Foundations of Gauge and Perspective Duality

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Joint work with
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Dedicated to Prof. B. S. Mordukhovich on the occasion of his 70th birthday
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Gauge Optimization and Duality

Suppose $\kappa$ and $\rho$ are gauges.

\[
\begin{align*}
\min_x & \quad \kappa(x) \quad \text{s.t.} \quad \rho(b - Ax) \leq \tau, & \quad (G_p) \\
\max_y & \quad \langle b, y \rangle - \tau \rho^\circ(y) \quad \text{s.t.} \quad \kappa^\circ(A^T y) \leq 1, & \quad (L_d) \\
\min_y & \quad \kappa^\circ(A^T y) \quad \text{s.t.} \quad \langle b, y \rangle - \tau \rho^\circ(y) \geq 1. & \quad (G_d)
\end{align*}
\]

When $\tau = 0$, we define $\tau \rho^\circ := \delta_{\text{cl\,dom}\,\rho^\circ}$. 
Minkowski (gauge) functionals and polarity

Let $0 \in C \subset \mathbb{R}^n$ be nonempty, closed, and convex. The gauge function for $C$ is given by

$$\gamma_C(x) := \inf \{ t \mid 0 \leq t, \ x \in tC \},$$

where the infimum over the empty set is $+\infty$. 

Example: $\|x\| = \gamma_B(x)$ for any norm with unit ball $B$. 

Gauge functions are sublinear, and so by Hörmander, $\gamma_C(x) = \sigma_D(x) := \sup \{ \langle x, y \rangle \mid y \in D \}$, where $D = \{ z \mid \langle z, x \rangle \leq 1 \ \forall x \in C \} = C^\circ$ and $\sigma_D$ is the support function for the set $D$. 
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Let $0 \in C \subset \mathbb{R}^n$ be nonempty, closed, and convex. The *gauge function* for $C$ is given by
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Gauge functions are sublinear, and so by Hörmander,
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where
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D = \{z \mid \langle z, x \rangle \leq 1 \ \forall \ x \in C\} =: C^\circ
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and $\sigma_D$ is the *support function* for the set $D$. 

Polar Gauges

Set $\mathcal{U}_\kappa := \{x \mid \kappa(x) \leq 1\}$ and define the polar gauge by

$$\kappa^\circ(y) = \sup \{ \langle y, x \rangle \mid \kappa(x) \leq 1 \} = \sigma_{\mathcal{U}_\kappa}(y).$$

If $\kappa$ is a norm then $\kappa^\circ$ is the corresponding dual norm.

$$\text{epi} \, \kappa^\circ = \{(y, -\lambda) : (y, \lambda) \in (\text{epi} \, \kappa)^\circ\}.$$  

The generalized Hölder inequality

$$\langle x, y \rangle \leq \kappa(x) \cdot \kappa^\circ(y) \quad \forall x \in \text{dom} \, \kappa, \, \forall y \in \text{dom} \, \kappa^\circ,$$

is known as the polar-gauge inequality.

In addition, for $\mathcal{H}_\kappa := \{u \mid \kappa(u) = 0\}$, we have

$$\mathcal{U}_\kappa^\circ = \mathcal{U}_{\kappa^\circ}, \quad \mathcal{U}_\kappa^\infty = \mathcal{H}_\kappa, \quad (\text{dom} \, \kappa)^\circ = \mathcal{H}_{\kappa^\circ}, \quad \text{and} \quad \mathcal{H}_\kappa^\circ = \text{cl} \, \text{dom} \, \kappa^\circ.$$
Gauge Optimization and Duality

Suppose $\kappa$ and $\rho$ are gauges.

$$\min_x \kappa(x) \quad \text{s.t.} \quad \rho(b - Ax) \leq \tau, \quad (G_p)$$

$$\max_y \langle b, y \rangle - \tau \rho^\circ(y) \quad \text{s.t.} \quad \kappa^\circ(A^T y) \leq 1, \quad (L_d)$$

$$\min_y \kappa^\circ(A^T y) \quad \text{s.t.} \quad \langle b, y \rangle - \tau \rho^\circ(y) \geq 1. \quad (G_d)$$

When $\tau = 0$, we define $\tau \rho^\circ := \delta_{\text{cl dom} \rho^\circ}$. 
Feasibility

Primal, Dual Domains:

\[ F_p := \{ x \mid \rho(b - Ax) \leq \tau \} \quad \text{and} \quad F_d := \{ y \mid \langle b, y \rangle - \tau \rho^\circ(y) \geq 1 \} . \]

Feasibility:

Primal \( F_p \cap (\text{dom } \kappa) \)
Dual \( A^T F_d \cap (\text{dom } \kappa^\circ) \)

Relative Strict Feasibility:

Primal \( \text{ri } F_p \cap (\text{ri dom } \kappa) \)
Dual \( A^T \text{ri } F_d \cap (\text{ri dom } \kappa^\circ) \neq \emptyset \)

Strict Feasibility:

Primal \( \text{int } (F)_p \cap (\text{ri dom } \kappa) \)
Dual \( A^T \text{int } (F)_d \cap (\text{ri dom } \kappa^\circ) \)
Fr"{u}nd (1987), Friedlander-Macedo-Pong (2014)

\[ v_p = \min_{\rho(b-Ax) \leq \tau} \kappa(x) \quad v_d = \min_{\langle b,y \rangle - \tau \rho^\circ(y) \geq 1} \kappa^\circ(A^T y) \]

**Theorem:** (2014)

1. (Weak duality)
   If \( x \) and \( y \) are P-D feasible, then
   \[ 1 \leq v_p v_d \leq \kappa(x) \cdot \kappa^\circ(A^T y). \]

2. (Strong duality)
   If the dual (resp. primal) is feasible and the primal (resp. dual) is relatively strictly feasible, then \( \nu_p \nu_d = 1 \) and the gauge dual (resp. primal) attains its optimal value.
Infimal Projection Duality Theory

Let $F: \mathbb{R}^n \times \mathbb{R}^m \to \overline{\mathbb{R}}$ be closed proper convex, and define the following optimal value functions by inf-projection:

$$p(y) := \inf_x F(x, y) \quad \text{and} \quad q(w) := \inf_z F^*(w, z).$$
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This set-up yields the primal-dual pair

$$p(0) = \inf_x F(x, 0) \quad \text{and} \quad p^{**}(0) = \sup_z -F^*(0, z) \ (= -q(0)).$$
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$$p(0) \geq p^{**}(0) = -q(0) \text{ always holds}$$
Duality Theory

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Duality Theory

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1. If \( 0 \in \text{ri} \ (\text{dom} \ p) \), then \( p(0) = -q(0) \) and the infimum \( q(0) \) is attained, if finite.

Similarly, if \( 0 \in \text{ri} \ (\text{dom} \ q) \), then \( p(0) = -q(0) \) and the infimum \( p(0) \) is attained, if finite.
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2. The set \( \text{argmax}_z -F^*(0, z) \) is nonempty and bounded if and only if \( 0 \in \text{int} (\text{dom} \, p) \) and \( p(0) \) is finite, in which case \( \partial p(0) = \text{argmax}_z -F^*(0, z) \).
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4. Optimal solutions are characterized by

\[
\begin{align*}
\bar{x} \in \arg\min_x F(x,0) \\
\bar{y} \in \arg\max_z -F^*(0,z) \\
F(\bar{x},0) = -F^*(0,\bar{z})
\end{align*}
\]

\[ \iff (0,\bar{z}) \in \partial F(\bar{x},0) \iff (\bar{x},0) \in \partial F^*(0,\bar{z}). \]
Fenchel-Rockafellar Duality

\[ F(x, y) = h(Ax + y) + g(x) \]

\[ p(0) = \inf_x \{ h(Ax) + g(x) \} \quad \text{and} \quad p^{**}(0) = \sup_z \{ -h^*(z) - g^*(-A^*z) \} \]
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A prototype problem:

\[ \mathcal{P} \quad \min \quad \|x\|_1 \]
\[ \text{s.t.} \quad \|Ax - b\|_2 \leq \tau \]
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A prototype problem:

\[ P \quad \begin{array}{c}
\min \|x\|_1 \\
\text{s.t. } \|Ax - b\|_2 \leq \tau
\end{array} \]

\[ g(x) = \|x\|_1 = \delta^* (x \mid \mathcal{B}_\infty) \quad g^*(w) = \delta (w \mid \mathcal{B}_\infty) \]

\[ h(y) = \delta (y - b \mid \tau \mathcal{B}_2) \quad h^*(z) = -\langle z, b \rangle + \delta^* (z \mid \tau \mathcal{B}_2) = -\langle z, b \rangle + \tau \|z\|_2 \]
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A prototype problem:

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\[ \mathcal{D}_L \quad \sup \quad \langle b, z \rangle - \tau \|z\|_2 \]

\[ \quad \text{s.t.} \quad \|A^T z\|_\infty \leq 1. \]
Gauge Duality and Sensitivity

\[ v_p(y) := \inf_{\mu>0, x} \{ \mu \mid \rho(b - Ax + \mu y) \leq \tau, \, \kappa(x) \leq \mu \} \]
Gauge Duality and Sensitivity

\[ v_p(y) := \inf_{\mu > 0, x} \{ \mu \mid \rho (b - Ax + \mu y) \leq \tau, \kappa(x) \leq \mu \} \]

\[ \lambda := 1/\mu \text{ and } w := x/\mu \]
Gauge Duality and Sensitivity

\[ v_p(y) := \inf_{\mu > 0, x} \{ \mu \mid \rho (b - Ax + \mu y) \leq \tau, \ k(x) \leq \mu \} \]

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\[ = \inf_{\lambda > 0, w} \{1/\lambda \mid \rho(\lambda b - Aw + y) \leq \tau \lambda, \ w \in U_k \}, \]

or

\[ \inf_{\lambda > 0, w} \{-\lambda \mid \rho(\lambda b - Aw + y) \leq \tau \lambda, \ w \in U_k \}. \]
Gauge Duality and Sensitivity

\[ v_p(y) := \inf_{\mu > 0, x} \{ \mu \mid \rho(b - Ax + \mu y) \leq \tau, \kappa(x) \leq \mu \} \]

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Variational framework:

\[ F(w, \lambda, y) := -\lambda + \delta_{(\text{epi } \rho) \times \mathcal{U}_\kappa} \left( W \begin{pmatrix} w \\ \lambda \\ y \end{pmatrix} \right), \quad W := \begin{pmatrix} -A & b & I \\ 0 & \tau & 0 \\ I & 0 & 0 \end{pmatrix} \]

\[ F^*(w, \lambda, y) = \delta_{\text{epi } \rho^o} \left( -\sigma^{-1}(1 + \lambda - \langle b, y \rangle) \right) + \kappa^o(w + A^T y) \]
Gauge Duality and Sensitivity

\[ p(y) := \inf_{w,\lambda} F(w, \lambda, y) \]

**Theorem:** The following relationships hold for the gauge primal-dual pair \( G_p \) and \( G_d \).

(a) If the primal is relatively strictly feasible and the dual is feasible, then the set of optimal solutions for the dual is nonempty and coincides with

\[ \partial p(0) = \partial (-1/v_p)(0). \]

If it is further assumed that the primal is strictly feasible, then the set of optimal solutions to the dual is bounded.

(b) If the dual is relatively strictly feasible and the primal is feasible, then the set of optimal solutions for the primal is nonempty with solutions \( x^* = w^*/\lambda^* \), where

\[ (w^*, \lambda^*) \in \partial v_d(0, 0) \text{ and } \lambda^* > 0. \]

If it is further assumed that the dual is strictly feasible, then the set of optimal solutions to the primal is bounded.
**Theorem:** Suppose both the gauge primal and gauge dual problems are relatively strictly feasible, and the pair \((x^*, y^*)\) is primal-dual feasible. Then \((x^*, y^*)\) is primal-dual optimal if and only if it satisfies the conditions

\[
\rho(b - Ax^*) = \tau \quad \text{or} \quad \rho^\circ(y^*) = 0 \quad \text{(primal activity)}
\]

\[
\langle b, y^* \rangle - \tau \rho^\circ(y^*) = 1 \quad \text{(dual activity)}
\]

\[
\langle x^*, A^T y^* \rangle = \kappa(x^*) \cdot \kappa^\circ(A^T y^*) \quad \text{(objective alignment)}
\]

\[
\langle bAx^*, y^* \rangle = \tau \rho^\circ(y^*) \quad \text{(constraint alignment)}
\]

By convention, when \(\tau = 0\), \(\tau \rho^\circ := \delta_{\text{cl dom} \rho^\circ}\).
**Gauge primal-dual recovery**

**Corollary:** Suppose that the primal-dual pair $(G_p)$ and $(G_d)$ are each relatively strictly feasible. If $y^*$ is optimal for $(G_d)$, then for any primal feasible $x$ the following conditions are equivalent:

(a) $x$ is optimal for $(G_p)$;

(b) $\langle x, A^Ty^* \rangle = \kappa(x) \cdot \kappa^\circ(A^Ty^*)$ and $b - Ax \in \partial(\sigma \rho^\circ)(y^*)$;

(c) $A^Ty^* \in \kappa^\circ(A^Ty^*) \cdot \partial \kappa(x)$ and $b - Ax \in \partial(\sigma \rho^\circ)(y^*)$, where, by convention, $\sigma \rho^\circ = \delta_{\text{cl dom} \rho^\circ}$ when $\sigma = 0$, in which case

$$\partial(\sigma \rho^\circ)(y^*) = N\left(y^* \mid \mathcal{H}_\rho^\circ\right).$$
Theorem:
Suppose that the gauge dual $G_d$ is relatively strictly feasible and the primal $G_p$ is feasible. Let $L_p$ denote the Fenchel-Rockafellar dual of $G_d$, and let $\nu_L$ denote its optimal value. Then

$$ z^* \text{ is optimal for } L_p \iff z^*/\nu_L \text{ is optimal for } G_p. $$
Perspective Duality

The Perspective Transform

\[ f^\pi(x, \mu) := \begin{cases} 
\mu f(\mu^{-1}x), & \mu > 0 \\
\infty(x), & \mu = 0 \\
+\infty, & \mu < 0 
\end{cases} \]

where

\[ f^\infty(x) := \sup_{z \in \text{dom}(f)} [f(x + z) - f(x)] \]

is the horizon function of \( f \).

\[ h^\pi(y, \mu) = \sigma_{\text{epi} h^*} ((y, -\mu)) \]
The Perspective-Polar Transform

\[ f^\#(x, \xi) := (f^\pi)^\circ(x, \xi) \]

\[ = \sigma_{epi}(f^*)^\circ(x, -\xi) \]

\[ = \gamma_{epi}(f^*) (x, -\xi) \]

\[ = \inf \{ \mu > 0 \mid \xi + \langle z, x \rangle \leq \mu f(z), \ \forall z \} \]

\[ f^\# \text{ is a gauge.} \]

If \( f \) is a gauge, then \( f^\#(x, \xi) = f^\circ(x) + \delta_{\mathbb{R}_-}(\xi) \).
Perspective duality

Suppose $f : \mathbb{R}^n \to \overline{\mathbb{R}}_+$ and $g : \mathbb{R}^m \to \overline{\mathbb{R}}_+$ are closed, convex and nonnegative over their domains.

$$N_p \min_x f(x) \quad \text{s.t.} \quad g(b - Ax) \leq \sigma,$$

$$N_d \min_{y, \alpha, \mu} f^\#(A^T y, \alpha) \quad \text{s.t.} \quad \langle b, y \rangle - \sigma \cdot g^\#(y, \mu) \geq 1 - (\alpha + \mu)$$
The Perspective-Polar of a PLQ Penalty

Piecewise linear-quadratic (PLQ) penalties:

\[ g(y) := \sup_{u \in U} \{ \langle u, y \rangle - \frac{1}{2} \| Lu \|_2^2 \} , \quad U := \left\{ u \in \mathbb{R}^l \mid W u \leq w \right\} , \]

\[ g^\#(y, \mu) = \delta_{\mathbb{R}^-}(\mu) + \max \left\{ \gamma_U(y), -\left(1/2\mu\right)\|Ly\|^2 \right\} \]

\[ = \delta_{\mathbb{R}^-}(\mu) + \max \left\{ -\left(1/2\mu\right)\|Ly\|^2, \max_{i=1,\ldots,k} \left\{ W_i^T y / w_i \right\} \right\} , \]

where \( W_1^T, \ldots, W_k^T \) are the rows of \( W \).
The Perspective Duality for PLQ Penalties

Assume $f$ is a gauge and $g$ is a PLQ penalty, then

$$\min_{(y, \mu, \xi)} f \circ (A^T y)$$

s.t. $\langle b, y \rangle + \mu - \sigma \xi = 1$

$$W y \leq \xi w, \quad \left\| \begin{bmatrix} 2Ly \\ \xi + 2\mu \end{bmatrix} \right\|_2 \leq \xi - 2\mu$$
\[
\begin{align*}
\min_x & \quad \|x\|_1 \\
\text{s.t.} & \quad \sum_{i=1}^m V((Ax - b)_i) \leq \sigma,
\end{align*}
\]

where \( V \) is the Huber function

\[
\begin{align*}
V(x) &= -Kx - \frac{1}{2}K^2; \quad x < -K \\
V(x) &= \frac{1}{2}x^2; \quad -K \leq x \leq K \\
V(x) &= Kx - \frac{1}{2}K^2; \quad K < x
\end{align*}
\]

Experiment:

\( m = 120, \; n = 512, \; \sigma = 0.2, \; \eta = 1, \) and \( A \) is a Gaussian matrix. The true solution \( x_{\text{true}} \in \{-1, 0, 1\} \) is a spike train which has been constructed to have 20 nonzero entries, and the true noise \( b - Ax_{\text{true}} \) has been constructed to have 5 outliers.
Chambolle-Pock (CP) algorithm
THANK YOU BORIS!!

Boris, thank you for your many mathematical gifts over the years!

and thank you for your warm friendship!