On Inner Calmness*, Generalized Calculus, and Derivatives of the Normal-cone Map

Matúš Benko
Institute of Computational Mathematics, Johannes Kepler University
Altenberger Str. 69, 4040 Linz, Austria

NuMa-Report No. 2019-03
October 2019
Technical Reports before 1998:

1995

95-1 Hedwig Brandstetter
Was ist neu in Fortran 90? March 1995

95-2 G. Haase, B. Heise, M. Kuhn, U. Langer
Adaptive Domain Decomposition Methods for Finite and Boundary Element Equations. August 1995

95-3 Joachim Schöberl
An Automatic Mesh Generator Using Geometric Rules for Two and Three Space Dimensions. August 1995

1996

96-1 Ferdinand Kickinger
Automatic Mesh Generation for 3D Objects. February 1996

96-2 Mario Goppold, Gundolf Haase, Bodo Heise und Michael Kuhn
Preprocessing in BE/FE Domain Decomposition Methods. February 1996

96-3 Bodo Heise
A Mixed Variational Formulation for 3D Magnetostatics and its Finite Element Discretisation. February 1996

96-4 Bodo Heise und Michael Jung
Robust Parallel Newton-Multilevel Methods. February 1996

96-5 Ferdinand Kickinger
Algebraic Multigrid for Discrete Elliptic Second Order Problems. February 1996

96-6 Bodo Heise
A Mixed Variational Formulation for 3D Magnetostatics and its Finite Element Discretisation. May 1996

96-7 Michael Kuhn
Benchmarking for Boundary Element Methods. June 1996

1997

97-1 Bodo Heise, Michael Kuhn and Ulrich Langer
A Mixed Variational Formulation for 3D Magnetostatics in the Space $H(\text{rot}) \cap H(\text{div})$ February 1997

97-2 Joachim Schöberl
Robust Multigrid Preconditioning for Parameter Dependent Problems I: The Stokes-type Case. June 1997

97-3 Ferdinand Kickinger, Sergei V. Nepomnyashchikh, Ralf Pfau, Joachim Schöberl
Numerical Estimates of Inequalities in $H^1$. August 1997

97-4 Joachim Schöberl
Programmbeschreibung NAOMI 2D und Algebraic Multigrid. September 1997

From 1998 to 2008 technical reports were published by SFB013. Please see
http://www.sfb013.uni-linz.ac.at/index.php?id=reports

From 2004 on reports were also published by RICAM. Please see
http://www.ricam.oeaw.ac.at/publications/list/

For a complete list of NuMa reports see
http://www.numa.uni-linz.ac.at/Publications/List/
On inner calmness*, generalized calculus, and derivatives of the normal-cone map

Matúš Benko*

Abstract. In this paper, we study the inner-type continuity and Lipschitzian properties of set-valued maps. We introduce the new notion of inner calmness* and show its remarkable features, in particular that it is satisfied by polyhedral maps. Then we utilize these inner-type conditions to extend the known and to build new generalized differential calculus rules, focusing on the primal objects (e.g. tangent cones). The exact chain rule for the graphical derivatives deserves the special attention. Finally, we apply these results to compute or estimate the generalized derivatives of the so-called normal cone mapping, that are critical for stability analysis, etc. As a specific application, we derive some interesting results regarding the newly developed property of semismoothness* of the normal cone maps.

Key words. inner calmness*, generalized differential calculus, tangents to image sets, chain rule, normal-cone mapping, polyhedral multifunction

AMS Subject classification. 49J53, 49J52, 90C31

1 Introduction

The so-called normal cone mapping, closely related to variational inequalities, is a standard tool of variational analysis that plays the crucial role in the study of various stability and sensitivity properties of the solutions of mathematical programs as well as in the formulation of optimality conditions for mathematical programs with equilibrium constraints. For more information about the normal cone mapping and related issues we refer to the standard textbooks [4, 8, 23, 28, 29, 34]. Recently a lot of success has been achieved in computation of the graphical derivative of the normal cone mapping, see, e.g., [3, 5, 14, 15, 17, 19]. These results were obtained by a direct approach, i.e., without relying on the generalized calculus rules. Apart from the obvious fact that the direct approach may be more flexible in situations where the calculus falls short, there is yet another basic limitation, namely the lack of a suitable calculus for primal objects, such as the graphical derivative based on the tangent cone.

Observing the above results and their proofs, we ask ourselves the question, whether there are some underlying calculus principles in play and whether we can properly understand and identify them and bring them to the light. Not only we can achieve this and propose improved as well as new calculus rules, we also discover a new property of inner calmness*, which turns out to be the most essential element of this calculus and it also seems to be very interesting on its own.

The inner-type conditions, be it the inner semicontinuity or some inner Lipschitzian property, are considerably underdeveloped compared to their outer counterparts, such as the outer semicontinuity

*Institute of Computational Mathematics, Johannes Kepler University Linz, A-4040 Linz, Austria, benko@numa.uni-linz.ac.at
and the calmness. Especially the calmness and its inverse equivalent, metric subregularity, have already been extensively studied by many prominent researchers, see [7, 8, 9, 10, 11, 20, 22, 23, 24, 29, 31] and the references therein. In this paper, the inner-type conditions are at the center of attention. In particular, in Section 3 we make the strong case for the inner semicompactness and the inner calmness*, by showing that they are satisfied in for certain general multiplier map. Moreover, we show that polyhedral set-valued maps enjoy the inner calmness* property, hence providing an inner counterpart to the famous result on calmness (upper Lipschitzness) of polyhedral maps by Robinson [32].

The generalized differential calculus belongs among the most fundamental tools of modern variational analysis [23, 26, 28, 29, 31, 34]. In calculus, there are two main principles, which we will refer to as “forward” and “backward”. The “forward” principle corresponds to the image rule, i.e., when the set under investigation is generated as an image of another given set under a given map (\( Q := \varphi(C) \)). The “backward” principle corresponds to the pre-image rule, i.e., when the set under investigation is generated as a pre-image of another given set under a given map (\( C := \varphi^{-1}(Q) \)). The image and pre-image rule form the base of the whole calculus and almost all the standard calculus rules for sets, functions and set-valued maps can be derived from these two results. Of course, one can choose a different set of results as a base. It is very common to start with (extended real-valued) functions.

The backward principle seems to be better understood and more worked out and is closely related to a condition of the (better known) outer-type. Indeed, the main assumption for the backward results, typically called qualification condition, is known to be the calmness of the associated perturbation mapping, often equivalently expressed via the metric subregularity of the feasibility mapping [20, 24]. In Section 4, we propose comprehensive forward calculus rules, where the inner-type properties play the key role.

The calculus rules are divided from yet another important perspective, namely whether they deal with the primal or the dual objects. Hence, the most studied and, arguably, the most important, are in fact backward rules for dual objects, while the backward rules for primal object are in turn the simplest ones. Indeed, in the pre-image rule for tangent cones [34, Theorem 6.31], one inclusion is always valid, while the other one also holds under the calmness [21, Proposition 1]. It is also well-known, that the inner semicontinuity and inner semicompactness yield the forward rules for dual objects [25]. In order to obtain the reasonable forward rules for primal objects, the least explored area, however, one needs to strengthen these inner notion to suitable inner Lipschitzian conditions. This is precisely where the inner calmness* comes in handy.

By filling the gap of forward rules for primal objects, we derive the particularly interesting chain rule for the graphical derivatives in the exact form.

Note also that there is the obvious connection between the tangent cones and directional limiting normal cones. Hence, this paper is heavily based on the material from [2], where a comprehensive calculus for directional limiting constructions was developed.

In Section 5, as an application we return to the normal cone mapping, where we compute or estimate its generalized derivatives. In particular, the computation of the graphical derivative is just an elegant and simple corollary of our approach, which works very robustly in three consider models. On the other hand, we also see the limitations of our calculus-based approach compared to the results obtained by the direct computations.

Interestingly, in Section 5 there is no mentioning of the inner calmness*, since the results are obtained as a combination of the Theorem 3.10 from Section 3 (where the inner calmness* is shown to holds for certain multiplier map) and the calculus from Section 4 (where the inner calmness* acts as an assumption). In other words, the inner calmness* appears only in the intermediate step, which also verifies that the inner calmness* was always there, just hidden.

The following notation is employed. Given a set \( A \subset \mathbb{R}^n \), the closure and interior of \( A \) are denoted,
respectively, by $\text{cl}A$ and $\text{int}A$, $\text{sp}A$ stands for the linear hull of $A$ and $A^o$ is the (negative) polar of $A$. We denote by $\text{dist}(\cdot, A) := \inf_{y \in A} \| \cdot - y \|$ the usual point to set distance with the convention $\text{dist}(\cdot, \emptyset) = \infty$ and $(\cdot, \cdot)$ stands for the standard scalar product. Further, $\mathcal{B}, \mathcal{S}$ stand respectively the closed unit ball and the unit sphere of the space in question. Given a vector $a \in \mathbb{R}^n$, $[a]$ is the linear space generated by $a$ and $[a]^\perp$ stands for the orthogonal complement to $[a]$. Given a (sufficiently) smooth function $f : \mathbb{R}^n \to \mathbb{R}$, denote its gradient and Hessian at $x$ by $\nabla f(x)$ and $\nabla^2 f(x)$, respectively. Considering further a vector function $\varphi : \mathbb{R}^n \to \mathbb{R}^s$ with $s > 1$, denote by $\nabla \varphi(x)$ the Jacobian of $\varphi$ at $x$, i.e., the mapping $x \to \nabla \varphi(x)$ goes from $\mathbb{R}^n$ into the space of $s \times n$ matrices, denoted by $(\mathbb{R}^s)^n$. Moreover, for a mapping $\beta : \mathbb{R}^n \to (\mathbb{R}^s)^m$ and a vector $y \in \mathbb{R}^s$, we introduce the scalarized map $\langle y, \beta \rangle : \mathbb{R}^n \to \mathbb{R}^m$ given by $\langle y, \beta \rangle(x) = \beta(x)^T y$. Finally, following traditional patterns, we denote by $o(t)$ for $t \geq 0$ a term with the property that $o(t)/t \to 0$ when $t \downarrow 0$.

## 2 Preliminaries

We begin by recalling several definitions and results from variational analysis. Let $\Omega \subset \mathbb{R}^n$ be an arbitrary closed set and $\bar{x} \in \Omega$. The tangent (also called Bouligand or contingent) cone to $\Omega$ at $\bar{x}$ is given by

$$T_{\Omega}(\bar{x}) := \{ u \in \mathbb{R}^n \mid \exists (t_k) \downarrow 0, (u_k) \to u : \bar{x} + t_k u_k \in \Omega \ \forall k \}.$$  

We denote by

$$\hat{N}_{\Omega}(\bar{x}) := T_{\Omega}(\bar{x})^o = \{ x^* \in \mathbb{R}^n \mid \langle x^*, u \rangle \leq 0 \ \forall u \in T_{\Omega}(\bar{x}) \}$$

the regular (Fréchet) normal cone to $\Omega$ at $\bar{x}$. The limiting (Mordukhovich) normal cone to $\Omega$ at $\bar{x}$ is defined by

$$N_{\Omega}(\bar{x}) := \{ x^* \in \mathbb{R}^n \mid \exists (u_k) \downarrow 0, (x_k) \to x^* : x_k^* \in \hat{N}_{\Omega}(x_k) \ \forall k \}.$$  

Finally, given a direction $u \in \mathbb{R}^n$, we denote by

$$N_{\Omega}(\bar{x}; u) := \{ x^* \in \mathbb{R}^n \mid \exists (t_k) \downarrow 0, (u_k) \to u, (x_k^*) \to x^* : x_k^* \in \hat{N}_{\Omega}(\bar{x} + t_k u_k) \ \forall k \}$$

the directional limiting normal cone to $\Omega$ in direction $u$ at $\bar{x}$.

If $\bar{x} \notin \Omega$, we put $T_{\Omega}(\bar{x}) = \emptyset$, $\hat{N}_{\Omega}(\bar{x}) = \emptyset$, $N_{\Omega}(\bar{x}) = \emptyset$ and $N_{\Omega}(\bar{x}; u) = \emptyset$. Further note that $N_{\Omega}(\bar{x}; u) = \emptyset$ whenever $u \notin T_{\Omega}(\bar{x})$. If $\Omega$ is convex, then $\hat{N}_{\Omega}(\bar{x}) = N_{\Omega}(\bar{x})$ amounts to the classical normal cone in the sense of convex analysis and we will write $N_{\Omega}(\bar{x})$. More generally, we say that $\Omega$ is Clarke regular at point $\bar{x}$, provided $\hat{N}_{\Omega}(\bar{x}) = N_{\Omega}(\bar{x})$ and we write $N_{\Omega}(\bar{x})$ in such case.

The following generalized derivatives of set-valued mappings are defined by means of the tangent cone and the normal cone to the graph of the mapping. Let $M : \mathbb{R}^n \rightrightarrows \mathbb{R}^n$ be a set-valued mapping having locally closed graph around $(\bar{x}, \bar{y}) \in \text{gph} M := \{(x, y) \mid y \in M(x)\}$. The set-valued map $D M(\bar{x}, \bar{y}) : \mathbb{R}^n \rightrightarrows \mathbb{R}^m$, defined by

$$D M(\bar{x}, \bar{y})(u) := \{ v \in \mathbb{R}^m \mid (u, v) \in T_{\text{gph} M}(\bar{x}, \bar{y}) \}, u \in \mathbb{R}^n$$

is called the graphical derivative of $M$ at $(\bar{x}, \bar{y})$. The set-valued map $D^* M(\bar{x}, \bar{y}) : \mathbb{R}^m \rightrightarrows \mathbb{R}^n$

$$D^* M(\bar{x}, \bar{y})(v^*) := \{ u^* \in \mathbb{R}^n \mid (u^*, -v^*) \in \hat{N}_{\text{gph} M}(\bar{x}, \bar{y}) \}, v^* \in \mathbb{R}^m$$

is called the regular (Fréchet) coderivative of $M$ at $(\bar{x}, \bar{y})$. The map $D^* M(\bar{x}, \bar{y}) : \mathbb{R}^m \rightrightarrows \mathbb{R}^n$

$$D^* M(\bar{x}, \bar{y})(v^*) := \{ u^* \in \mathbb{R}^n \mid (u^*, -v^*) \in N_{\text{gph} M}(\bar{x}, \bar{y}) \}, v^* \in \mathbb{R}^m$$

is called the contingent coderivative of $M$ at $(\bar{x}, \bar{y})$. The map $D^* M(\bar{x}, \bar{y}) : \mathbb{R}^m \rightrightarrows \mathbb{R}^n$
is called the limiting (Mordukhovich) coderivative of $M$ at $(\bar{x}, \bar{y})$. Given a pair of directions $(u, v) \in \mathbb{R}^n \times \mathbb{R}^m$, the map $D^\delta M((\bar{x}, \bar{y}); (u, v)) : \mathbb{R}^m \rightrightarrows \mathbb{R}^n$, given by

$$D^\delta M((\bar{x}, \bar{y}); (u, v))(v^*) := \{u^* \in \mathbb{R}^n \mid (u^* , -v^*) \in N_{gph,M}((\bar{x}, \bar{y}); (u, v))\}, v^* \in \mathbb{R}^m$$

is called the directional limiting coderivative of $M$ in direction $(u, v)$ at $(\bar{x}, \bar{y})$.

We briefly sum up some basic results from variational analysis of polyhedral sets. Recall that a set $D \subset \mathbb{R}^n$ is said to be convex polyhedral if it can be represented as the intersection of finitely many halfspaces. We say that a set $E \subset \mathbb{R}^n$ is polyhedral if it is the union of finitely many convex polyhedral sets. A set-valued map is called (convex) polyhedral, if its graph is a (convex) polyhedral set.

If a set $E$ is polyhedral, then for every $\bar{z} \in E$ there is a neighborhood $W$ of $\bar{z}$ such that

$$(E - \bar{z}) \cap W = T_E(\bar{z}) \cap W.$$ Given a convex polyhedral set $D$ and a point $\bar{z} \in D$, the tangent cone $T_D(\bar{z})$ and the normal cone $N_D(\bar{z})$ are convex polyhedral cones and there is a neighborhood $W$ of $\bar{z}$ such that

$$T_D(z) = T_D(\bar{z}) + [z - \bar{z}] \supseteq T_D(\bar{z}), \quad N_D(z) = N_D(\bar{z}) \cap [z - \bar{z}]^\perp \subset N_D(\bar{z}) \quad \forall z \in W.$$ The graph of the normal cone mapping to $D$ is a polyhedral set and for every pair $(z, z^*) \in gph N_D$ the reduction lemma [8, Lemma 2E.4] yields

$$T_{gph N_D}(z, z^*) = gph N_{\mathbb{R}^n(z, z^*)}, \quad (2.1)$$

where $\mathcal{N}_{D}(z, z^*) := T_D(z) \cap [z^*]^\perp$ stands for the critical cone to $D$ at $(z, z^*)$ (this definition is not restricted to polyhedral sets).

For two convex polyhedral cones $K_1, K_2 \subset \mathbb{R}^n$ their polars as well as their sum $K_1 + K_2$ and their intersection $K_1 \cap K_2$ are again convex polyhedral cones and

$$(K_1 + K_2)^\circ = K_1^\circ \cap K_2^\circ, \quad (K_1 \cap K_2)^\circ = K_1^\circ + K_2^\circ.$$

For a convex polyhedral cone $K \subset \mathbb{R}^n$ and a point $z \in K$ we have

$$T_K(z) = K + [z], \quad N_K(z) = K^\circ \cap [z]^\perp.$$ A face $\mathcal{F}$ of $K$ can always be written in the form $\mathcal{F} = K \cap [z^*]^\perp$ for some $z^* \in K^\circ$ and there is only finitely many faces of convex polyhedral cones.

In the rest of the section, we recall some well-known properties of set-valued maps. Before introducing the Lipschitzian conditions, which, admittedly, are of the prime interest, we begin with some continuity notions. For set-valued maps, continuity is composed of two semicontinuities, inner and outer. First, we want to briefly discuss some ideas and principles related to this inner and outer paradigm, which later extends to the Lipschitzian properties. For simplicity, we explain these ideas in slightly informal manner. Given a mapping $S : \mathbb{R}^m \rightrightarrows \mathbb{R}^n$, continuity of $S$ at $\bar{y} \in \mathbb{R}^m$ is related to the following condition. For every $\rho, \varepsilon > 0$ there is a neighborhood $V$ of $\bar{y}$ such that

$$S(y') \cap \rho \mathcal{D} \subset S(y) + \varepsilon \mathcal{D} \quad \forall y', y \in V.$$ With respect to the above estimate let us call $y$ the estimating and $y'$ the estimated variable. Then, the outer semicontinuity is related to the same estimate with the estimating variable $y$ being fixed to $\bar{y}$, while the inner semicontinuity is related to the estimate with the estimated variable $y'$ being fixed to $\bar{y}$. We refer to [34, Proposition 5.12, Exercise 5.13] for the precise results.
The outer semicontinuity seems to be easier to deal with and better understood and this issue is even more obvious when comparing the well-known and heavily utilized “outer-Lipschitzian” notions with the quite undeveloped “inner-Lipschitzian” ones. It turns out, however, that the inner paradigm, related to fixing the estimated variable \( y' \), is also very important and interesting. In this paper, we will mainly work with four properties of inner-type.

Let us proceed with the exact definitions. Recall that \( S \) is inner semicompact at \( \bar{y} \) with respect to \( \Omega \subset \mathbb{R}^m \) if for every sequence \( y_k \rightarrow \bar{y} \) with \( y_k \in \Omega \) there exists a subsequence \( K \) of \( \mathbb{N} \) and a sequence \( (x_k)_{k \in K} \) with \( x_k \in S(y_k) \) for \( k \in K \) converging to some \( \bar{x} \). Given \( \bar{x} \in S(\bar{y}) \), we say that \( S \) is inner semicontinuous at \( (\bar{y}, \bar{x}) \) wrt \( \Omega \) if for every sequence \( y_k \rightarrow \bar{y} \) with \( y_k \in \Omega \) there exists a sequence \( x_k \in S(y_k) \) with \( x_k \rightarrow \bar{x} \). If \( \Omega = \mathbb{R}^m \), we speak only about inner semicompactness at \( \bar{y} \) and inner semicontinuity at \( (\bar{y}, \bar{x}) \). For more details regarding these standard notions we refer to [28].

We point out the inner semicompactness is implied by the simpler local boundedness condition. In fact, the local boundedness is often imposed in the development of the calculus and the inner semicompactness is avoided, see [34]. We believe, however, that the boundedness assumption is slightly misleading, since its purpose is to restrict the map, while the inner semicompactness, in a sense, says the opposite - be as unbounded as you like, I just need a convergent subsequence. In Section 3, we will see the impact of these differences when dealing with the multiplier map.

Moreover, we stress that the inner semicontinuity from [34] is considered not at point \((\bar{y}, \bar{x})\) but only at \( \bar{y} \) and it actually corresponds to the requirement that \( S \) is inner semicontinuous at \((\bar{y}, \bar{x})\) for every \( \bar{x} \in S(\bar{y}) \), which is obviously stronger condition.

In [2], we needed to strengthen these properties by controlling the rate of convergence \( x_k \rightarrow \bar{x} \). To this end, we introduced the inner calmness by building upon the inner semicontinuity, namely, we called \( S \) inner calm at \((\bar{y}, \bar{x})\) in \( \text{gph} S \) wrt \( \Omega \) if there exist \( \kappa > 0 \) and a neighborhood \( V \) of \( \bar{y} \) such that

\[
\bar{x} \in S(\bar{y}) + \kappa \| y - \bar{y} \|_Ω, \quad \forall y \in V \cap \Omega,
\]

or, equivalently, if there exist \( \kappa > 0 \) such that for every sequence \( y_k \rightarrow \bar{y} \) with \( y_k \in \Omega \) there exists a sequence \( x_k \in S(y_k) \) with

\[
\| x_k - \bar{x} \| \leq \kappa \| y_k - \bar{y} \|. \tag{2.2}
\]

In the literature, this property can be found also under several other names, such as, e.g., the Lipschitz lower semicontinuity [27] or the recession with linear rate [6, 23]. In particular, [6] contains a comprehensive study of this property.

Naturally, one can also define the stronger version of inner calmness at \( \bar{y} \), based on the inner semicontinuity at \( \bar{y} \). Taking into account that even the inner calmness at \((\bar{y}, \bar{x})\) is often too restrictive, we follow the opposite approach and introduce a milder concept of inner calmness based on the inner semicompactness.

**Definition 2.1.** A set-valued mapping \( S : \mathbb{R}^m \rightrightarrows \mathbb{R}^n \) is called inner calm* at \( \bar{y} \in \mathbb{R}^m \) wrt \( \Omega \subset \mathbb{R}^m \) if there exists \( \kappa > 0 \) such that for every sequence \( y_k \rightarrow \bar{y} \) with \( y_k \in \Omega \), there exist a subsequence \( K \) of \( \mathbb{N} \), together with a sequence \((x_k)_{k \in K}\) and \( \bar{x} \in \mathbb{R}^n \) with \( x_k \in S(y_k) \) for \( k \in K \) and (2.2). Moreover, we say that \( S \) is inner calm* at \( \bar{y} \) wrt \( \Omega \) in the fuzzy sense, provided \( x_k \in S(y_k + o(\| y_k - \bar{y} \|)) \) instead of \( x_k \in S(y_k) \).
often consider these properties wrt to the domain of map \( S \), given by \( \text{dom} S := \{ y \in \mathbb{R}^m \mid S(y) \neq \emptyset \} \), adding no restriction at all.

Next we briefly introduce one important outer Lipschitzian notion. We say that \( S \) is calm at \((\bar{y}, \bar{x}) \in \text{gph} S\), provided there exist \( \kappa > 0 \) and neighborhoods \( U \) of \( \bar{x} \) and \( V \) of \( \bar{y} \) such that

\[
S(y) \cap U \subset S(\bar{y}) + \kappa \|y - \bar{y}\| \quad \forall y \in V. \tag{2.3}
\]

Interestingly, in the definition of calmness, the crucial neighborhood is \( U \), not \( V \). Indeed, neighborhood \( U \) can be reduced (if necessary) in such a way that neighborhood \( V \) can be replaced by the whole space \( \mathbb{R}^m \), cf. [8, Exercise 3H.4]. This is also related to the well-known fact that calmness of \( S \) at \((\bar{y}, \bar{x}) \) is equivalent to the metric subregularity of \( M := S^{-1} \) at \((\bar{x}, \bar{y})\).

**Definition 2.2.** Let \( M : \mathbb{R}^n \to \mathbb{R}^m \) and \((\bar{x}, \bar{y}) \in \text{gph} M\). We say that \( M \) is metrically subregular at \((\bar{x}, \bar{y})\) provided there exist \( \kappa > 0 \) and a neighborhood \( U \) of \( \bar{x} \) such that

\[
\text{dist}(x, M^{-1}(\bar{y})) \leq \kappa \text{dist}(\bar{y}, M(x)) \quad \forall x \in U.
\]

In case of a single-valued mapping \( \varphi : \mathbb{R}^m \to \mathbb{R}^n \), the inner calmness at \((\bar{y}, \varphi(\bar{y}))\) reads as

\[
\|\varphi(y) - \varphi(\bar{y})\| \leq \kappa \|y - \bar{y}\| \quad \forall y \in V. \tag{2.4}
\]

We will refer to this property as calmness of \( \varphi \) at \( \bar{y} \). Quite surprisingly, however, neither the calmness definition from (2.3) nor the inner calmness* yield (2.4)! This is due to the neighborhood \( U \) in case of calmness and due to not requiring \( \bar{x} \in S(\bar{y}) \) in the definition of inner calmness*. Indeed, \( \varphi : \mathbb{R} \to \mathbb{R} \) given by

\[
\varphi(y) = \begin{cases} 
0 & \text{for } y \leq 0, \\
1 & \text{for } y > 0
\end{cases}
\]

is clearly calm at \((\bar{y}, \varphi(\bar{y})) = (0, 0) \) by (2.3) as well as inner calm* at \( \bar{y} \), despite being discontinuous at \( \bar{y} \). Naturally, if we restrict ourselves to continuous mappings, all three notions coincide and read as (2.4). Further, \( \varphi \) is called Lipschitz continuous near \( \bar{y} \) if the inequality

\[
\|\varphi(y) - \varphi(y')\| \leq \kappa \|y - y'\| \quad \forall y, y' \in V
\]

is fulfilled with \( \kappa > 0 \) and \( V \) being a neighborhood of \( \bar{y} \).

Finally, we will make use of the directional counterparts of the above properties. For the purpose of this paper, it is sufficient to say that a sequence \( y_k \in \mathbb{R}^m \) converges to some \( \bar{y} \) from direction \( v \in \mathbb{R}^m \) if there exist \( t_k \downarrow 0 \) and \( v_k \to v \) with \( y_k = \bar{y} + t_k v_k \). Then, the directional versions of the above properties are obtain by replacing the standard converge by the converge from a prescribed direction \( v \).

Note that the standard approach is to define the directional properties by means of the directional neighborhoods, see [10] for the details.

### 3 Inner semicompactness and inner calmness*

In this section, we provide some remarkable results regarding our newly introduced concept of inner calmness*. More precisely, we discuss some interesting cases when the inner calmness* is satisfied, while its role as an assumption is highlighted in the next section dealing with the calculus rules. We point out that some principles can be explained in terms of the inner semicompactness. Then, adding certain polyhedrality assumptions allows us to control the rate of convergence and hence leads to the inner calmness*. From a different angle, we show that the inner semicompactness and the inner calmness* are very suitable relaxations of quite restrictive properties of inner semicontinuity and inner calmness.
3.1 Polyhedral set-valued maps

We begin by the simple example showing the limitations of inner semicontinuity and inner calmness.

Example 3.1. Let $S : \mathbb{R} \rightrightarrows \mathbb{R}$ by given by

$$S(y) = \begin{cases} 
0 & \text{for } y \leq 0, \\
1 & \text{for } y \geq 0.
\end{cases}$$

It is easy to see that $S$ is not inner semicontinuous at $(\bar{y}, \bar{x}) = (0, 0)$, due to $y_k := 1/k \to \bar{y}$ and $S(y_k) = 1 \not\to 0$, or at $(\bar{y}, \bar{x}) = (0, 1)$, due to $y_k := -1/k \to \bar{y}$ and $S(y_k) = 0 \not\to 1$.

On the other hand, $S$ is clearly inner semicompact (even inner calm*) at $\bar{y}$. Indeed, given a sequence $y_k \to \bar{y}$, we can choose $\bar{x}$ to be either 0 or 1, depending on which of the two values is attained by $S(y_k)$ infinitely many times.

The above example shows that the lack of convexity of the graph can easily lead to the violation of this property. Let us now look at maps $S$ with the graph having a special structure. More precisely, consider a map $S : \mathbb{R}^m \rightrightarrows \mathbb{R}^n$ with its graph being a finite union of closed sets $G_i$ for $i = 1, \ldots, l$ and denote by $S_i$ the maps with $\text{gph} S_i = G_i$, referred to as the components of $S$.

Note that since the finite union of closed sets remains a closed set, so is the graph of $S$. This, in turn, is equivalent to $S$ being outer semicontinuous everywhere, see [34, Theorem 5.7(a)]. The closedness of $\text{gph} S$ is not very restrictive and often needed in order to work with generalized derivatives of $S$. This also suggests that the outer semicontinuity is easier to handle than its inner counterpart.

We will now show that, unless special assumptions are made, it is not easy to extend the inner semicontinuity, or even inner semicompactness, to the boundary of domain of a graph-convex map.

Lemma 3.2. Given a map $S : \mathbb{R}^m \rightrightarrows \mathbb{R}^n$, assume that its components $S_i$ are inner semicompact at $\bar{y} \in \mathbb{R}^m$ wrt to $\text{dom} S_i$. Then $S$ is inner semicompact at $\bar{y}$ wrt to its domain.

Proof. If $\bar{y} \notin \text{cl}(\text{dom} S_i)$, the inner semicompactness follows. Hence, let $y_k \to \bar{y}$ with $y_k \in \text{dom} S$. By passing to a subsequence if necessary, we may assume that there exists $i$ with $y_k \in \text{dom} S_i$ for all $k$. The inner semicompactness of $S_i$ now yields the existence of a sequence $x_k \in S_i(y_k)$ converging to some $\bar{x}$. Since $x_k \in S(y_k)$, the claim follows.

Note that we did not have to require the domains to be closed, since in the definition of inner semicompactness we do not impose $\bar{y}$ to be in the domain.

Clearly, we can strengthen the assumptions to inner semicontinuity, but we only need to ask for the inner semicontinuity of those components $S_i$ with $\bar{y} \in \text{cl}(\text{dom} S_i)$. For the other components the inner semicompactness follows for free.

Recalling the classical result [34, Theorem 5.9] on inner semicontinuity from the graph-convexity, one may wonder whether it is possible to derive the inner semicompactness of maps with the graph being the finite union of convex sets. Since [34, Theorem 5.9] yields the inner semicontinuity at every point of the interior of domain, we readily obtain the following statement.

Corollary 3.3. Assume that $\text{gph} S$ can be written as a finite union of convex sets and $\bar{y} \in \text{int}(\text{dom} S_i)$ for some $i$. Then $S$ is inner semicompact at $\bar{y}$.

Note that $S$ does not have to be inner semicompact at every $\bar{y} \in \text{int}(\text{dom} S)$, since such $\bar{y}$ may lie on the boundaries of several domains of $S_i$.

Next we will show that, unless special assumptions are made, it is not easy to extend the inner semicontinuity, or even inner semicompactness, to the boundary of domain of a graph-convex map.
Now let \( S : \mathbb{R}^2 \Rightarrow \mathbb{R} \) be the set-valued map with the graph being the closure of the convex hull of \( G \). Note also that the domain of \( S \) is the closed unit ball. We claim that \( S \) is not inner semicompact at \( \bar{y} \) wrt to \( \text{dom} \). Indeed, consider a sequence \( t_k \downarrow 0 \) and set \( y_k := (\cos(t_k), \sin(t_k)) \rightarrow \bar{y} \). We will show that there is no \( x_k \in S(y_k) \) with \( x_k < 1/t_k \rightarrow \infty \). To this end, for every \( k \) we construct a halfspace containing set \( G \) but no \( (y_k, x_k) \) with \( x_k < 1/t_k \). Set

\[
b_k := \left( 1 - \cos(t_k) \right) \sin(t_k) + t_k \left( 1 - \cos(t_k) \right), \frac{1}{t_k} \cos(t_k) + \sin(t_k) \right) \]

and consider the halfspace \( \mathcal{H}_k := \{ (y, x) \mid \langle b_k, (y, x) \rangle \leq 1 \} \). Clearly, \( (1, 0, 0) \in \mathcal{H}_k \). Moreover, every point \( (y_1, y_2, x) \) of the form (3.5) also belongs to \( \mathcal{H}_k \), since the function

\[
t \rightarrow \langle b_k, (\cos(t), \sin(t), 1/t) \rangle
\]

attains the global maximum over \((0, 2\pi)\) at \( t = t_k \) with value 1. Finally, a point \( (y_k, x) \) belongs to \( \mathcal{H}_k \) if and only if \( x \geq 1/t_k \). Hence, taking into account that \( \text{gph} S \) is the intersection of all the closed halfspaces containing \( G \) by [33, Corollary 11.5.1], there is no \( x_k \in S(y_k) \) with \( x_k < 1/t_k \). Hence, \( S \) is not inner semicompact at \( \bar{y} \) wrt to \( \text{dom} S \).

Next, we turn our attention to the corresponding Lipschitzian notions. It is not surprising that the analogous principles hold true here, where the only difference is that we control the rate of convergence.

**Lemma 3.5.** Given a map \( S : \mathbb{R}^m \Rightarrow \mathbb{R}^m \) with \( \text{gph} S = \bigcup G_i \) for closed sets \( G_i \), assume that its components \( S_i \) are inner calm* at \( \bar{y} \in \mathbb{R}^m \) wrt to \( \text{dom} S_i \). Then \( S \) is inner calm* at \( \bar{y} \) wrt to its domain.

The proof follows by the same arguments as the proof of the previous lemma, with the constant \( \kappa \) of inner calmness* of \( S \) given as the maximum of the constants \( \kappa_i \) of inner calmness* of \( S_i \).

The above lemma allows us to establish the main result of this section regarding polyhedral maps. In the polyhedral setting, there is no problem with the points on the boundary of the domain. Indeed, the prominent result of Walkup and Wets [35], see also [34, Example 9.35], says that a convex polyhedral map \( S \) is Lipschitz continuous on its domain, i.e., there exist \( \kappa > 0 \) such that

\[
S(y') \subset S(y) + \kappa \| y' - y \| A \quad \forall y, y' \in \text{dom} S.
\]

Since this is obviously stronger even than inner calmness at any \( \bar{y} \), we obtain the following remarkable result, taking also into account the automatic closedness of the domain of convex polyhedral maps. For the sake of completeness, we include also the well-known result regarding the (outer) calmness due to Robinson [32], who used the name upper Lipschitzness.
Theorem 3.6. Let \( S : \mathbb{R}^m \rightrightarrows \mathbb{R}^n \) be a polyhedral set-valued map. Then there exists a constant \( \kappa \) such that \( S \) is inner calm* with constant \( \kappa \) wrt \( \text{dom}S \) at every \( \bar{y} \in \mathbb{R}^m \) as well as calm with constant \( \kappa \) at every \( \bar{y} \in \text{dom}S \), i.e.,
\[
S(y) \subset S(\bar{y}) + \kappa \|y - \bar{y}\| \mathcal{B}
\]
for all \( y \) near \( \bar{y} \).

Note that, in inner calmness* we have found a suitable inner Lipschitzian property that, from the Lipschitzness of convex polyhedral maps, extends to the polyhedral maps. The key reason is that the inner calmness* is based on the suitable notion of inner semicompactness, which is preserved under finite unions. To the best of our knowledge, there has not been any inner Lipschitzian property known to hold for the polyhedral maps.

It seems quite intriguing that a map which is not Lipschitz continuous, just like the polyhedral maps in general, may still be inner calm* as well as (outer) calm. Interestingly, in [16, Theorem 8] Gfrerer and Outrata also established some sufficient conditions to ensure both, calmness and inner calmness*, of certain class of solution maps. Perhaps a reasonable analysis can be achieved in some situations, where Lipschitzness is typically assumed, by relaxing the assumption to fulfilment of some kind of the “two-sided” calmness.

### 3.2 Multiplier mappings

In [16, Proposition 4.1.], Gfrerer and Outrata showed the following remarkable result.

Proposition 3.7. [16, Proposition 4.1] Let \( M : \mathbb{R}^n \rightrightarrows \mathbb{R}^m \) be a set-valued mapping having locally closed graph around \( (x, \bar{y}) \in \text{gph}M \) and assume that \( M \) is metrically subregular at \( (x, \bar{y}) \) with modulus \( \kappa \). Then
\[
N_{M^{-1}(\bar{y})}(x) \subset \left\{ x^* \mid \exists y^* \in \kappa \|x^*\| \mathcal{B} : (x^*, y^*) \in N_{\text{gph}M}(x, \bar{y}) \right\}.
\]

In fact, [16, Proposition 4.1.] contains, apart from the additional result for tangent cone, the stronger, directional, estimate. Nevertheless, it can be easily seen that the above statement is really the essential one, while the directional version is just one of its admirable corollaries. Indeed, taking into account the straightforward fact that, given a direction \( u \in \mathbb{R}^n \) as well as sequences \( t_k \downarrow 0 \) and \( u_k \to u \), the metric subregularity of \( M \) in direction \( u \) at \( (x, \bar{y}) \) yields metric subregularity of \( M \) at every point \( (x + t_k u_k, \bar{y}) \in \text{gph}M \) with the same modulus, applying (3.6) at \( (x + t_k u_k, \bar{y}) \) and taking the limit, one immediately obtains
\[
N_{M^{-1}(\bar{y})}(x; u) \subset \left\{ x^* \mid \exists y^* \in \kappa \|x^*\| \mathcal{B} : (x^*, y^*) \in N_{\text{gph}M}(x, \bar{y}; (u, 0)) \right\}.
\]

We point out that taking the corresponding limits is only possible thanks to the bound \( \|y^*\| \leq \kappa \|x^*\| \) in (3.6). More generally, in the area of second-order analysis and related stability and sensitivity issues, one often deals with a sequence \( (x_k, x_k^*) \in \text{gph}N_{M^{-1}(\bar{y})} \), where \( M \) is typically a constraint mapping, see below. Under the metric subregularity, one gets the existence of some suitable multipliers \( y_k^* \), but needs to find also some limit multiplier \( y^* \) with \( y_k^* \to y^* \). Hence, many authors used to assume boundedness of multipliers, for which they had to impose some stronger conditions, such as GMFCQ, see also [12] for more subtle approach. Thanks to the bound \( \|y^*\| \leq \kappa \|x^*\| \), however, we know that the metric subregularity alone is sufficient for this task. This fact was already heavily utilized in several recent works, see, e.g., [1, 3, 13, 14]. We also point out that the idea that the metric subregularity yields the bound \( \|y^*\| \leq \kappa \|x^*\| \) appeared already in the proof of [20, Theorem 4.1.]. Moreover, similar arguments were also used in [5, Lemma 3.2] in the setting of nonlinear programs.
For the constraint mapping $M(x) = \varphi(x) - Q$, where $Q \subset \mathbb{R}^m$ is a closed set and $\varphi : \mathbb{R}^n \rightarrow \mathbb{R}^m$ is calm at $x \in M^{-1}(0)$, one can easily show that $D^*M(x,0)(-y^*) \subset D^*\varphi(y^*)$ if $y^* \in N_Q(\varphi(x))$, or, even the directional version
\[
D^*M((x,0);(u,0))(-y^*) \subset \bigcup_{w \in D\varphi(x)(u);y^* \in N_Q(\varphi(x);w)} D^*\varphi(x;(u,w))(y^*),
\]
valid under the calmness of $\varphi$ at $x$ in direction $u$, c.f. [2, Lemma 6.1]. Consequently, Proposition 3.7 yields also the standard as well as the directional pre-image calculus rule, c.f. [2, Theorem 3.1].

**Corollary 3.8.** Assume that $\varphi$ is calm at $x$ in some direction $u \in \mathbb{R}^n$ and that the set-valued mapping $M(x) = Q - \varphi(x)$ is metrically subregular at $(x,0)$ in direction $u$ with modulus $\kappa$. Then, for $C := M^{-1}(0) = \varphi^{-1}(Q)$ we have
\[
N_C(x;u) \subset \{x^* \mid \exists v \in D\varphi(x)(u) \cap T_Q(\varphi(x)), \exists y^* \in N_Q(\varphi(x);v) \cap \kappa\|x^*\| R : x^* \in D^*\varphi(x;(u,v))(y^*)\}.
\]

Let us now discuss the result of Proposition 3.7 in the light of the inner semicompactness. To this end, suppose that we are not interested in finding an estimate for the whole set $\nabla M^{-1}(\bar{y})(x)$, but, instead, we have a fixed $x^* \in N_{M^{-1}(\bar{y})}(x)$ and we are looking for $y^* \in D^*M^{-1}(\bar{y},x)(-x^*)$. Clearly, the metric subregularity of $M$ does not take into account the specific $x^*$.

On the other hand, assuming that the mapping
\[
\Lambda(x,x^*) := D^*M^{-1}(\bar{y},x)(-x^*)
\]
is inner semicompact at some point $(x,x^*)$ wrt $gph N_{M^{-1}(\bar{y})}$ means that, for every $(x_k,x^*_k) \rightarrow (x,x^*)$ with $(x_k,x^*_k) \in gph N_{M^{-1}(\bar{y})}$, there exists $y^*_k \in D^*M^{-1}(\bar{y},x_k)(-x^*_k)$ together with $y^* \in D^*M^{-1}(\bar{y},x)(-x^*)$ such that $y^*_k \rightarrow y^*$. Of course, one loses the bound of $\|y^*\|$ here. Nevertheless, taking into account the discussion after Proposition 3.7, the inner semicompactness of $\Lambda$ itself is often precisely of the main interest. This will become even more clear in the next sections.

Applying Proposition 3.7 at $(x_k,x^*_k) \in gph N_{M^{-1}(\bar{y})}$ readily yields the following corollary.

**Corollary 3.9.** Let $M : \mathbb{R}^n \rightrightarrows \mathbb{R}^m$ be a set-valued mapping having locally closed graph around $(x,\bar{y}) \in gph M$. Then the metric subregularity of $M$ at $(x,\bar{y})$ implies the inner semicompactness of $\Lambda$ at $(x,x^*)$ wrt $gph N_{M^{-1}(\bar{y})}$ for every $x^* \in N_{M^{-1}(\bar{y})}(x)$.

We conclude this section by showing even stronger statement in case of the smooth constraints. Hence, assume that $M = \varphi(x) - Q$ for a closed set $Q$ and a twice continuously differentiable mapping $\varphi$ and set $C := M^{-1}(0) = \{x \mid \varphi(x) \in Q\}$. Denoting $\hat{\beta}(x) := \nabla \varphi(x)$, the (multiplier) mapping $\Lambda$ attains the standard form
\[
\Lambda(x,x^*) := \{\lambda \in N_Q(\varphi(x)) \mid \hat{\beta}(x)^T \lambda = x^*\},
\]
where we are using $\hat{\lambda}$ instead of $y^*$ to denote the multipliers. Note also that the metric subregularity of $M = \varphi(x) - Q$ at $(x,0)$ yields that locally around $(x,x^*)$ one has $gph N_C \subset \text{dom} \Lambda$ and the equality holds, e.g., if $Q$ is Clarke regular near $\varphi(x)$, in particular convex.

**Theorem 3.10.** Let $(x,x^*) \in gph N_C$ for $C = \varphi^{-1}(Q)$ and assume that the constraint mapping $M(x) = \varphi(x) - Q$ is metrically subregular at $(x,0)$. Then
\begin{enumerate}
  \item the multiplier map $\Lambda$ is inner semicompact at $(x,x^*)$ wrt $gph N_C$;
  \item if $Q$ is convex polyhedral, then $\Lambda$ is even inner calm* at $(x,x^*)$ wrt its domain in the fuzzy sense.
\end{enumerate}
Proof. The first statement follows from Corollary 3.9.

To show the second one, assume that \( Q \) is convex polyhedral and consider a sequence \((x_k, x_k^*) \rightarrow (x, x^*)\) with \((x_k, x_k^*) \in \text{dom} \Lambda \) and denote \((u_k, u_k^*)) := \{(x_k - x, x_k^* - x^*)/t_k \rightarrow (u, u^*) \in \mathcal{F} \) for \( t_k := \|(x_k, x_k^*) - (x, x^*)\| \). The convexity of \( Q \) yields that \((x_k, x_k^*) \in \text{gph} N_Q \) and hence the inner semicompactness of \( \Lambda \) wrt \( \text{gph} N_Q \) yields the existence of \( \tilde{\lambda}_k \in N_Q(\phi(x + t_k u_k)) \) with

\[
x^* + t_k u_k^* = \beta(x + t_k u_k)^T \tilde{\lambda}_k
\]

(3.7)
as well as \( \lambda \in N_Q(\phi(x)) \) with \( x^* = \beta(x)^T \lambda \) such that \( \tilde{\lambda}_k \rightarrow \lambda \).

The polyhedrality of \( Q \) yields the polyhedrality of \( \text{gph} N_Q \) and hence

\[
\left( \frac{\phi(x + t_k u_k) - \phi(x)}{t_k}, \frac{\tilde{\lambda}_k - \lambda}{t_k} \right) \in T_{\text{gph} N_Q}(\phi(x), \lambda) = \text{gph} N_{\mathcal{F}_Q}(\phi(x), \lambda),
\]

by the reduction lemma formula (2.1). This means that

\[
\begin{align*}
(\phi(x + t_k u_k) - \phi(x))/t_k & \in \mathcal{K}_Q(\phi(x), \lambda), \\
(\tilde{\lambda}_k - \lambda)/t_k & \in (\mathcal{K}_Q(\phi(x), \lambda))^\circ,
\end{align*}
\]

(3.8)
hence, for every \( k \) there exists a face \( \mathcal{F}_k := \mathcal{K}_Q(\phi(x), \lambda) \cap [(\tilde{\lambda}_k - \lambda)/t_k]^\perp \) of the critical cone with \( \phi(x + t_k u_k) - \phi(x) \in \mathcal{F}_k \) and, due to the finiteness of faces of a polyhedral cone, we may assume that \( \mathcal{F}_k \equiv \mathcal{F} \) with

\[
(\tilde{\lambda}_k - \lambda)/t_k \in (\mathcal{K}_Q(\phi(x), \lambda))^\circ \cap (\text{sp} \mathcal{F})^\perp.
\]

Moreover, the Taylor expansion of (3.7) yields

\[
\beta(x)^T \frac{\tilde{\lambda}_k - \lambda}{t_k} = u_k^* - \nabla \phi(\lambda, x) u + o(1).
\]

(3.8)
Hence, we can now invoke Hoffman’s lemma [4, Theorem 2.200] to find for every \( k \) some \( \eta_k \in (\mathcal{K}_Q(\phi(x), \lambda))^\circ \cap (\text{sp} \mathcal{F})^\perp \) satisfying

\[
\beta(x)^T \eta_k = \beta(x)^T \frac{\tilde{\lambda}_k - \lambda}{t_k}
\]

and \( \| \eta_k \| \leq \alpha \| \beta(x)^T (\tilde{\lambda}_k - \lambda)/t_k \| \) for some constant \( \alpha > 0 \) not depending on \( k \). Since the right hand side of (3.8) is bounded, so is \( \eta_k \) and by possibly passing to a subsequence we can assume that \( \eta_k \) converges to some \( \eta \in (\mathcal{K}_Q(\phi(x), \lambda))^\circ \cap (\text{sp} \mathcal{F})^\perp \) satisfying

\[
\beta(x)^T \eta = u^* - \nabla \phi(\lambda, x) u.
\]

We have

\[
\eta \in (\mathcal{K}_Q(\phi(x), \lambda))^\circ = (T_Q(\phi(x)))^\circ \cap [\lambda]^\perp = T_{N_Q(\phi(x))}(0) + [\lambda] = T_{N_Q(\phi(x))}(\lambda)
\]

and the polyhedrality of \( N_Q(\phi(x)) \) yields that \( \lambda_k := \lambda + t_k \eta \in N_Q(\phi(x)) \). Moreover, from \( \eta \in (\text{sp} \mathcal{F})^\perp \), \( \phi(x + t_k u_k) - \phi(x) \in \mathcal{F} \) as well as \( \langle \lambda, \phi(x + t_k u_k) - \phi(x) \rangle = 0 \) we infer

\[
\langle \lambda_k, \phi(x + t_k u_k) - \phi(x) \rangle = 0
\]

and, consequently, \( \lambda_k \in N_Q(\phi(x + t_k u_k)) \). Note that for \( \kappa := \| \eta \| \) we obtain \( \| \lambda_k - \lambda \| = t_k \kappa \).
Finally, denoting
\[ x_k^* := \beta(x + t_k u_k)^T \lambda_k = x^* + t_k u^* + o(t_k) = x_k^* + o(t_k) \]
yields the statement, taking also into account that the fact that locally \( \text{dom} \Lambda = \text{gph} N_C \) holds due to the convexity of \( Q \).

**Remark 3.11.** Let us briefly comment the above results.

1. We did not use the fact that \( \beta(x) := \nabla \varphi(x) \) in the proof. In other words, for arbitrary sufficiently smooth function \( \beta(x) \) it holds that \( \Lambda(x,x^*) \) is inner calm* at \( (x,x^*) \) wrt its domain in the fuzzy sense, provided \( \Lambda \) is inner semicompact at \( (x,x^*) \) wrt \( \text{gph} N_C \) and \( Q \) is convex polyhedral. This enables us to handle the parametrized setting in Section 5 with ease.

2. As already mentioned, in order to replace the inner semicompactness in (i) by the local boundedness, one has to impose a stronger assumption, such as GMFCQ. Moreover, in order to obtain the analogous results in terms of the inner semicontinuity and the inner calmness, one can, e.g., assume the uniqueness of the multiplier. In turn, one needs to strengthen the assumption even more and require some kind of the nondegeneracy.

3. Finally, note that our proof closely follows the arguments from the proof of [3, Theorem 5.3].

## 4 Selected calculus rules in primal and dual form

This section contains the “forward” calculus rules based on the four inner-type conditions. To shorten and unburden the presentation, we put here the list of the assumptions that serves as a template. In the following, we will impose these assumptions on different mappings, hence the subscript.

**Assumption 4.1.** Given a set-valued map \( S : \mathbb{R}^m \rightrightarrows \mathbb{R}^n \) and a point \( \bar{y} \in \mathbb{R}^m \), we assign the four labels to the following assumptions:

(i) \( S \) is inner semicompact at \( \bar{y} \) wrt its domain in direction \( v \);

(ii) \( S \) is inner semicontinuous at \( (\bar{y},\bar{x}) \) wrt its domain in direction \( v \) for some \( \bar{x} \in S(\bar{y}) \);

(iii) \( S \) is inner calm* at \( \bar{y} \) wrt its domain in direction \( v \);

(iv) \( S \) is inner calm at \( (\bar{y},\bar{x}) \) wrt its domain in direction \( v \) for some \( \bar{x} \in S(\bar{y}) \).

### 4.1 Tangents and directional normals to image sets

In this section, we deal with the rules for image sets, which provide the base for all of the remaining calculus. Given a closed set \( C \subset \mathbb{R}^n \) and a continuous mapping \( \varphi : \mathbb{R}^n \to \mathbb{R}^l \), set \( Q := \varphi(C) \) and consider \( \bar{y} \in Q \). Moreover, let \( \Psi : \mathbb{R}^l \rightrightarrows \mathbb{R}^n \) be given by \( \Psi(y) := \varphi^{-1}(y) \cap C \) and note that \( \text{dom} \Psi = Q \).

**Theorem 4.2** (Tangents to image sets). Assume that \( \varphi : \mathbb{R}^n \to \mathbb{R}^l \) is calm at some \( \bar{x} \in \Psi(\bar{y}) \). Then, we have
\[
T_C(\bar{x}) \subset \{ u \mid \exists v \in T_Q(\bar{y}) \text{ with } v \in D\varphi(\bar{x})u \}.
\]

On the other hand, if (iii) holds, then
\[
T_Q(\bar{y}) \subset \bigcup_{\bar{x} \in \Psi(\bar{y})} \{ v \mid \exists u \in T_C(\bar{x}) \text{ with } v \in D\varphi(\bar{x})u \}.
\]
and, moreover, if there exists $\bar{x} \in \Psi(\bar{y})$ such that (iv$\Psi$) holds, then the estimate holds with this $\bar{x}$, i.e., the union over $\Psi(\bar{y})$ is superfluous.

**Proof.** Pick $u \in T_C(\bar{x})$. We will show a slightly stronger statement, namely that $D\phi(\bar{x})u \cap T_Q(\bar{y}) \neq \emptyset$, provided $\phi$ is calm at $\bar{x}$ in direction $u$. Indeed, consider $t_k \downarrow 0$ and $u_k \to u$ with $\bar{x} + t_k u_k \in C$ and observe that

$$Q \ni \phi(\bar{x} + t_k u_k) = \bar{y} + t_k v_k,$$

(4.9)

where $v_k := (\phi(\bar{x} + t_k u_k) - \bar{y})/t_k$ is bounded by the assumed calmness in direction $u$ and we may assume that $v_k \to v$ for some $v \in T_Q(\bar{y})$. Moreover, (4.9) can be written as $(\bar{x} + t_k u_k, \bar{y} + t_k v_k) \in \text{gph} \phi$, showing also $v \in D\phi(\bar{x})u$.

Consider now $v \in T_Q(\bar{y})$ as well as $t_k \downarrow 0$ and $v_k \to v$ with $\bar{y} + t_k v_k \in Q$. As before, the inner calmness* of $\Psi$ at $\bar{y}$ wrt its domain in direction $v$ yields the existence of $x_k \in C$ and $\bar{x}$ with

$$\bar{y} + t_k v_k = \phi(x_k) \text{ and } \|x_k - \bar{x}\| \leq \kappa t_k \|v_k\|$$

for some $\kappa > 0$. This means, however, that $(\bar{x} + t_k u_k, \bar{y} + t_k v_k) \in \text{gph} \phi$ for the bounded sequence $u_k := (x_k - \bar{x})/t_k$ and the existence of $u \in T_C(\bar{x})$ with $v \in D\phi(\bar{x})u$ follows. Moreover, the closedness of $C$ and the continuity of $\phi$ imply $\bar{x} \in \Psi(\bar{y})$.

The last statement now follows easily from the definition of inner calmness.

**Remark 4.3.** In order to keep things simpler, we assumed the standard inner calmness* and we will continue in this manner. Nevertheless, the statement holds also under the inner calmness* in the fuzzy sense, since this yields $\bar{x}_k \in C$ with

$$\bar{y} + t_k v_k + o(t_k) = \phi(\bar{x}_k) \text{ and } \|\bar{x}_k - \bar{x}\| \leq \kappa t_k \|v_k\|$$

and the rest of the proof remains valid with $\bar{v}_k := (\phi(\bar{x}_k) - \bar{y})/t_k \to v$.

The following lemma highlights the underlying principle behind the above theorem.

**Lemma 4.4.** If $(\bar{y}, \bar{x}) \in \text{gph} \Psi$ and $u \in D\Psi(\bar{y}, \bar{x})(v)$, then

$$u \in T_C(\bar{x}), \quad v \in T_Q(\bar{y}), \quad \text{and} \quad v \in D\phi(\bar{x})u.$$ 

**Proof.** Having $t_k \downarrow 0$ and $(u_k, v_k) \to (u, v)$ with $(\bar{y}, \bar{x}) + t_k (v_k, u_k) \in \text{gph} \Psi$ means precisely that $\bar{x} + t_k u_k \in C$, $\bar{y} + t_k v_k \in Q$, and $(\bar{x} + t_k u_k, \bar{y} + t_k v_k) \in \text{gph} \phi$. \hfill \Box

**Remark 4.5.** Note that the proof of Theorem 4.2 in fact goes as follows. If $u \in T_C(\bar{x})$ and $\phi$ is calm at $\bar{x}$ in direction $u$, then there exists $v$ with $u \in D\Psi(\bar{y}, \bar{x})(v)$. On the other hand, if $v \in T_Q(\bar{y})$ and $\Psi$ is inner calm* at $\bar{y}$ wrt its domain in direction $v$, then there exist $\bar{x} \in \Psi(\bar{y})$ and $u \in D\Psi(\bar{y}, \bar{x})(v)$.

In the differentiable case, $D\phi(\bar{x})u = \{\nabla \phi(\bar{x})u\}$ is a singleton and we obtain the following simpler estimates. Again, note that directional differentiability of $\phi$ is also sufficient.

**Corollary 4.6** (Tangents to image sets - differentiable case). If $\phi$ is continuously differentiable, then

$$T_Q(\bar{y}) \supset \bigcup_{\bar{x} \in \Psi(\bar{y})} \nabla \phi(\bar{x}) T_C(\bar{x}).$$

The above inclusion becomes equality under (iii)$\Psi$, and, moreover, the union over $\Psi(\bar{y})$ is superfluous if even (iv)$\Psi$ holds for some $\bar{x} \in \Psi(\bar{y})$. 

13
Naturally, the estimates for directional normals to image sets from [2, Theorem 3.2], as well as the estimates for directional subdifferentials and coderivatives which are based on this result, can also be enriched by the inner calmness* assumption. Thus, we will now summarize the enhanced results, mostly following the structure and notation from [2]. Since the proofs are presented in [2] and the needed adjustments are usually minor, we only briefly describe the ideas and principles here.

The estimates in next theorem will differ based on which of the four assumptions we utilize. Given a direction \( v \in \mathbb{R}^l \), let us also denote
\[
\Sigma(v) := \{y^* \mid D^* \phi(x; (u, v))(y^*) \cap \mathbb{N}_C(x; u) \neq \emptyset\}.
\] (4.10)

Trivial modifications of the proof of [2, Theorem 3.2] to incorporate assumption (iii\(\Psi\)) yield the following result.

**Theorem 4.7** (Directional normals to image sets). Consider a direction \( v \in \mathbb{R}^l \) and assume that \( \phi \) is Lipschitz continuous near every \( x \in \Psi(y) \) in all directions \( u \in \mathbb{D}(\bar{y}, \bar{x})(v) \) and \( u \in \mathbb{D}(\bar{y}, \bar{x})(0) \cap \mathcal{J} \).

Then
- under (i\(\Psi\)) in direction \( v \), one has
  \[
  \mathbb{N}_Q(y; v) \subset \bigcup_{\bar{x} \in \Psi(y)} \bigg( \bigcup_{u \in \mathbb{D}(\bar{y}, \bar{x})(v)} \Sigma(v) \cup \bigcup_{u \in \mathbb{D}(\bar{y}, \bar{x})(0) \cap \mathcal{J}} \Sigma(0) \bigg);
  \]
- under (ii\(\Psi\)) in direction \( v \) with the prescribed \( \bar{x} \in \Psi(y) \), one has
  \[
  \mathbb{N}_Q(y; v) \subset \bigcup_{u \in \mathbb{D}(\bar{y}, \bar{x})(v)} \Sigma(v) \cup \bigcup_{u \in \mathbb{D}(\bar{y}, \bar{x})(0) \cap \mathcal{J}} \Sigma(0);
  \]
- under (iii\(\Psi\)) in \( v \), one has
  \[
  \mathbb{N}_Q(y; v) \subset \bigcup_{x \in \Psi(y)} \bigcup_{u \in \mathbb{D}(\bar{y}, \bar{x})(v)} \Sigma(v);
  \]
- finally, under (iv\(\Psi\)) in \( v \) with the prescribed \( \bar{x} \in \Psi(y) \), one has
  \[
  \mathbb{N}_Q(y; v) \subset \bigcup_{u \in \mathbb{D}(\bar{y}, \bar{x})(v)} \Sigma(v) = \bigcup_{u \in \mathbb{D}(\bar{y}, \bar{x})(v)} \{y^* \mid D^* \phi(x; (u, v))(y^*) \cap \mathbb{N}_C(x; u) \neq \emptyset\}.
  \]

Naturally, with strengthening the assumptions of \( \Psi \), one can relax the Lipschitzness of \( \phi \) accordingly.
E.g., under (iv\(\Psi\)) one only needs \( \phi \) to be Lipschitz near the fixed \( x \in \Psi(y) \) in direction \( u \in \mathbb{D}(\bar{y}, \bar{x})(v) \).

Note that directions \( u \in \mathbb{D}(\bar{y}, \bar{x})(v) \) and \( u \in \mathbb{D}(\bar{y}, \bar{x})(0) \cap \mathcal{J} \) can be written in terms of the data \( C, \phi \) and \( Q \) as clarified in Lemma 4.4.

### 4.2 Directional subdifferentials of value function

Following [2], we consider directional limiting subdifferentials with respect to a pair of directions. More precisely, given an extended real-valued function \( f : \mathbb{R}^n \to \overline{\mathbb{R}} \), a point \( \bar{x} \in \text{dom} f := \{x \in \mathbb{R}^n \mid f(x) \in \mathbb{R}\} \) in the domain of \( f \) as well as a direction \( (u, \mu) \in \mathbb{R}^{n+1} \), the *directional limiting subdifferential* of \( f \) at \( \bar{x} \) in direction \( (u, \mu) \) is given via
\[
\partial f(\bar{x}; (u, \mu)) := \{\xi \in \mathbb{R}^n \mid \langle \xi, -1 \rangle \in \mathbb{N}_{\text{epi} f}(\bar{x}, f(\bar{x})); (u, \mu)\},
\] (4.11)
where \( \text{epi } f := \{(x, \alpha) \in \mathbb{R}^{n+1} \mid a \geq f(x)\} \) stands for the epigraph of \( f \). Moreover, we say that \( f \) is lower semicontinuous (lsc) around \( \bar{x} \) if \( \text{epi } f \) is locally closed around \( (\bar{x}, f(\bar{x})) \).

In order to discuss the value (or marginal) function, consider an lsc function \( f : \mathbb{R}^n \times \mathbb{R}^l \to \mathbb{R} \), set \( \bar{\vartheta}(y) = \inf_{x \in \mathbb{R}^n} f(x, y) \) and assume that \( \bar{\vartheta} \) is finite at \( \bar{y} \). Moreover, let \( S : \mathbb{R}^l \to \mathbb{R}^n \) be the solution mapping given by \( S(y) = \arg \min f(\cdot, y) \) and consider a direction \((v, \mu) \in \mathbb{R}^{l+1} \). Following the approach from [25, Proposition 3.2., Proposition 3.3.], we impose the crucial inner condition on mapping \( S \), but without the restriction to the domain.

Under the mildest assumption (i\(_S\)), the connection between the subdifferentials of \( \bar{\vartheta} \) and \( f \) is provided by \( \text{epi } \bar{\vartheta} = \varphi(\text{epi } f) \) with \( \varphi : \mathbb{R}^{n+1} \to \mathbb{R}^{l+1} \) given by \( \varphi(x, y, \alpha) = (y, \alpha) \), see [34, Theorem 10.13]. Hence, in order to apply Theorem 4.7, consider also the map

\[
\Psi(y, \alpha) := \varphi^{-1}(y, \alpha) \cap \text{epi } f = \{(x, y, \alpha) \mid (x, y, \alpha) \in \text{epi } f\},
\]

(4.12)

and note that \( \text{dom } \Psi = \text{epi } \bar{\vartheta} \).

Based on the simple observation that

\[
\{(x, y, \alpha) \mid (y, \alpha) \in \text{epi } \bar{\vartheta}, x \in S(y)\} \subset \Psi(y, \alpha),
\]

(4.13)

it was shown in [2, Proof of Theorem 4.2] that the assumptions (i\(_S\)), (ii\(_S\)) and (iv\(_S\)) imply the corresponding assumptions on \( \Psi \). To give the reader a better insight, we prove that (iii\(_S\)) implies (iii\(_\Psi\)) to obtain the following lemma.

**Lemma 4.8.** The assumptions 4.1 on \( S \) (without the restriction to the domain of \( S \)) imply the corresponding assumptions on \( \Psi \), namely (i\(_S\)) implies (i\(_\Psi\)), (ii\(_S\)) implies (ii\(_\Psi\)), (iii\(_S\)) implies (iii\(_\Psi\)) and (iv\(_S\)) implies (iv\(_\Psi\)).

**Proof.** Consider \( \text{epi } \bar{\vartheta} \ni (y_k, \alpha_k) \to (\bar{y}, \bar{\vartheta}(\bar{y})) \) from direction \((v, \mu)\), i.e., \( y_k \to \bar{y} \) from direction \( v \). The inner calmness* of \( S \) at \( \bar{y} \) in direction \( v \) yields the existence of \( \kappa > 0 \) as well as \( \bar{x} \) and a sequence \( x_k \to \bar{x} \) such that, by passing to a subsequence, we have \( x_k \in S(y_k) \) and \( \|x_k - \bar{x}\| \leq \kappa \|y_k - \bar{y}\| \). Hence \( (x_k, y_k, \alpha_k) \in \Psi(y_k, \alpha_k) \) by (4.13) with \( (x_k, y_k, \alpha_k) \to (\bar{x}, \bar{y}, \bar{\vartheta}(\bar{y})) \). Moreover,

\[
\| (x_k, y_k, \alpha_k) - (\bar{x}, \bar{y}, \bar{\vartheta}(\bar{y})) \| \leq \| x_k - \bar{x} \| + \| (y_k, \alpha_k) - (\bar{y}, \bar{\vartheta}(\bar{y})) \| \leq \kappa \| y_k - \bar{y} \| + \| (y_k, \alpha_k) - (\bar{y}, \bar{\vartheta}(\bar{y})) \| \leq (\kappa + 1) \| (y_k, \alpha_k) - (\bar{y}, \bar{\vartheta}(\bar{y})) \|,
\]

showing the inner calmness* of \( \Psi \) at \( (\bar{y}, \bar{\vartheta}(\bar{y})) \) wrt \( \text{dom } \Psi = \text{epi } \bar{\vartheta} \) in direction \((v, \mu)\).

Naturally, one can also formulate the next theorem in terms of \( \Psi \). We stress again that the assumption on \( S \) are understood without the restriction to the domain of \( S \).

**Theorem 4.9** (Directional subdifferentials of value function). Let \( y^* \in \partial \bar{\vartheta}(\bar{y}; (v, \mu)) \). Then

- under (i\(_S\)) in direction \( v \), one has

\[
(0, y^*) \in \bigcup_{x \in S(y)} \left( \bigcup_{u \in DS(y, x)(v)} \partial f((x, y); (u, v, \mu)) \cup \bigcup_{u \in DS(y, x)(0)} \partial f((x, y); (u, 0, 0)) \right);
\]

- under (ii\(_S\)) in direction \( v \) with the prescribed \( \bar{x} \in S(\bar{y}) \), one has

\[
(0, y^*) \in \bigcup_{u \in DS(\bar{y}, \bar{x})(v)} \partial f((\bar{x}, \bar{y}); (u, v, \mu)) \cup \bigcup_{u \in DS(\bar{y}, \bar{x})(0)} \partial f((\bar{x}, \bar{y}); (u, 0, 0));
\]
- under (iii$\varepsilon$) in $v$, one has

$$(0, y^*) \in \bigcup_{\bar{x} \in S(y)} \bigcup_{u \in DS(\bar{y}, \bar{x})} \partial f((\bar{x}, \bar{y}); (u, v, \mu));$$

- under (iv$\varepsilon$) in $v$ with the prescribed $\bar{x} \in S(\bar{y})$, one has

$$(0, y^*) \in \bigcup_{u \in DS(\bar{y}, \bar{x})} \partial f((\bar{x}, \bar{y}); (u, v, \mu)).$$

The proof follows from Lemma 4.8 and Theorem 4.7, see also [2, Theorem 4.2] for more details. We point out that, in order to conclude that the estimates hold also with some $\bar{x} \in S(\bar{y})$ instead of $\bar{x}$ with $(\bar{x}, \bar{y}, \bar{\vartheta}(\bar{y})) \in \Psi(\bar{y}, \bar{\vartheta}(\bar{y}))$, one actually has to look into the proof of [2, Theorem 3.2] and put it together with the arguments from the proof of Lemma 4.8. The same applies for picking the directions $u$ from $DS(\bar{y}, \bar{x})(v)$ and $DS(\bar{y}, \bar{x})(0) \cap \mathcal{J}$, naturally. Alternatively, one can also prove the theorem directly, without relying on Theorem 4.7.

### 4.3 Chain rule and sum rule for set-valued maps, primal and dual form

Let us begin with the chain rule. To this end, consider the mappings $S_1 : \mathbb{R}^n \rightrightarrows \mathbb{R}^m, S_2 : \mathbb{R}^m \rightrightarrows \mathbb{R}^d$ with closed graphs, i.e., $S_1$ and $S_2$ are outer semicontinuous (osc), and set $S = S_2 \circ S_1$. Let $(\bar{x}, \bar{z}) \in gph S$ and $(u, w) \in \mathbb{R}^n \times \mathbb{R}^d$ be a pair of directions. Finally, consider the “intermediate” map $\Xi : \mathbb{R}^n \times \mathbb{R}^d \rightrightarrows \mathbb{R}^m$ defined by

$$\Xi(x, z) := S_1(x) \cap S_2^{-1}(z) = \{ y \in S_1(x) \mid z \in S_2(y) \}.$$

Following the approach from [34, Theorem 10.37] one has that

$$\text{dom} \Xi = gph S = \phi(\Phi^{-1}(gph S_1 \times gph S_2)),$$

where $\Phi : (x, y, z) \mapsto (x, z)$ and $\phi : (x, y, z) \mapsto (x, y, y, z)$. This suggests applying first the image set rule and then the pre-image set rule.

Note that

$$\Psi(x, z) := \Phi^{-1}(x, z) \cap \Phi^{-1}(gph S_1 \times gph S_2) = \{ (x, y, z) \mid (x, y) \in gph S_1, (y, z) \in gph S_2 \}$$

$$= \{ (x, y, z) \mid y \in \Xi(x, z) \},$$

so it is not surprising that the crucial assumptions 4.1 needed for the image set rule can be imposed of $\Xi$, instead of $\Psi$. Naturally, these conditions are understood wrt to point $(\bar{x}, \bar{z})$, domain $\text{dom} \Xi = gph S$ and some $\bar{y} \in \Xi(\bar{x}, \bar{z})$.

On the other hand, for the pre-image set rule we will need metric subregularity of the constraint mapping

$$F(x, y, z) := gph S_1 \times gph S_2 - \phi(x, y, z) = \begin{bmatrix} gph S_1 - (x, y) \\ gph S_2 - (y, z) \end{bmatrix}.$$ 

We first propose the following chain rule for graphical derivatives.

**Theorem 4.10** (Chain rule for graphical derivatives). **Under (iii$\Xi$)** it holds that

$$DS(\bar{x}, \bar{z}) \subset \bigcup_{\bar{y} \in \Xi(\bar{x}, \bar{z})} DS_2(\bar{y}, \bar{z}) \circ DS_1(\bar{x}, \bar{y}) \quad (4.14)$$
and the union over $\Xi(x, z)$ becomes superfluous if (iv$_2$) holds with the prescribed $y \in \Xi(x, z)$. On the other hand, given some $\bar{y} \in \Xi(x, z)$,

$$DS_2(\bar{y}, z) \circ DS_1(\bar{x}, \bar{y}) \subset DS(\bar{x}, \bar{z})$$

(4.15)

holds provided $F$ is metrically subregular at $((\bar{x}, \bar{y}, \bar{z}),(0,0))$ and

$$(u,v,w) \in T_{gphS_1 \times gphS_2}(\bar{x},\bar{y},\bar{z},\bar{z}) \iff (u,v) \in T_{gphS_1}(\bar{x},\bar{y}), (v,w) \in T_{gphS_2}(\bar{y},\bar{z}).$$

(4.16)

Proof. The proof follows from Corollaries 4.6 and 3.8, taking also into account that inclusion $\subset$ in formula (4.16) always holds due to the well-known fact that

$$T_{gphS_1 \times gphS_2}(\bar{x},\bar{y},\bar{z},\bar{z}) \subset T_{gphS_1}(\bar{x},\bar{y}) \times T_{gphS_2}(\bar{y},\bar{z}),$$

see [34, Proposition 6.41].

For more details we refer to the proof of [2, Theorem 5.1]. Let us take a look into the underlying principle in terms of the graphical derivative of $\Xi$. Realizing that

$$gphS = \varphi(gph \Xi), \quad gph \Xi = \varphi^{-1}(gphS_1 \times gphS_2)$$

and taking into account [34, Proposition 6.41] immediately gives the following lemma.

Lemma 4.11. Let $\bar{y} \in \Xi(x, z)$ and $v \in D\Xi((\bar{x}, \bar{z}), \bar{y})(u, w)$. Then

$$w \in DS(\bar{x}, \bar{z})(u) \quad \text{and} \quad w \in DS_2(\bar{y}, \bar{z}) \circ DS_1(\bar{x}, \bar{y})(u).$$

Remark 4.12. In Theorem 4.10, assumption (iii$_2$) (or (iv$_2$)) in fact allows one to estimate $DS(\bar{x}, \bar{z})$ via $D\Xi((\bar{x}, \bar{z}), \bar{y})$, while the metric subregularity of $F$, together with (4.16), provide the estimate of $DS_2(\bar{y}, \bar{z}) \circ DS_1(\bar{x}, \bar{y})$ via $D\Xi((\bar{x}, \bar{z}), \bar{y})$. Naturally, these two assumptions can be replaced by asking directly for the implication

$$w \in DS_2(\bar{y}, \bar{z}) \circ DS_1(\bar{x}, \bar{y})(u) \quad \Longrightarrow \quad \exists v \in D\Xi((\bar{x}, \bar{z}), \bar{y})(u, w).$$

(4.17)

Note that in [34, p. 454], the authors argue that it is difficult to obtain reasonable chain rule for graphical derivatives, since the image set and pre-image set rules for tangent cones in general work in “opposite direction”, see [34, Theorems 6.31 and 6.43]. More precisely, the upper estimate of the tangent cone to image set in [34, Theorem 6.43] was obtained only under quite restrictive assumptions. This also emphasizes the importance of the inner calmness and the inner calmness*.

Theorem 4.13 (Directional coderivative chain rule). Assume that (i$_{2z}$) in direction $(u, w)$ holds and that $F$ is metrically subregular (at $((\bar{x}, \bar{y}, \bar{z}),(0,0))$ for all $\bar{y} \in \Xi(x, z)$ in directions $(u, v, w)$ with $v \in D\Xi((\bar{x}, \bar{z}), \bar{y})(u, w)$ and in directions $(0, v, 0)$ with $v \in D\Xi((\bar{x}, \bar{z}), \bar{y})(0, 0) \cap \mathcal{S}$. Then one has

$$D^*S((\bar{x}, \bar{y}, \bar{z});(u, w)) \subset \bigcup_{\bar{y} \in \Xi(\bar{x}, \bar{z})} \left( \bigcup_{v \in D\Xi((\bar{x}, \bar{z}), \bar{y})(u, w)} D^*S_1((\bar{x}, \bar{y});(u, v)) \circ D^*S_2((\bar{y}, \bar{z});(v, w)) \right) \bigcup_{v \in D\Xi((\bar{x}, \bar{z}), \bar{y})(0, 0) \cap \mathcal{S}} D^*S_1((\bar{x}, \bar{y});(0, v)) \circ D^*S_2((\bar{y}, \bar{z});(v, 0)).$$

(4.18)

Moreover, assuming the stronger properties (ii$_{2z}$), (iii$_{2z}$) or (iv$_{2z}$) in direction $(u, w)$ yields the evident simplifications in the above estimate, whereby the assumption of metric subregularity of $F$ can be accordingly restricted to the corresponding points and directions, analogously to Theorem 4.7.
Next we briefly discuss the situation when one of the mappings is single-valued. We begin by the following lemma.

**Lemma 4.14.** Let $\overline{y} \in \Xi(\overline{x}, \overline{z})$. Then (4.17) holds provided one of the following conditions is satisfied:

(a) $S_1$ is single-valued, differentiable at $\overline{x}$ with $\nabla S_1(\overline{x})$ being injective and $S_1^{-1}$ is inner calm at $(\overline{y}, \overline{x})$. This holds, in particular, if $S_1$ is linear and injective.

(b) $S_2$ is single-valued and differentiable at $\overline{y}$.

**Proof.** Consider $(u, v, w)$ with $(u, v) \in T_{\text{gph} S_1}(\overline{x}, \overline{y})$ and $(v, w) \in T_{\text{gph} S_2}(\overline{y}, \overline{z})$ and let $t_k \downarrow 0$, $(u_k, v_k) \rightarrow (u, v)$ and $\tau_k \downarrow 0$, $(\tilde{v}_k, w_k) \rightarrow (v, w)$ with $\overline{y} + t_k u_k \in S_1(\overline{x} + t_k u_k)$ and $\overline{z} + \tau_k w_k \in S_2(\overline{y} + \tau_k \tilde{v}_k)$.

Under (a), we obtain from the inner calmness of $S_1^{-1}$ the existence of $\kappa > 0$ and $x_k$ with $\|x_k - \overline{x}\|/\tau_k \leq \kappa \|\tilde{v}_k\|$ and $\overline{y} + \tau_k \tilde{v}_k = S_1(x_k) = \overline{y} + \nabla S_1(\overline{x})(x_k - \overline{x}) + o(\|x_k - \overline{x}\|)$. Hence, by passing to a subsequence we may assume that $\tilde{u}_k := (x_k - \overline{x})/\tau_k \rightarrow \overline{u}$ and we conclude that $v = \nabla S_1(\overline{x})\overline{u}$, showing that $\overline{u} = u$ by the assumed injectivity of $\nabla S_1(\overline{x})$. This means, however, that $(\overline{x}, \overline{y}, \overline{\tilde{v}}) + \tau_k (\tilde{u}_k, w_k, \tilde{v}_k) \in \text{gph} \Xi$ and (4.17) follows.

On the other hand, (b) yields $S_2(\overline{y} + t_k v_k) = S_2(\overline{y}) + t_k \tilde{w}_k$ for $\tilde{w}_k = \nabla S_2(\overline{y})v + o(1) \rightarrow w$. Thus $(\overline{x}, \overline{y}, \overline{\tilde{w}}) + t_k (u_k, \tilde{w}_k, v_k) \in \text{gph} \Xi$ and (4.17) follows again. \qed

It is easy to see that if $S_1$ is single-valued and calm at $\overline{x}$, then $\Xi$ is single- (or empty-) valued and the strongest assumption (iv$_2$) is fulfilled. Hence, we obtain the following corollary.

**Corollary 4.15.** Assume that $S_1$ is single-valued and calm at $\overline{x}$. Then

$$DS(\overline{x}, \overline{z}) \subset DS_2(S_1(\overline{x}), \overline{z}) \circ DS_1(\overline{x})$$

and the above inclusion becomes equality under (4.17). Moreover, (4.17) holds, in particular, if either $F$ is metrically subregular at $((\overline{x}, \overline{y}, \overline{z}), (0, 0))$ and (4.16) holds, or, alternatively, if condition (a) of Lemma 4.14 is satisfied.

For the corresponding rule for coderivatives, we refer to [2, Corollary 5.1], noting that the Lipschitz-norm assumption on $S_1$ can be relaxed to calmness.

Now if $S_2$ is single-valued, on the basis of Lemma 4.14, we infer the following result.

**Corollary 4.16.** Assume that $S_2$ is single-valued. Then (iii$_\Xi$) yields (4.14) and the union becomes superfluous under (iv$_\Xi$). On the other hand, given $\overline{y} \in \Xi(\overline{x}, \overline{z})$, (4.15) holds under (4.17), which follows, in particular, if $S_2$ is also differentiable at $\overline{y}$.

Again, we skip the corresponding result for coderivatives, since it does not bring any new insights.

Indeed, apart from the evident simplifications in estimate (4.18), one just does not have to impose the subregularity assumption, provided $S_2$ is Lipschitz continuous, see also [2, Corollary 5.2].

Next, we present the sum rule, where for simplicity we consider only the sum of two maps, i.e., $S = S_1 + S_2$ for osc mappings $S_1, S_2 : \mathbb{R}^n \rightrightarrows \mathbb{R}^m$. Further, let $(\overline{x}, \overline{z}) \in \text{gph} S$ and $(u, w) \in \mathbb{R}^n \times \mathbb{R}^m$ be a pair of directions.

Here, the computation is done by applying the chain rule twice, since

$$S = F_2 \circ P$$

for $P : x \rightrightarrows S_1(x) \times S_2(x)$ and $F_2 : (y_1, y_2) \rightarrow y_1 + y_2$, 18
taking into account that $\mathcal{P}$ can be again written as a composition $S_o \circ F_1$ for $F_1 : x \to (x,x)$ and $S_o : (q_1,q_2) \mapsto S_1(q_1) \times S_2(q_2)$.

We point out here that the mapping $\mathcal{P}$ is interesting on its own, since it naturally appears whenever one is dealing with a mapping given by some operation applied to two mappings. In another words, $\mathcal{P}$ can be composed with other mappings to obtain interesting results. Hence, we first compute the generalized derivatives of $\mathcal{P}$. To this end, we introduce the following constraint mapping

$$F(x,q,y) := \begin{bmatrix} (x,x) - (q_1,q_2) \\ gphS_1 - (q_1,y_1) \\ gphS_2 - (q_2,y_2) \end{bmatrix}$$

and let $(\bar{x},\bar{y}) = (\bar{x},(\bar{y}_1,\bar{y}_2)) \in gph \mathcal{P}$ and $(u,v) = (u,(v_1,v_2)) \in \mathbb{R}^n \times (\mathbb{R}^m \times \mathbb{R}^m)$ be a pair of directions. We use here the simplified map $F$ with the first row replaced by $F_1(x) - (q_1,q_2)$. It is not difficult to show that this is possible due to the Lipschitzness of $F_1$.

Since $F_1 : x \to (x,x)$ clearly fulfills condition (a) of Lemma 4.14 and

$$gphS_0 = \sigma(gphS_1 \times gphS_2),$$

where $\sigma$ merely permutes the variables, we readily obtain the following result.

**Proposition 4.17.** We have

$$D\mathcal{P}(\bar{x},\bar{y}) \subset (DS_1(\bar{x},\bar{y}_1),DS_1(\bar{x},\bar{y}_2))$$

and for equality one needs to assume

$$T_{gphS_1 \times gphS_2}(\bar{x},\bar{y}_1,\bar{x},\bar{y}_2) = T_{gphS_1}(\bar{x},\bar{y}_1) \times T_{gphS_2}(\bar{x},\bar{y}_2). \quad (4.19)$$

In addition, if $F$ is metrically subregular at $((\bar{x},\bar{x},\bar{y}_1,\bar{y}_2),(0,\ldots,0))$ in direction $(u,u,u,v_1,v_2)$, then

$$D^* \mathcal{P}((\bar{x},\bar{y});(u,v)) \subset \big(D^*S_1((\bar{x},\bar{y}_1);(u,v_1)),D^*S_1((\bar{x},\bar{y}_2);(u,v_2))\big). \quad (4.20)$$

**Remark 4.18.** If one of the mappings $S_1$, $S_2$ is single-valued and differentiable at $\bar{x}$, one can easily see that (4.19) as well as the metric subregularity of $F$ hold and we have (4.20) and $D\mathcal{P}(\bar{x},\bar{y}) = (DS_1(\bar{x},\bar{y}_1),DS_1(\bar{x},\bar{y}_2))$.

Now we may proceed with the sum rule. In order to deal with the outer composition $F_2 \circ \mathcal{P}$ we will need the corresponding “intermediate” mapping. Thus, consider the map $\Xi : \mathbb{R}^n \times \mathbb{R}^m \mapsto \mathbb{R}^m \times \mathbb{R}^m$ defined by

$$\Xi(x,z) := \mathcal{P}(x) \cap F_2^{-1}(z) = \{y = (y_1,y_2) \in \mathbb{R}^m \times \mathbb{R}^m \mid y_1 \in S_1(x),y_2 \in S_2(x),y_1+y_2 = z\}.$$

**Theorem 4.19** (Sum rule for graphical derivatives). Under (iii) it holds that

$$DS(\bar{x},\bar{z}) \subset \bigcup_{\bar{y} \in \Xi(\bar{x},\bar{z})} DS_1(\bar{x},\bar{y}_1) + DS_2(\bar{x},\bar{y}_2) \quad (4.21)$$

and the union over $\Xi(\bar{x},\bar{z})$ becomes superfluous if (iv) holds with the prescribed $\bar{y} \in \Xi(\bar{x},\bar{z})$. On the other hand, given some $\bar{y} \in \Xi(\bar{x},\bar{z})$ such that (4.19) holds, we have

$$DS_1(\bar{x},\bar{y}_1) + DS_2(\bar{x},\bar{y}_2) \subset DS(\bar{x},\bar{z}). \quad (4.22)$$
In addition, the sum rule for the directional coderivatives can be formulated analogously to the chain rule from Theorem 4.13 with the main estimate (4.18) replaced by

$$D^*S((\bar{x}, \bar{z}); (u, w)) \subset \bigcup_{\tilde{y} \in \Xi(\bar{x}, \bar{z})} \bigg( \bigcup_{v \in D\Xi((\bar{x}, \bar{z}), \bar{y})(u, w)} D^*S_1((\bar{x}, \bar{y}_1); (u, v_1)) + D^*S_2((\bar{x}, \bar{y}_2); (u, v_2)) \bigg)$$

We also refer to [2, Theorem 5.2] for more details.

We conclude this section by a simple product rule, where $S = S_1 \cdot S_2$ for an osc mapping $S_2 : \mathbb{R}^m \rightrightarrows \mathbb{R}^m$ and a single-valued differentiable $S_1 : \mathbb{R}^n \to (\mathbb{R}^m)^l$. More precisely, $S_1(x)$ is a matrix of $m$ rows and $l$ columns and so $S(x) = \bigcup_{y \in S_2(x)} S_1(x)^T y = \bigcup_{y \in S_2(x)} \langle y, S_1(x) \rangle$. Further, let $(\bar{x}, \bar{z}) \in \text{gph} S$ and $(u, w) \in \mathbb{R}^n \times \mathbb{R}^l$ be a pair of directions.

Clearly, we can make use of mapping $\mathcal{P}$ again, since $S$ can be written as $F_3 \circ \mathcal{P}$ for $F_3 : (\mathbb{R}^m)^l \times \mathbb{R}^m \to \mathbb{R}^l$ given by $F(A, y) = A^T y$. Taking into account the single-valuedness of $S_1$, instead of $\mathcal{P}(x) \cap F_3^{-1}(z)$, we can use the following simplified “intermediate” mapping $\tilde{\Xi} : \mathbb{R}^n \times \mathbb{R}^l \rightrightarrows \mathbb{R}^m$ given by

$$\tilde{\Xi}(x, z) := \{ y \in S_2(x) \mid S_1(x)^T y = z \}.$$  \hspace{1cm} (4.23)

On the basis of Remark 4.18 and the simple structure of $F_3$, we arrive at the following elegant result.

**Theorem 4.20 (Product rule).** Under (iii), for all $z^* \in \mathbb{R}^l$ it holds that

$$DS(\bar{x}, \bar{z})(u) = \bigcup_{\tilde{y} \in \tilde{\Xi}(\bar{x}, \bar{z})} \nabla \langle \tilde{y}, S_1(\bar{x}) \rangle u + S_1(\bar{x})^T DS_2(\bar{x}, \bar{y})(u),$$

$$D^*S((\bar{x}, \bar{z}); (u, w))(z^*) \subset \bigcup_{\tilde{y} \in \tilde{\Xi}(\bar{x}, \bar{z})} \bigcup_{v \in D\tilde{\Xi}((\bar{x}, \bar{z}), \bar{y})(u, w)} \nabla \langle \tilde{y}, S_1(\bar{x}) \rangle (\bar{x})^T z^* + D^*S_2((\bar{x}, \bar{y}); (u, v))(S_1(\bar{x})z^*).$$

The union over $\tilde{\Xi}(\bar{x}, \bar{z})$ become superfluous if (iv) holds with the prescribed $\bar{y} \in \tilde{\Xi}(\bar{x}, \bar{z})$. Moreover, under just (i) we have

$$D^*S((\bar{x}, \bar{z}); (u, w))(z^*) \subset \bigcup_{\tilde{y} \in \tilde{\Xi}(\bar{x}, \bar{z})} \nabla \langle \tilde{y}, S_1(\bar{x}) \rangle (\bar{x})^T z^* + D^*S_2((\bar{x}, \bar{y}); (u, v))(S_1(\bar{x})z^*).$$

## 5 Application: Generalized derivatives of the normal-cone mapping

In this section, we apply the proposed calculus rules to compute the graphical derivative of the normal-cone mapping and to estimate its directional limiting coderivative. On one hand, we will show that our calculus-based approach is very robust and easy to apply in the variety of settings. On the other hand, we will also see its shortcomings compared to the results obtained by a direct computation. In the first part, we deal with the simple constraints and afterwards we consider the parametrized setting.

As a specific application we derive very interesting results regarding the newly developed concept of semismoothness*, which plays the crucial role in the new remarkable Newton method for generalized equations [18].
5.1 Simple constraints

Consider the simple constraint system \( g(x) \in D \), where \( D \subset \mathbb{R}^s \) is a convex polyhedral set and \( g : \mathbb{R}^n \to \mathbb{R}^t \) is twice continuously differentiable and denote

\[
\Gamma := g^{-1}(D) = \{ x \in \mathbb{R}^n \mid g(x) \in D \}.
\]  (5.24)

Moreover, fix \( \bar{x} \in \Gamma \) and assume that the constraint map \( g(x) - D \) is metrically subregular at \( \bar{x} \), which, in turn, means that the metric subregularity holds at all \( x \) near to \( \bar{x} \) and, consequently,

\[
N_{\Gamma}(x) = \nabla g(x)^T N_D(g(x)).
\]

Given also \( x^* \in N_{\Gamma}(x) \), Theorem 3.10 yields that the multiplier mapping

\[
\Lambda(x, x^*) = \{ \lambda \in N_D(g(x)) \mid \nabla g(x)^T \lambda = x^* \}
\]

is inner calm\(^*\) at \( (x, x^*) \) wrt its domain (in the fuzzy sense). Noting that \( \Lambda \) is precisely the “intermediate” mapping \( \widetilde{\Xi} \) from (4.23) appearing in the product rule from Theorem 4.20, we immediately obtain the following auxiliary estimates.

**Proposition 5.1.** For all \( u \in \mathbb{R}^n \), we have

\[
DN_{\Gamma}(x, x^*)(u) = \bigcup_{\lambda \in \Lambda(x, x^*)} \nabla^2(\lambda, g)(x) u + \nabla g(x)^T \nabla D(N_D \circ g)(x, \lambda)(u)
\]

and for all \( w^* \in \mathbb{R}^n \) and \( u^* \in DN_{\Gamma}(x, x^*)(u) \) we obtain

\[
D^*N_{\Gamma}((x, x^*); (u, u^*))((w^*)) \subset \bigcup_{\lambda \in \Lambda(x, x^*)} \bigcup_{\eta \in \partial N_D((x, x^*), \lambda)(u, u^*)} \nabla^2(\lambda, g)(x) w^* + D^*(N_D \circ g)((x, \lambda); (u, \eta))(\nabla g(x) w^*).
\]

Note that the analogous estimate for the standard limiting coderivative holds for any closed set \( D \), which is Clarke regular near \( g(x) \), in particular convex.

These estimates, however, still contain a composition \( N_D \circ g \) that needs to be dealt with. Applying Corollary 4.15 as well as the reduction lemma formula (2.1) yields the estimate

\[
DN_{\Gamma}(x, x^*)(u) \subset \bigcup_{\lambda \in \Lambda(x, x^*)} \nabla^2(\lambda, g)(x) u + \nabla g(x)^T \nabla D(N_D(g(x), \lambda))(\nabla g(x) u)
\]

\[
= \bigcup_{\lambda \in \Lambda(x, x^*)} \nabla^2(\lambda, g)(x) u + \nabla g(x)^T N_{\mathcal{K}_D(g(x), \lambda)}(\nabla g(x) u).
\]

In order to reverse the above inclusion, one seemingly needs to impose some constraint qualification, e.g., the metric subregularity of the mapping \( (x, \lambda) \rightrightarrows (g(x), \lambda) - \text{gph} D \). Note also that the same applies if one wants to proceed with the estimates for coderivatives.

Moreover, we can further adjust the above estimate. Indeed, for every \( \bar{\lambda} \in \Lambda(x, x^*) \) it holds that

\[
\mathcal{K}_D(x, x^*) = \nabla g(x)^{-1} \mathcal{K}_D(g(x), \bar{\lambda}).
\]

Since \( u \rightrightarrows \nabla g(x) u - \mathcal{K}_D(g(x), \bar{\lambda}) \) is a polyhedral map and hence metrically subregular by the Robinson’s results [32, Proposition 1], see also Theorem 3.6, we obtain

\[
N_{\mathcal{K}_D(x, x^*)}(u) = \nabla g(x)^T N_{\mathcal{K}_D(g(x), \bar{\lambda})}(\nabla g(x) u).
\]
Let us now compare it with the standard calculus-free approach from the literature. To the best of our knowledge, the most powerful result was obtained recently by Gfrerer and Mordukhovich in [14, Corollary 5.4] and it states that

$$DN_{\Gamma}(x,x')(u) = \bigcup_{\lambda \in \Lambda(x,x^*:u)} \nabla^2 \langle \lambda, g \rangle(x)u + N_{\Lambda(x,x^*)}(u)$$

holds without any additional assumptions. Here \(\Lambda(x,x^*:u)\) denotes the set of directional (or maximal) multipliers. Moreover, this result is not limited to the polyhedral setting and with the addition of the suitable curvature term, which vanishes in the polyhedral setting, the formula holds for set \(D\) being so-called \(C^2\)-cone reducible at \(g(x)\).

Let us briefly comment on the above-mentioned differences.

- **Multipliers.** It is not difficult to show that \(D(N_D \circ g)(x,\lambda)(u) \neq \emptyset\) implies \(\lambda \in \Lambda(x,x^*:u)\). Hence, despite the impression, there is in fact no difference regarding the multipliers between the two approaches and only the maximal multipliers are used.

- **Additional metric subregularity.** In order to show the equality

$$D(N_D \circ g)(x,\lambda)(u) = N_{\Lambda_D(g(x),\lambda)}(\nabla g(x)u),$$

one indeed needs an addition assumption. It is worth of noting, however, that we do not really need these sets to be the same. In particular, for our purposes it is sufficient to show that

$$\nabla g(x)^T D(N_D \circ g)(x,\lambda)(u) = N_{\Lambda_D(x,x^*)}(u).$$

- **Polyhedrality.** Of course, our approach is not really limited to the polyhedral case, since we only need the inner calmness* of \(\Lambda(x,x^*)\). Thus, we may state our results in very general setting, even without the convexity, using the inner calmness* of \(\Lambda(x,x^*)\) as an assumption. The question is, however, how often will this assumption be fulfilled in the nonpolyhedral setting.

Finally, as a specific application we derive the following result regarding the semismoothness* of the normal cone mapping.

**Proposition 5.2.** If the mapping \((x',\lambda') \Rightarrow (g(x'),\lambda') - \text{gph}N_D\) is metrically subregular at \((x,\lambda),(0,0)\) for every \(\lambda \in \Lambda(x,x^*)\), then the normal cone mapping \(x' \Rightarrow N_{\Gamma}(x')\) is semismooth* at \((x,x^*)\), i.e., for every pair of directions \((u,u') \in \mathbb{R}^n \times \mathbb{R}^n\) we have

$$\langle u,w \rangle = \langle u^*,w^* \rangle \quad \forall (w^*,w) \in \text{gph}D^*N_{\Gamma}(x,x^*);(u,u^*).$$

**Proof.** Clearly, if \(u^* \notin DN_{\Gamma}(x,x^*)(u)\), then \(D^*N_{\Gamma}(x,x^*);(u,u^*) = \emptyset\) and there is nothing to prove. Hence, let \(u^* \in DN_{\Gamma}(x,x^*)(u)\) and consider \(w \in D^*N_{\Gamma}(x,x^*);(u,u^*)\). Proposition 5.1 yields the existence of \(\lambda \in \Lambda(x,x^*)\) and \(\eta \in D\Lambda((x,x^*),\lambda)(u,u^*)\), in particular,

$$\eta \in D(N_D \circ g)(x,\lambda)(u) \quad \text{and} \quad \nabla^2 \langle \lambda, g \rangle(x)u + \nabla g(x)^T \eta = u^*,$$

with

$$w \in \nabla^2 \langle \lambda, g \rangle(x)w^* + D^*(N_D \circ g)((x,\lambda);(u,\eta))(\nabla g(x)w^*).$$

Hence

$$\langle u,w \rangle = \langle u,\nabla^2 \langle \lambda, g \rangle(x)w^* \rangle + \langle \eta, \nabla g(x)w^* \rangle = \langle \nabla^2 \langle \lambda, g \rangle(x)u + \nabla g(x)^T \eta, w^* \rangle = \langle u^*,w^* \rangle,$$
provided the mapping $N_D \circ g$ is semismooth* at $(x, \lambda)$.

The semismoothness* of $N_D \circ g$, however, follows from

$$D^* (N_D \circ g)((x, \lambda); (u, \eta)) (\xi^*) \subset \nabla g(x)^T D^* N_D((g(x), \lambda); (\nabla g(x)u, \eta)) (\xi^*),$$

which holds due to the assumed metric subregularity, together with the fact that the (polyhedral) map $(y, \lambda) \rightrightarrows N_D(y, \lambda)$ is semismooth* at every point of its graph [18, page 7]. Indeed, given $\xi \in D^* (N_D \circ g)((x, \lambda); (u, \eta)) (\xi^*)$, there exist $\xi \in D^* N_D((g(x), \lambda); (\nabla g(x)u, \eta)) (\xi^*)$ with $\xi = \nabla g(x)^T \xi$ and hence

$$\langle u, \xi \rangle = \langle u, \nabla g(x)^T \xi \rangle = \langle \nabla g(x)u, \xi \rangle = \langle \eta, \xi^* \rangle$$

by the semismoothness* of mapping $N_D$.

**Remark 5.3.** We decomposed the argument into two steps to emphasize their independence. On one hand, one can see that the assumed metric subregularity can be replaced by just asking directly for the semismoothness* of $N_D \circ g$. More importantly, it shows that the proof with trivial adjustments can be used to obtain also the parametrized versions of this result from Propositions 5.4 and 5.6.

### 5.2 Parametrized constraints

Given again a convex polyhedral set $D \subset \mathbb{R}^s$ and twice continuously differentiable $g : \mathbb{R}^l \times \mathbb{R}^n \to \mathbb{R}^s$, consider now the following parameter-dependent constraints $g(p, x) \in D$ and denote

$$\Gamma(p) := \{ x \in \mathbb{R}^n \mid g(p, x) \in D \}. \tag{5.25}$$

Here, given a reference point $(\bar{p}, \bar{x})$ with $g(\bar{p}, \bar{x}) \in D$, instead of metric subregularity we require the existence of $\kappa > 0$ such that for all $(p, x)$ belonging to a neighborhood of $(\bar{p}, \bar{x})$ the inequality

$$\text{dist}(x, \Gamma(p)) \leq \kappa \text{dist}(g(p, x), D)$$

holds. This yields, in particular, that for all $(p, x) \in \text{gph} \Gamma$ sufficiently close to $(\bar{p}, \bar{x})$ the mapping $g(p, \cdot) - D$ is metrically subregular at $(x, 0)$ with modulus $\kappa$ and hence

$$N_{\Gamma(p)}(x) = \beta(p, x)^T N_D(g(p, x))$$

for $\beta(p, x) = \nabla_2 g(p, x)$. Moreover, given $x^* \in N_{\Gamma(p)}(x)$, for every

$$\lambda \in \Lambda((p, x), x^*) = \{ \lambda \in N_D(g(p, x)) \mid \beta(p, x)^T \lambda = x^* \}$$

we have

$$\mathcal{K}_{\Gamma(p)}(x, x^*) = \beta(p, x)^{-1} \mathcal{K}_D(g(p, x), \lambda), \quad N_{\mathcal{K}_{\Gamma(p)}(x, x^*)}(u) = \beta(p, x)^T N_{\mathcal{K}_D(g(p, x), \lambda)}(\beta(p, x)u).$$

Finally, since $\text{gph} \Gamma = \{(p, x) \mid g(p, x) \in D\}$ and $\text{dist}((p, x), \text{gph} \Gamma) \leq \text{dist}(x, \Gamma(p))$, we conclude that the mapping $g(\cdot) - D$ is metrically subregular at $((p, x), 0)$ for every $(p, x) \in \text{gph} \Gamma$ sufficiently close to $(\bar{p}, \bar{x})$. Therefore, denoting $y = (p, x)$, we have

$$T_{\text{gph} \Gamma}(y) = \nabla g(y)^{-1} T_D(g(y)), \quad N_{\text{gph} \Gamma}(y) = \nabla g(y)^T N_D(g(y))$$

and hence the critical cone to $\text{gph} \Gamma$ can be also expressed via the critical cone to $D$ in the obvious manner. In particular, given $\lambda \in N_D(g(y))$ with $\nabla g(y)^T \lambda \in N_{\text{gph} \Gamma}(y)$, for every $v = (q, u)$ we obtain

$$N_{\mathcal{K}_{\text{gph} \Gamma}(y, \nabla g(y)^T \lambda)}(v) = \nabla g(y)^T N_{\mathcal{K}_{\Gamma}(g(y), \lambda)}(\nabla g(y)v).$$
Note that we again arrive at the analogous product structure as in the nonparametrized setting. Hence, the product rule from Theorem 4.20 can be applied, taking into account that the map \((y, x^*) \mapsto \Lambda(y, x^*)\), inner calm* by Theorem 3.10, again acts as the “intermediate” mapping. The corresponding auxiliary result for the graphical derivative, together with the same arguments as those after Proposition 5.1, give

\[
DN_{\Gamma(p)}(y, x^*)(v) = \bigcup_{\lambda \in \Lambda(y, x^*)} \nabla \langle \lambda, \beta \rangle (y)v + \beta(y)^T D(N_D \circ g)(y, \lambda)(v),
\]

and

\[
\subset \bigcup_{\lambda \in \Lambda(y, x^*)} \nabla \langle \lambda, \beta \rangle (y)v + \beta(y)^TN_{\mathcal{X}_D(g(y), \lambda)}(\nabla g(y)v).
\]

Since \(\nabla g(y)v = \nabla_1 g(y)q + \beta(y)u\) and

\[
N_{\mathcal{X}_D(g(y), \lambda)}(\nabla g(y)v) = \left(\mathcal{X}_D(g(y), \lambda)\right)^\circ \cap (\nabla_1 g(y)q + \beta(y)u)^\perp,
\]

in case of the “weak parametrization” (\(rg \nabla_1 g(y) = \{0\}\)), we obtain same result as in the nonparametrized setting. In fact, the weak parametrization can be relaxed to condition \(rg \nabla_1 g(y) \subset lin T_D(g(y))\).

With no additional assumptions, we have two ways how to proceed. First, simply forgetting the argument \(\nabla g(y)v\), i.e., replacing it by 0, yields

\[
DN_{\Gamma(p)}(y, x^*)(v) \subset \bigcup_{\lambda \in \Lambda(y, x^*)} \nabla \langle \lambda, \beta \rangle (y)v + \left(\mathcal{X}_D(p, x^*)\right)^\circ, \tag{5.26}
\]

and we can restrict the multipliers to those fulfilling \(\langle \lambda, \nabla g(y)v \rangle = 0\) due to \(\nabla g(y)v \in \mathcal{X}_D(g(y), \lambda)\).

On the other hand, one can also provide an estimate in terms of the graph of \(\Gamma\). Indeed, taking into account that \(\nabla g(y)^T = (\nabla_1 g(y), \beta(y))^T\) we obtain

\[
DN_{\Gamma(p)}(y, x^*)(v) \subset \bigcup_{\lambda \in \Lambda(y, x^*)} \nabla \langle \lambda, \beta \rangle (y)v + \pi_2\left(N_{\mathcal{X}_{\mathcal{G}^\Gamma}(y, \nabla g(y)^T, \lambda)}(v)\right), \tag{5.27}
\]

where \(\pi_2 : \mathbb{R}^d \times \mathbb{R}^n \rightarrow \mathbb{R}^n\) denotes the projection operator given by \(\pi_2(p, x) = x\).

The aforementioned paper [14] by Gfrerer and Mordukhovich actually deals with the same parametrized setting (5.25), while the results for the nonparametrized setting are just a special case of the weak parametrization. Firstly, based on [14, Lemma 4.1(i)], one can infer that (5.26) holds without the polyhedrality assumption in the \(C^2\)-cone reducible case, with the addition of the suitable curvature term, naturally. On the other hand, the estimate (5.27) holds either in the polyhedral setting, or under \(rg \nabla_1 g(y) \subset rg \beta(y) + lin T_D(g(y))\), see [14, Theorem 5.3]. Moreover, in the \(C^2\)-cone reducible case, the opposite inclusion in (5.27) follows without additional assumptions from [14, Theorem 3.3].

Finally, the analogous arguments as used in the proof of Proposition 5.2 yield the following parametrized version, see also Remark 5.3.

**Proposition 5.4.** Suppose that the mapping \((y', \lambda') \mapsto (g(y'), \lambda')\) - \(gph N_D\) is metrically subregular at \(((y, \lambda), \{0, 0\})\) for every \(\lambda \in \Lambda(y, x^*)\). Then the normal cone mapping \((p', x^*) \mapsto N_{\Gamma(p')}(x^*)\) is semismooth* at \((y, x^*) = (p, x, x^*)\).

### 5.3 Constraints depending on the parameter and the solution

Let \(D \subset \mathbb{R}^d\) be again convex polyhedral, consider twice continuously differentiable mapping \(g : \mathbb{R}^l \times \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}^n\) and denote

\[
\Gamma(p, x) := \{z \in \mathbb{R}^n \mid g(p, x, z) \in D\}, \tag{5.28}
\]
i.e., the feasible set depends also on the solution $x$. As before, given a reference point $(\bar{p}, \bar{x})$ with $g(\bar{p}, \bar{x}, \bar{x}) \in D$, assume that there exists some $\kappa > 0$ such that for all $(p, x, z)$ belonging to a neighborhood of $(\bar{p}, \bar{x}, \bar{x})$ the inequality

$$\text{dist}(z, \Gamma(p, x)) \leq \kappa \text{dist}(g(p, x, z), D)$$

(5.29)

holds. Denoting $\beta(p, x) = \nabla g(p, x, x)$ and $\bar{g}(p, x) = g(p, x, x)$, we obtain

$$N_{\Gamma(p, x)}(x) = \beta(p, x)^T N_D(\bar{g}(p, x)) = \beta(y)^T N_D(\bar{g}(y))$$

for $y = (p, x)$. On top of it, all the analogous relations for computing the normals, tangents and critical directions remain valid.

Given $v = (q, u) \in \mathbb{R}^l \times \mathbb{R}^n$ and $w^* \in \mathbb{R}^n$, Theorem 4.20 yields

$$DN_{\Gamma(p, x)}(y, x^*)(v) = \bigcup_{\lambda \in \Lambda(y, x^*)} \nabla (\lambda, \beta)(y) v + \beta(y)^T D(N_D \circ \bar{g})(y, \lambda)(v)$$

and for $u^* \in DN_{\Gamma(p, x)}(y, x^*)(v)$ also

$$D^* N_{\Gamma(p, x)}((y, x^*); (v, u^*))(w^*) \subset \bigcup_{\lambda \in \Lambda(y, x^*)} \nabla (\lambda, \beta)(y)^T w^* + D^* (N_D \circ \bar{g})(y, \lambda; (v, \eta))(\beta(y) w^*)$$

Proceeding as in the previous section, we can immediately derive two estimates for the graphical derivative as follows. First, applying the calculus to $N_D \circ \bar{g}$ as well as the reduction lemma as before, and then replacing the argument $\nabla \bar{g}(y) v$ by $0$, yields

$$DN_{\Gamma(p, x)}(y, x^*)(v) \subset \bigcup_{\lambda \in \Lambda(y, x^*)} \nabla (\lambda, \beta)(y) v + (N_{\Gamma(p, x)}(x, x^*))^c,$$

where $(\lambda, \nabla \bar{g}(y)) v = 0$. On the other hand, from $\nabla g(y)^T = (\nabla_1 g(y), \nabla_2 g(y), \beta(y))^T$ we infer

$$DN_{\Gamma(p)}(y, x^*)(v) \subset \bigcup_{\lambda \in \Lambda(y, x^*)} \nabla (\lambda, \beta)(y) v + \pi_3(N_{\Gamma_p(y, x^*)}(\nabla g(y)^T \lambda)),$$

where $\pi_3 : \mathbb{R}^l \times \mathbb{R}^n \times \mathbb{R}^n \to \mathbb{R}^n$ denotes the projection operator given by $\pi_3(p, x, z) = z$.

Moreover, we obtain the following more delicate result.

**Theorem 5.5.** For every $v \in \mathbb{R}^l \times \mathbb{R}^n$ we have

$$DN_{\Gamma(p, x)}(y, x^*)(v) \subset \bigcup_{\lambda \in \Lambda(y, x^*)} \nabla (\lambda, \beta)(y) v + \beta(y)^T N_{\Gamma(p, x)}(y, \lambda)(\nabla g(y) v).$$

On the other hand, given $v \in \mathbb{R}^l \times \mathbb{R}^n$, $\lambda \in \Lambda(y, x^*)$ and $\eta \in N_{\Gamma(p, x)}(\nabla g(y), \lambda)(\nabla g(y) v)$, assume that the mapping $F : \mathbb{R}^l \times \mathbb{R}^n \times \mathbb{R}^4 \to \mathbb{R}^8 \times \mathbb{R}^8$ given by

$$F(y, \lambda') := (\bar{g}(y)', \lambda') - g_D$$

is metrically subregular in direction $(v, \eta)$ at $((y, \lambda), (0, 0))$. Then we have

$$\nabla (\lambda, \beta)(y) v + \beta(y)^T \eta \in DN_{\Gamma(p, x)}(y, x^*)(v)$$

and, moreover, for $u^* \in DN_{\Gamma(p, x)}(y, x^*)(v)$ and arbitrary $w^* \in \mathbb{R}^n$ one has the estimate

$$D^* N_{\Gamma(p, x)}((y, x^*); (v, u^*))(w^*) \subset \bigcup_{\lambda \in \Lambda(y, x^*)} \bigcup_{\eta \in D \Lambda((y, x^*), \lambda)} \nabla (\lambda, \beta)(y)^T w^* + \nabla \bar{g}(y)^T D^* N_D((\bar{g}(y), \lambda); (\nabla \bar{g}(y) v, \eta))(\beta(y) w^*).$$
The model was investigated already in [30] by using the classical calculus of Mordukhovich.

Recently, in [17], Gfrerer and Outrata computed the graphical derivative and estimated the directional limiting coderivative of the normal-cone mapping $N_{\Gamma(p,x)}$. The latter task was done using similar calculus rules. In order to proceed, however, they imposed much stronger assumption that guarantees the uniqueness of the multiplier $\lambda$ and the “direction” $\eta$. The underlying reason was that, without explicitly mentioning it, they were in fact relying on the stronger property of inner calmness, see, e.g., [17, Lemmas 4.1 and 4.2].

The huge difference between these restrictive, nondegeneracy-type assumptions on one hand, and our mild, subregularity-like inequality (5.29) on the other, signifies the gap between the inner calmness and the inner calmness*.

On the other hand, in [3], the authors worked with the same assumption (5.29) to obtain also the same result for the graphical derivative. The explicit estimation of the coderivative was, however, bypassed by addressing the related stability issues directly, see [3, Theorem 6.1].

To sum up, our new calculus approach unifies the computation of the graphical derivative and the estimation of the directional limiting coderivative and it also provides the estimate for the directional limiting coderivative under (5.29). Note that in this case of the constraints depending also on the solution, which is arguably the most challenging case, we actually recover the best known results. We believe that our approach brings an important insight into the demanding proofs and computations. For instance, in [3, 17], the formula for the graphical derivative is derived from [14, Theorem 5.3]. Hence, in order to understand it, one has to go through much more laborious material than actually needed. Our paper clarifies that and offers considerably simpler arguments.

We conclude this section by the corresponding semismoothness* result.

**Proposition 5.6.** If the mapping (5.30) is metrically subregular at $((y,\lambda),(0,0))$ for every $\lambda \in \Lambda(y,x^*)$, then the normal cone mapping $(p',x') \mapsto N_{\Gamma(p',x')}(x')$ is semismooth* at $(y,x^*) = (p,x,x^*)$.

**Conclusion**

Looking closely at the remarkable results regarding computation of the graphical derivative of the normal cone mapping, we provide new insights by revealing the underlying calculus. Although the main purpose is to better understand these known results and to simplify and unify their proofs, our attempt yields also several novelties. Indeed, we propose the new calculus rules, in particular the chain rule for the graphical derivative, as well as the new property of inner calmness*. We believe that this paper has already shown that the inner calmness* is very interesting and we also believe that it deserves further study.

We point out that our calculus-based approach does not fully cover the result obtained by the direct approach. Hence, it seems that, when dealing with generalized derivatives, it is not good to rely solely on the calculus rules. On the other hand, we also believe that the calculus provides very solid foundation and offers a simpler, unified view. Therefore, we think it is still useful to look whether new results contain some calculus principles, either the well-established ones or some new, yet-to-be-formulated ones.

**Acknowledgements**

The research was supported by the Austrian Science Fund (FWF) under grant P29190-N32. The author would like to thank Helmut Gfrerer and Jiří V. Outrata for valuable discussions and support.
References

[1] M. Benko, H. Gfrerer, B. S. Mordukhovich, Characterizations of tilt-stable minimizers in second-order cone programming, accepted to SIAM J. Optim., 28 p. (2018), arXiv: 1809.03607.

[2] M. Benko, H. Gfrerer, J. V. Outrata, Calculus for directional limiting normal cones and subdifferentials, Set-Valued Var. Anal., 27 (2019), pp. 713–745.

[3] M. Benko, H. Gfrerer, J. V. Outrata, Stability analysis for parameterized variational systems with implicit constraints, Set-Valued Var. Anal. (2019), DOI 10.1007/s11228-019-00516-1.

[4] J. F. Bonnans, A. Shapiro, Perturbation Analysis of Optimization Problems, Springer, New York, 2000.

[5] N. H. Chieu, L. V. Hien, Computation of graphical derivative for a class of normal cone mappings under a very weak condition, SIAM J. Optim. 27 (2017), pp. 190–204.

[6] R. Cibulka, M. Fabian, A. Y. Kruger, On semiregularity of mappings, Journal of Mathematical Analysis and Applications, 473 (2019), pp. 811–836.

[7] A. L. Dontchev, R. T. Rockafellar, Regularity and conditioning of solution mappings in variational analysis, Set-Valued Anal., 12 (2004), pp. 79–109.

[8] A. L. Dontchev, R. T. Rockafellar, Implicit Functions and Solution Mappings, Springer, Heidelberg, 2014.

[9] M. Fabian, R. Henrion, A. Y. Kruger, J. V. Outrata, Error bounds: necessary and sufficient conditions, Set-Valued Var. Anal., 18 (2010), pp. 121–149.

[10] H. Gfrerer, On directional metric regularity, subregularity and optimality conditions for nonsmooth mathematical programs, Set-Valued Var. Anal., 21 (2013), pp. 151–176.

[11] H. Gfrerer, D. Klatte, Lipschitz and Hölder stability of optimization problems and generalized equations, Math. Program., Ser. A, 158 (2016), pp. 35–75.

[12] H. Gfrerer, B. S. Mordukhovich, Complete characterizations of tilt stability in nonlinear programming under weakest qualification conditions, SIAM J. Optim., 25 (2015), pp. 2081–2119.

[13] H. Gfrerer, B. S. Mordukhovich, Robinson stability of parametric constraint systems via variational analysis, SIAM J. Optim., 27 (2017), pp. 438–465.

[14] H. Gfrerer, B. S. Mordukhovich, Second-order variational analysis of parametric constraint and variational systems, SIAM J. Optim., 29 (2019), pp. 423–453.

[15] H. Gfrerer, J. V. Outrata, On computation of generalized derivatives of the normal-cone mapping and their applications, Math. Oper. Res. 41 (2016), pp. 1535–1556.

[16] H. Gfrerer, J. V. Outrata, On Lipschitzian properties of implicit multifunctions, SIAM J. Optim., 26 (2016), pp. 2160–2189.
[17] H. FRERER, J. V. OUTRATA, On the Aubin property of solution maps to parameterized variational systems with implicit constraints, Optimization, (2019), DOI 10.1080/02331934.2019.1657427.

[18] H. FRERER, J. V. OUTRATA, On a semismooth* Newton method for solving generalized equations, (2019), submitted, arXiv:1904.09167.

[19] N. T. V. HANG, B. S. MORDUKHOVICH, M. E. SARABI, Second-order variational analysis in second-order cone programming, Math. Program. (2018), DOI 10.1007/s10107-018-1345-6.

[20] R. HENRION, A. JOURANI, J. V. OUTRATA, On the calmness of a class of multifunctions, SIAM J. Optim., 13 (2002), pp. 603–618.

[21] R. HENRION, J. V. OUTRATA, Calmness of constraint systems with applications, Math. Program., Ser. B, 104 (2005), pp. 437–464.

[22] A. D. IOFFE, Necessary and sufficient conditions for a local minimum 1: A reduction theorem and first order conditions, SIAM J. Control Optim., 17 (1979), pp. 245–250.

[23] A. D. IOFFE, Variational Analysis of Regular Mappings, Springer Monographs in Mathematics, Springer, Cham, 2017.

[24] A. D. IOFFE, J. V. OUTRATA, On metric and calmness qualification conditions in subdifferential calculus, Set-Valued Anal., 16 (2008), pp. 199–227.

[25] A. D. IOFFE, J.-P. PENOT, Subdifferentials of performance functions and calculus of coderivatives of set-valued mappings, Serdica Math. J., 22 (1996), pp. 359–384.

[26] D. KLATTE, B. KUMMER, Nonsmooth Equations in Optimization. Regularity, Calculus, Methods and Applications, Nonconvex Optimization and its Applications 60, Kluwer Academic Publishers, Dordrecht, Boston, London, 2002.

[27] D. KLATTE, B. KUMMER, On calmness of the Argmin mapping in parametric optimization problems, J. Optim. Theory Appl., 165 (2015), pp. 708–719.

[28] B. S. MORDUKHOVICH, Variational Analysis and Generalized Differentiation, Vol.I: Basic Theory, Springer, Berlin, Heidelberg, 2006.

[29] B. S. MORDUKHOVICH, Variational Analysis and Applications, Springer, Cham, 2018.

[30] B. S. MORDUKHOVICH, J. V. OUTRATA, Coderivative analysis of quasi-variational inequalities with applications to stability and optimization, SIAM J. Optim., 18 (2007), pp. 389–412.

[31] J.-P. PENOT, Calculus Without Derivatives, Springer, New York, NY, 2013.

[32] S. M. ROBINSON, Some continuity properties of polyhedral multifunctions, Math. Program. Studies, 14 (1981), pp. 206–214.

[33] R. T. ROCKAFELLAR, Convex Analysis, Princeton, New Jersey, 1970.

[34] R. T. ROCKAFELLAR, R. J-B. WETS, Variational Analysis, Springer, Berlin, 1998.

[35] D. W. WALKUP, R. J-B. WETS, A Lipschitzian characterization of convex polyhedra, Proc. of the AMS, 23 (1969), pp. 167–173.
Latest Reports in this series

2009 - 2017

[...]

2018

2018-01 Jarle Sogn and Stefan Takacs
Robust Multigrid Solvers for the Biharmonic Problem in Isogeometric Analysis
January 2018

2018-02 Irina Georgieva and Clemens Hofreither
Greedy Low-Rank Approximation in Tucker Format of Tensors and Solutions of Tensor Linear Systems
March 2018

2018-03 Katharina Rafetseder and Walter Zulehner
A New Mixed Isogeometric Approach to Kirchhoff-Love Shells
March 2018

2018-04 Matúš Benko, Helmut Gfrerer and Boris S. Mordukhovich
Characterizations of Tilt-Stable Minimizers in Second-Order Cone Programming
September 2018

2018-05 Helmut Gfrerer and Jane J. Ye
New Sharp Necessary Optimality Conditions for Mathematical Programs with Equilibrium Constraints
December 2018

2018-06 Helmut Gfrerer and Jiří V. Outrata
On the Aubin Property of Solution Maps to Parameterized Variational Systems with Implicit Constraints
December 2018

2018-07 Matúš Benko, Helmut Gfrerer and Jiří V. Outrata
Stability Analysis for Parameterized Variational Systems with Implicit Constraints
December 2018

2019

2019-01 Helmut Gfrerer and Jiří V. Outrata
On a Semismooth* Newton Method for Solving Generalized Equations
April 2019

2019-02 Matúš Benko, Michal Červinka and Tim Hoheisel
New Verifiable Sufficient Conditions for Metric Subregularity of Constraint Systems with Applications to Disjunctive Programs
June 2019

2019-03 Matúš Benko
On Inner Calmness*, Generalized Calculus, and Derivatives of the Normal-cone Map
October 2019

From 1998 to 2008 reports were published by SFB013. Please see
http://www.sfb013.uni-linz.ac.at/index.php?id=reports

From 2004 on reports were also published by RICAM. Please see
http://www.ricam.oeaw.ac.at/publications/list/

For a complete list of NuMa reports see
http://www.numa.uni-linz.ac.at/Publications/List/