right) \geq \epsilon \quad \text{for all} \quad r.
\]

By taking a subsequence, we can suppose that there is an index \( i \) such that \( x_r \in X_i \) for all \( r \). But then we know
\[
\text{dist} \left( \frac{\bar{x} - x_r}{\| \bar{x} - x_r \|}, T_{X_i}(x_r) \right) \rightarrow 0,
\]
which contradicts inequality (8.7), since \( T_{X_i}(x_r) \subset T_{\bigcup_j X_j}(x_r) \). \qed

A key concept in variational analysis is the idea of Clarke regularity (see for example [8, 9, 23]). We make no essential use of this concept in our development, but it is worth remarking on the relationship (or lack of it) between the nearly radial property and Clarke regularity. Note first that nearly radial sets need not be Clarke regular: the union of the two coordinate axes in \( \mathbb{R}^2 \) is nearly radial at the origin, for example, but it is not Clarke regular there.

On the other hand, Clarke regular sets need not be nearly radial.

**Example 8.5.** Consider the function \( f : \mathbb{R} \rightarrow \mathbb{R} \) defined by
\[
f(x) = \begin{cases} 
2^{-n} - 2^{-n-1}(2 - 2^{n+1}|x|)^{1+2^{-n}} & \text{if} \ 2^{-n-1} \leq |x| \leq 2^{-n} \ (n \in \mathbb{N}) \\
0 & \text{if} \ x = 0.
\end{cases}
\]
The function \( f \) is even, and its graph consists of concave segments on each interval \( x \in [2^{-n-1}, 2^{-n}] \), passing through the point \( 2^{-n}(1, 1) \) with left derivative zero, and through the point \( 2^{-n-1}(1, 1) \) with right derivative \( 1+2^{-n} \).

A routine calculation now shows that this function is everywhere regular, and hence its epigraph \( \text{epi} \ f \) is everywhere Clarke regular. However, \( \text{epi} \ f \)
Lipschitz Behavior of the Robust Regularization

is not nearly radial at the origin. To see this, observe that for each \( n \in \mathbb{N} \), if we consider the sequence \( x_n = 2^{-n}(1, 1) \to (0, 0) \), then we have

\[
T_{\text{epi}} f(x_n) = \{ (x, y) : y \geq (1 + 2^{1-n}) \max\{x, 0\} \},
\]

so

\[
\text{dist}(0, x_n + T_{\text{epi}} f(x_n)) = \frac{\|x_n\|}{\sqrt{2}},
\]

contradicting the definition of a nearly radial set. \( \diamond \)

This is yet another attractive property for semi-algebraic sets.

**Theorem 8.6.** (semi-algebraic sets) Semi-algebraic sets are nearly radial.

**Proof.** Suppose the origin lies in a semi-algebraic set \( X \subset \mathbb{R}^n \). We will show that \( X \) is nearly radial at the origin.

If the result fails, then there is a real \( \delta > 0 \) and a sequence of points \( y_r \to 0 \) in \( X \) such that

\[
\|u + \frac{y_r}{\|y_r\|}\| > \delta \quad \text{for all } u \in T_X(y_r).
\]

Hence for each index \( r \) there exists a real \( \gamma_r > 0 \) such that

\[
\left\| \frac{z - y_r}{\|z - y_r\|} + \frac{y_r}{\|y_r\|} \right\| > \delta \quad \text{for all } z \in X \text{ such that } 0 < \|z - y_r\| < \gamma_r.
\]

Consequently, each point \( y_r \) lies in the set

\[
X_0 = \left\{ y \in X \mid \exists \gamma > 0 \text{ so } \left\| \frac{z - y}{\|z - y\|} + \frac{y}{\|y\|} \right\| > \delta \quad \forall z \in X \setminus \{y\} \text{ with } \|z - y\| < \gamma \right\},
\]

so \( 0 \in \text{cl} \, X_0 \).

By quantifier elimination (see for example the discussion of the Tarski-Seidenberg Theorem in [2, p. 62]), the set \( X_0 \) is semi-algebraic. Hence the Curve Selection Lemma (see [2, p. 98] and [19]) shows that there is a real-analytic path \( p : [0, 1] \to \mathbb{R}^n \) such that \( p(0) = 0 \) and \( p(t) \in X_0 \) for all \( t \in (0, 1] \). For some positive integer \( k \) and nonzero vector \( g \in \mathbb{R}^n \) we have, for small \( t > 0 \),

\[
p(t) = gt^k + O(t^{k+1})
\]

\[
p'(t) = kgt^{k-1} + O(t^k),
\]

and in particular both \( p(t) \) and \( p'(t) \) are nonzero. For any such \( t \) we know

\[
\left\| \frac{z - p(t)}{\|z - p(t)\|} + \frac{p(t)}{\|p(t)\|} \right\| > \delta
\]
for any point \( z \in X \setminus \{ p(t) \} \) close to \( p(t) \). Hence for any real \( s \neq t \) close to \( t \) we have
\[
\left\| \frac{p(s) - p(t)}{\|p(s) - p(t)\|} + \frac{p(t)}{\|p(t)\|} \right\| > \delta.
\]
Taking the limit as \( s \uparrow t \) shows
\[
\left\| \frac{p(t)}{\|p(t)\|} - \frac{p'(t)}{\|p'(t)\|} \right\| \geq \delta
\]
for all small \( t > 0 \). But since
\[
\lim_{t \downarrow 0} \frac{p(t)}{\|p(t)\|} = \frac{g}{\|g\|} = \lim_{t \downarrow 0} \frac{p'(t)}{\|p'(t)\|},
\]
this is a contradiction. \( \square \)

By contrast, semi-algebraic sets need not be nearly convex. For example, the union of the two coordinate axes in \( \mathbb{R}^2 \) is semi-algebraic, but it is not nearly convex at the origin.

Acknowledgement. Thanks to Jim Renegar for helpful discussions concerning Theorem 8.6 (semi-algebraic sets), and to Jon Borwein for the statement of the definition of nearly radial sets before Proposition 4.5. The first author’s research was supported in part by U.S. NSF grant DMS-080657.

REFERENCES

ADRIAN S. LEWIS, SCHOOL OF OPERATIONS RESEARCH AND INFORMATION ENGINEERING, CORNELL UNIVERSITY, ITHACA, NY, 14853.
E-mail address: aslewis@orie.cornell.edu

C. H. JEFFREY PANG, CENTER FOR APPLIED MATHEMATICS, CORNELL UNIVERSITY, ITHACA, NY, 14853.
E-mail address: cp229@cornell.edu