VARIATIONAL ANALYSIS IN OPTIMIZATION AND CONTROL

BORIS MORDUKHOVICH

Wayne State University

Talk given at the

King Fahd University of Petroleum and Minerals

Dhahran, Saudi Arabia

March 2008

Supported by NSF grants DMS-0304989 and DMS-0603846

THE FUNDAMENTAL VARIATIONAL PRINCIPLE

Namely, because the shape of the whole universe is the most perfect and, in fact, designed by the wisest creator, nothing in all the world will occur in which no maximum or minimum rule is somehow shining forth...

Leonhard Euler (1744)

INTRINSIC NONSMOOTHNESS

is typically encountered in applications of modern variational principles and techniques to numerous problems arising in pure and applied mathematics particularly in analysis, geometry, dynamical systems (ODE,PDE), optimization, equilibrium, mechanics, control, economics, ecology, biology, computers science...

REMARKABLE CLASSES OF NONSMOOTH FUNCTIONS

MARGINAL/VALUE FUNCTIONS

$$\mu(x) := \inf\Big\{\varphi(x,y)\Big|\ y \in G(x)\Big\}$$

crucial in perturbation and sensitivity analysis, stability, and many other issues. In particular, **DISTANCE FUNCTIONS**

$\text{dist}(x;\Omega) := \inf\Big\{\|x-y\|\ \Big|\ y \in \Omega\Big\}$ or generally $\rho(x,z) := \text{dist}(x;F(z))$

naturally appear via variational principles and penalization.

INTRINSIC NONSMOOTHNESS (cont.)

MAXIMUM FUNCTIONS

$$f(x) = \max_{u \in U} g(x, u),$$

in particular, **HAMILTONIANS** in physics, mechanics, calculus of variations, systems control, variational inequalities, etc.

NONSMOOTH/NONCONVEX SETS AND MAPPINGS

Parametric sets of feasible and optimal solutions in various problems of equilibrium, optimization, dynamics
Preference and production sets in economic modeling
Reachable sets in dynamical and control systems
Sets of Equilibria and **Equilibrium Constraints** in physical, mechanical, economic, ecological, and biological models

SUBDIFFERENTIALS

of $\varphi\colon R^n \to \overline{R} := (-\infty, \infty]$ with $\varphi(\bar{x}) < \infty$ should satisfy:

1) for convex functions φ reduces to

$$\partial^{\bullet}\varphi(\bar{x}) = \Big\{ v \Big|\ \varphi(x) - \varphi(\bar{x}) \ge \langle v, x - \bar{x} \rangle \ \text{ for all } \ x \in R^n \Big\}.$$

2) If $\bar{x}$ is a local minimizer for φ, then $0 \in \partial^{\bullet}\varphi(\bar{x})$.

3) Sum Rule (Basic Calculus)

$$\partial^{\bullet}(\varphi_1 + \varphi_2)(\bar{x}) \subset \partial^{\bullet}\varphi_1(\bar{x}) + \partial^{\bullet}\varphi_2(\bar{x}).$$

4) Robustness

$$\partial^{\bullet}\varphi(\bar{x}) = \mathop{\text{Lim}\,\text{sup}}_{x \xrightarrow{\varphi} \bar{x}} \partial^{\bullet}\varphi(x),$$

where $\text{Lim}\,\text{sup}\, F(x) := \Big\{ y \Big|\ \exists x_k \to x,\ y_k \to y \ \text{ with } \ y_k \in F(x_k) \Big\}$ and $x \xrightarrow{\varphi} \bar{x}:\ x \to \bar{x},\ \varphi(x) \to \varphi(\bar{x})$.

THE BASIC SUBDIFFERENTIAL

of $\varphi\colon I\!R^n \to \overline{I\!R}$ at $\bar{x}$ [Mor-1976] is

$$\partial\varphi(\bar{x}) := \operatorname*{Lim\,sup}_{x \xrightarrow{\varphi} \bar{x}} \widehat{\partial}\varphi(x)$$

where Fréchet/viscosity subdifferential of φ at x is defined by

$$\widehat{\partial}\varphi(x) := \left\{ v \middle| \liminf_{u \to x} \frac{\varphi(u) - \varphi(x) - \langle v, u - x \rangle}{\|u - x\|} \ge 0 \right\}.$$

The **basic subdifferential** is **minimal** among all subdifferentials satisfying 1)-4), nonempty

$$\partial\varphi(\bar{x}) \neq \emptyset \ \text{ for Lipschitz functions,}$$

while often nonconvex, e.g., $\partial(-|x|)(0) = \{-1, 1\}$. Moreover, its convexification, made for convenience, can dramatically worsen the basic properties and applications.

VARIATIONAL GEOMETRY

The (basic) **NORMAL CONE** $N(\bar{x};\Omega) := \partial\delta(\bar{x};\Omega)$ to Ω at $\bar{x} \in \Omega$ is equivalent to

$$N(\bar{x};\Omega) = \mathop{\mathrm{Lim\,sup}}_{x \to \bar{x}} \Big[\mathrm{cone}(x - \Pi(x;\Omega))\Big]$$

where $\Pi(x;\Omega)$ is the Euclidean projector. Then

$$\partial\varphi(\bar{x}) = \Big\{v\Big|\ (v,-1) \in N((\bar{x},\varphi(\bar{x}));\mathrm{epi}\,\varphi)\Big\}.$$

The convexified normal cone

$$\overline{N}(\bar{x};\Omega) = \mathrm{clco}\ N(\bar{x};\Omega)$$

turns out to be a linear subspace for any nonsmooth Lipschitzian manifolds. This happens, e.g., for graphs of locally Lipschitz vector functions and maximal monotone operators that typically occur in variational inequalities and complementarity problems.

EXTREMALITY OF SET SYSTEMS

DEFINITION. $\bar{x} \in \Omega_1 \cap \Omega_2$ is a **LOCAL EXTREMAL POINT** of the system of closed sets $\{\Omega_1, \Omega_2\}$ in a normed space X if there exists a neighborhood U such that for any $\varepsilon > 0$ there is $a \in X$ with $\|a\| < \varepsilon$ satisfying

$$(\Omega_1 + a) \cap \Omega_2 \cap U = \emptyset.$$

EXAMPLES:

—boundary point of closed sets

—local solutions to constrained optimization, multiobjective optimization, and other optimization-related problems

—minimax solutions and equilibrium points

—Pareto-type allocations in economics

—stationary points in mechanical and ecological models, etc.

EXTREMAL PRINCIPLE

THEOREM. Let $\bar{x}$ be a **LOCAL EXTREMAL POINT** for the system of closed sets $\{\Omega_1, \Omega_2\}$ in X.Then there exists a dual element $0 \neq x^* \in X^*$ such that

$$x^* \in N(\bar{x}; \Omega_1) \cap (-N(\bar{x}; \Omega_2)).$$

This is a **VARIATIONAL** counterpart of the separation theorem for the case of nonconvex sets, which plays a fundamental role in variational analysis and its applications.
PROOF. Perturbation techniques and special iterative procedures+geometry of Banach/Asplund spaces.
SOME APPLICATIONS: Full Calculus for nonconvex subdifferentials and normals;Metric regularity/Openess/Stability and Optimality Conditions; Sensitivity Analysis, ODE and PDE Control, Economic and Mechanical Equilibria, Numerical Analysis...

CODERIVATIVES OF MAPPINGS

Let $F\colon X \rightrightarrows Y$ be a set-valued mapping with $(\bar{x},\bar{y}) \in \text{gph}F$. Then $D^*F(\bar{x},\bar{y})\colon Y^* \rightrightarrows X^*$ defined by

$$D^*F(\bar{x},\bar{y})(y^*) := \Big\{x^*\Big|\ (x^*,-y^*) \in N((\bar{x},\bar{y});\text{gph}\,F)\Big\}$$

is called the **coderivative** of F at $(\bar{x},\bar{y})$.

If $F\colon X \to Y$ is smooth around $\bar{x}$, then

$$D^*F(\bar{x})(y^*) = \Big\{\nabla F(\bar{x})^* y^*\Big\} \ \text{ for all } \ y^* \in Y^*,$$

i.e., the coderivative is a proper generalization of the classical adjoint derivative. If $F\colon X \to Y$ is single-valued and locally Lipschitzian around $\bar{x}$, then the scalarization formula holds:

$$D^*F(\bar{x})(y^*) = \partial\langle y^*, F\rangle(\bar{x}).$$

ENJOY FULL CALCULUS!

CHARACTERIZATION OF METRIC REGULARITY

DEFINITION. A set-valued mapping $F(\cdot)$ is METRICALLY REGULAR around $(\bar{x}, \bar{y}) \in \operatorname{gph} F$ if there are neighborhoods U of $\bar{x}$, V of $\bar{y}$ and positive numbers M, ε such that

$$\operatorname{dist}(x, F^{-1}(y)) \leq M \operatorname{dist}(y, F(x))$$

for all $x \in U$ and $y \in V$ with $\operatorname{dist}(y, F(x)) \leq \varepsilon$.

THEOREM. Let $F\colon X \rightrightarrows Y$ be an arbitrary set-valued mapping of closed graph. Then it is **METRICALLY REGULAR** around $(\bar{x}, \bar{y})$ **IF AND ONLY IF**

$$\ker D^* F(\bar{x}, \bar{y}) = \left\{0\right\}.$$

Furthermore, the **EXACT REGULARITY BOUND** is

$$\operatorname{reg} F(\bar{x}, \bar{y}) = \|D^* F^{-1}(\bar{y}, \bar{x})\| = \|D^* F(\bar{x}, \bar{y})^{-1}\|.$$

DISTANCE TO INFEASIBILITY AND CONDITIONING

Quantitative measuring the bounds of perturbations do not violate well-posedness: Eckart-Young, Renegar–the latter is motivated by the analysis of complexity of numerical algorithms. Then Donchev, Lewis and Rockafellar:

RADIUS OF METRIC REGULARITY

$$\operatorname{rad} F(\bar{x},\bar{y}) := \inf_g \Big\{ \|g\| \,\Big|\; \text{metric regularity fails for } \; F+g \Big\},$$

where the infimum is taken over linear bounded operators.

THE EXACT FORMULA FOR COMPUTING THE RADIUS:

$$\operatorname{rad} F(\bar{x},\bar{y}) = \frac{1}{\operatorname{reg} F(\bar{x},\bar{y})}.$$

Great many **applications** to **Sensitivity Analysis and Conditioning** in various constrained systems in mathematical programming, equilibrium models, control, etc.

FAILURE OF METR. REGULARITY FOR VARIATIONAL SYST.

Major classes of variational systems including solutions maps to parametric variational/hemivariational inequalities, complementarity problems, KKT systems, and other generalized equations/equilibrium conditions are given in the subdifferential forms:

$$S_1(x) = \Big\{ y \in Y \Big|\; 0 \in f(x,y) + \partial\big(\psi \circ g\big)(y) \Big\},$$

$$S_2(x) = \Big\{ y \in Y \Big|\; 0 \in f(x,y) + \big(\partial\psi \circ g\big)(y) \Big\}.$$

THEOREM. Under general assumptions, metric regularity fails for these classes of variational systems provided that φ is a lower semicontinuous convex function or, more generally, prox-regular function in both finite and infinite dimensions.

MATHEMATICAL PROGRAMMING

Consider the nonsmooth NP problem:

minimize $\varphi_0(x)$ subject to
$$\begin{aligned} &\varphi_i(x) \le 0,\ i = 1, \ldots, m \\ &\varphi_i(x) = 0,\ i = m+1, \ldots, m+r \\ &x \in \Omega. \end{aligned}$$

THEOREM (generalized Lagrange multipliers). Let φ_i be **locally Lipschitzian** and Ω be locally closed around an optimal solution $\bar{x}$. Then there are $(\lambda_0, \ldots, \lambda_{m+r}) \neq 0$ satisfying

$$\lambda_i \ge 0,\ i = 0, \ldots, m, \quad \lambda_i \varphi_i(\bar{x}) = 0,\ i = 1, \ldots, m,$$
$$0 \in \partial\Big(\sum_{i=0}^{m+r} \lambda_i \varphi_i\Big)(\bar{x}) + N(\bar{x}; \Omega).$$

Moreover, $\lambda_0 \neq 0$ **(Normality)** under appropriate **Constraint Qualification Conditions.**

DYNAMICAL SYSTEMS

governed by evolution inclusions

$$\dot{x}(t) \in F(x(t), t), \quad t \in [a, b], \quad x(a) = x_0 \in X,$$

where $\dot{x}$ stands for an appropriate time derivative and where $F\colon X \times [a, b] \rightrightarrows X$ is a set-valued is a set-valued mapping. This describes ordinary differential inclusions (for $X = \mathbb{R}^n$) and also partial differential inclusions and equations of parabolic, hyperbolic, and mixed types. Important for qualitative theory of dynamical system and numerous applications, e.g., to various economic, ecological, biological, financial systems, climate research...

In particular, this covers parameterized control systems with

$$\dot{x} = g(x, u, t), \;\; u(\cdot) \in U(x, t)$$

where the control region $U(x, t)$ depends on time and state.

DISCRETE APPROXIMATIONS

Euler's finite difference (for simplicity)

$$\dot{x}(t) \approx \frac{x(t+h) - x(t)}{h}, \quad h \to 0,$$

Consider the mesh as $N \to \infty$

$$t_j := a + jh_N, \quad j = 0, \ldots, N, \qquad t_0 = a, \; t_N = b, \; h_N = (b-a)/N.$$

Discrete Inclusions

$$x_N(t_{j+1}) \in x_N(t_j) + h_N F(x_N(t_j), t_j)$$

with piecewise linear Euler broken lines.

Various Well-Posedness, Convergence, and Stability Issues of Numerical and Qualitative Analysis in Finite-Dimensional and Infinite-Dimensional Spaces.

OPTIMAL CONTROL OF DIFFERENTIAL INCLUSIONS

minimize the cost functional

$$J[x] = \varphi\Big(x(b)\Big) \text{ subject to}$$

$$\dot{x}(t) \in F(x(t), t) \text{ a.e. } t \in [a, b], \quad x(a) = x_0,$$

$$x(b) \in \Omega \subset I\!R^n$$

where $F \colon I\!R^n \rightrightarrows I\!R^n$ is a Lipschitz continuous set-valued mapping, Ω is a closed set, φ is a l.s.c. function.
This covers various open-loop and closed-loop control systems with ODE dynamics and hard control and state constraints.

EXTENDED EULER-LAGRANGE+MAXIMUM PRINCIPLE

THEOREM. Let $\bar{x}(\cdot)$ be an optimal solution to the control problem. Then one has:

Euler-Lagrange inclusion

$$\dot{p}(t) \in D^*F\Big(\bar{x}(t), \dot{x}(t)\Big)\Big(-p(t)\Big) \text{ a.e.,}$$

Weierstrass-Pontryagin maximum condition condition

$$\Big\langle p(t), \dot{\bar{x}}(t)\Big\rangle = \max_{v \in F(\bar{x}(t))} \Big\langle p(t), v\Big\rangle \text{ a.e.,}$$

transversality condition

$$-p(b) \in \lambda \partial \varphi\Big(\bar{x}(b)\Big) + N\Big(\bar{x}(b); \Omega\Big)$$

with nontriviality condition $\Big(\lambda, p(\cdot)\Big) \neq 0$.

PROOF: DISCRETE APPROXIMATIONS.

HAMILTONIAN CONDITION

THEOREM. Let the sets $F(x) \subset I\!R^n$ be convex. Then the extended Euler-Lagrange inclusion is equivalent to the extended Hamiltonian inclusion

$$\dot{p}(t) \in \text{co}\left\{u \,\middle|\, \Big(-u, \dot{x}(t)\Big) \in \partial H\Big(\bar{x}(t), p(t)\Big)\right\} \text{ a.e.}$$

in terms of the basic subdifferential of the (true) Hamiltonian

$$H(x,p,t) := \sup\left\{\Big\langle p, v\Big\rangle \,\middle|\, v \in F(x,t)\right\},$$

which is intrinsically nonsmooth.

SEMILINEAR EVOLUTION INCLUSIONS AND PDEs

minimize $J[x] := \varphi(x(b))$ subject to
mild solutions to the semilinear evolution inclusion

$$\dot{x}(t) \in Ax(t) + F(x(t),t), \quad x(a) = x_0$$

with the endpoint constraints

$$x(b) \in \Omega \subset X,$$

where A is an unbounded generator of the C_0 semigroup, i.e.,

$$\begin{aligned} &x(t) = e^{A(t-a)}x_0 + \int_a^t e^{A(t-s)}v(s)\,ds, \quad t \in [a,b] \\ &v(t) \in F(x(t),t), \quad t \in [a,b] \end{aligned}$$

in the sense of Bochner integration.
Cover PDE systems with parabolic and hyperbolic dynamics.

REFERENCES

1. **B. S. MORDUKHOVICH**, **VARIATIONAL ANALYSIS AND GENERALIZED DIFFERENTIATION, I: BASIC THEORY, II: APPLICATIONS**, Grundlehren Series (Fundamental Principles of Mathematical Sciences), Vol. **330, 331**, Springer, 2006.

2. **B. S. MORDUKHOVICH**, VARIATIONAL ANALYSIS OF EVOLUTION INCLUSIONS, **SIAM J. OPTIM.**, to appear.

2. **B. S. MORDUKHOVICH**, FAILURE OF METRIC REGULARITY FOR MAJOR VARIATIONAL SYSTEMS, **NONLINEAR ANALYSIS.**, to appear.