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Lecture 2: Looking into the Black Box. Structural Optimization.

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Outline

Nonsmooth Unconstrained Optimization

Problem: $\min \{ f(x) : x \in R^n \} \quad \Rightarrow \quad x^*, \; f^* = f(x^*)$,
where $f(x)$ is a nonsmooth convex function.

Subgradients: $g \in \partial f(x) \Leftrightarrow f(y) \geq f(x) + \langle g, y - x \rangle \quad \forall y \in R^n$.

Main difficulties:

- $g \in \partial f(x)$ is *not* a descent direction at x.
- $g \in \partial f(x^*)$ does not imply $g = 0$.

Example

$$f(x) = \max_{1 \leq j \leq m} \{ \langle a_j, x \rangle + b_j \},$$
$$\partial f(x) = \mathrm{Conv} \, \{ a_j : \; \langle a_j, x \rangle + b_j = f(x) \}.$$

Subgradient methods in Nonsmooth Optimization

Advantages

- Very simple iteration scheme.
- Low memory requirements.
- Optimal rate of convergence (uniformly in the dimension).
- Interpretation of the process.

Objections:

- Low rate of convergence. (Confirmed by theory!)
- No acceleration.
- High sensitivity to the step-size strategy.

Lower complexity bounds

Nemirovsky, Yudin 1976

If $f(x)$ is given by a local *black-box*, it is impossible to converge faster than $O\left(\frac{1}{\sqrt{k}}\right)$ uniformly in n. (k is the # of calls of oracle.)

NB: Convergence is very slow.

Question: We want to find an ϵ-solution of the problem

$$\max_{1 \leq j \leq m} \{\langle a_j, x \rangle + b_j\} \quad \rightarrow \quad \min_x : \; x \in R^n,$$

by a gradient scheme (n and m are big).

What is the worst-case complexity bound?

"Right answer" (Complexity Theory): $O\left(\frac{1}{\epsilon^2}\right)$ calls of oracle.

Our target: A gradient scheme with $O\left(\frac{1}{\epsilon}\right)$ complexity bound.

Reason of speed up: our problem *is not* in a black box.

Complexity of Smooth Minimization

Problem: $f(x) \to \min\limits_x : \; x \in R^n$, where f is a convex function and $\|\nabla f(x) - \nabla f(y)\|_* \leq L(f)\|x - y\|$ for all $x, y \in R^n$.

(For measuring gradients we use dual norms: $\|s\|_* = \max\limits_{\|x\|=1} \langle s, x \rangle$.)

Rate of convergence: Optimal method gives $O\left(\frac{L(f)}{k^2}\right)$.

Complexity: $O\left(\sqrt{\frac{L(f)}{\epsilon}}\right)$. The difference with $O\left(\frac{1}{\epsilon^2}\right)$ is very big.

Smoothing the convex function

For function f define its Fenchel conjugate:

$$f_*(s) = \max_{x \in R^n} [\langle s, x \rangle - f(x)].$$

It is a closed convex function with $\mathrm{dom}\, f_* = \mathrm{Conv}\{f'(x) : x \in R^n\}$.

Moreover, under very mild conditions $(f_*(s))_* \equiv f(x)$.

Define $f_\mu(x) = \max\limits_{s \in \mathrm{dom}\, f_*} [\langle s, x \rangle - f_*(s) - \frac{\mu}{2}\|s\|_*^2]$, where $\|\cdot\|_*$ is a Euclidean norm.

Note: $f'_\mu(x) = s_\mu(x)$, and $x = f'_*(s_\mu(x)) + \mu s_\mu(x)$. Therefore,

$$\|x^1 - x^2\|^2 = \|f'_*(s^1) - f'_*(s_2)\|^2 + 2\mu \langle f'_*(s^1) - f'_*(s^2), s^1 - s^2 \rangle$$
$$+\mu^2 \|s^1 - s^2\|^2 \ \geq \ \mu^2 \|s^1 - s^2\|^2.$$

Thus, $f_\mu \in C^{1,1}_{1/\mu}$ and $f(x) \geq f_\mu(x) \geq f(x) - \mu D^2$,
where $D = \mathrm{Diam}(\mathrm{dom}\, f_*)$.

Main questions

1. Given by a non-smooth convex $f(x)$, can we form its computable smooth ϵ-approximation $f_\epsilon(x)$ with

$$L(f_\epsilon) = O\left(\frac{1}{\epsilon}\right)?$$

If yes, we need only $O\left(\sqrt{\frac{L(f_\epsilon)}{\epsilon}}\right) = O\left(\frac{1}{\epsilon}\right)$ iterations.

2. Can we do this in a systematic way?

Conclusion: We need a convenient *model* of our problem.

Adjoint problem

Primal problem: Find $f^* = \min\limits_x \{ f(x) : \ x \in Q_1 \}$, where $Q_1 \subset E_1$ is convex closed and bounded.

Objective: $f(x) = \hat{f}(x) + \max\limits_u \{ \langle Ax, u \rangle_2 - \hat{\phi}(u) : \ u \in Q_2 \}$, where

- $\hat{f}(x)$ is differentiable and convex on Q_1.
- $Q_2 \subset E_2$ is a closed convex and bounded.
- $\hat{\phi}(u)$ is continuous convex function on Q_2.
- linear operator $A : E_1 \to E_2^*$.

Adjoint problem: $\max\limits_u \{ \phi(u) : \ u \in Q_2 \}$, where

$$\phi(u) = -\hat{\phi}(u) + \min_x \{ \langle Ax, u \rangle_2 + \hat{f}(x) : \ x \in Q_1 \}.$$

NB: Adjoint problem is not unique!

Example

Consider $f(x) = \max\limits_{1 \le j \le m} |\langle a_j, x\rangle_1 - b_j|$.

1. $Q_2 = E_1^*$, $A = I$, $\hat{\phi}(u) \equiv f_*(u) = \max\limits_{x}\{\langle u, x\rangle_1 - f(x) : \; x \in E_1\}$

$$= \min_{s \in R^m} \left\{ \sum_{j=1}^m s_j b_j : \; u = \sum_{j=1}^m s_j a_j, \; \sum_{j=1}^m |s_j| \le 1 \right\}.$$

2. $E_2 = R^m$, $\hat{\phi}(u) = \langle b, u\rangle_2$, $f(x) = \max\limits_{1 \le j \le m} |\langle a_j, x\rangle_1 - b_j|$

$$= \max_{u \in R^m} \left\{ \sum_{j=1}^m u_j [\langle a_j, x\rangle_1 - b_j] : \; \sum_{j=1}^m |u_j| \le 1 \right\}.$$

3. $E_2 = R^{2m}$, $\hat{\phi}(u)$ is a linear, Q_2 is a simplex:

$$f(x) = \max_{u \in R^{2m}} \{ \sum_{j=1}^m (u_j^1 - u_j^2)[\langle a_j, x\rangle_1 - b_j] : \sum_{j=1}^m (u_j^1 + u_j^2) = 1, \; u \ge 0 \}.$$

NB: Increase in dim E_2 decreases the complexity of representation.

Smooth approximations

Prox-function: $d_2(u)$ is continuous and *strongly convex* on Q_2:

$$d_2(v) \geq d_2(u) + \langle \nabla d_2(u), v - u \rangle_2 + \tfrac{1}{2}\sigma_2 \|v - u\|_2^2.$$

Assume: $d_2(u_0) = 0$ and $d_2(u) \geq 0 \; \forall u \in Q_2$.

Fix $\mu > 0$, the *smoothing* parameter, and define

$$f_\mu(x) = \max_u \{ \langle Ax, u \rangle_2 - \hat{\phi}(u) - \mu d_2(u) : \; u \in Q_2 \}.$$

Denote by $u(x)$ the solution of this problem.

Theorem: $f_\mu(x)$ is convex and differentiable for $x \in E_1$. Its gradient $\nabla f_\mu(x) = A^* u(x)$ is Lipschitz continuous with

$$L(f_\mu) = \frac{1}{\mu \sigma_2} \|A\|_{1,2}^2,$$

where $\|A\|_{1,2} = \max\limits_{x,u} \{ \langle Ax, u \rangle_2 : \; \|x\|_1 = 1, \; \|u\|_2 = 1 \}$.

NB: 1. For any $x \in E_1$ we have $f_0(x) \geq f_\mu(x) \geq f_0(x) - \mu D_2$, where $D_2 = \max\limits_u \{ d_2(u) : \; u \in Q_2 \}$.

2. All norms are very important.

Optimal method

Problem: $\min\limits_{x}\{f(x):\ x \in Q_1\}$ with $f \in C^{1,1}(Q_1)$.

Prox-function: strongly convex $d_1(x)$, $d_1(x^0) = 0$, $d_1(x) \geq 0$, $x \in Q_1$.

Gradient mapping:

$$T_L(x) = \arg\min_{y \in Q_1} \left\{ \langle \nabla f(x), y - x \rangle_1 + \tfrac{1}{2} L \| y - x \|_1^2 \right\}.$$

Method. **For** $k \geq 0$ **do:**

1. Compute $f(x^k), \nabla f(x^k)$.

2. Find $y^k = T_{L(f)}(x^k)$.

3. Find $z^k = \arg\min\limits_{x \in Q_1} \left\{ \frac{L(f)}{\sigma} d_1(x) + \sum\limits_{i=0}^{k} \frac{i+1}{2} \langle \nabla f(x^i), x \rangle_1 \right\}$.

4. Set $x^{k+1} = \frac{2}{k+3} z^k + \frac{k+1}{k+3} y^k$.

Convergence: $f(y^k) - f(x^*) \leq \frac{4L(f) d_1(x^*)}{\sigma_1 (k+1)^2}$, where x^* is the optimal solution.

Applications

Smooth problem: $\bar{f}_\mu(x) = \hat{f}(x) + f_\mu(x) \quad \to \quad \min: \ x \in Q_1.$

Lipschitz constant: $L_\mu = L(\hat{f}) + \frac{1}{\mu\sigma_2}\|A\|^2_{1,2}$. Denote $D_1 = \max_x \{ d_1(x) : \ x \in Q_1 \}$.

Theorem: Let us choose $N \geq 1$. Define

$$\mu = \mu(N) = \frac{2\|A\|_{1,2}}{N+1} \cdot \sqrt{\frac{D_1}{\sigma_1\sigma_2 D_2}}.$$

After N iterations set $\hat{x} = y^N \in Q_1$ and

$$\hat{u} = \sum_{i=0}^{N} \frac{2(i+1)}{(N+1)(N+2)} \, u(x^i) \in Q_2.$$

Then $0 \leq f(\hat{x}) - \phi(\hat{u}) \leq \frac{4\|A\|_{1,2}}{N+1} \cdot \sqrt{\frac{D_1 D_2}{\sigma_1\sigma_2}} + \frac{4L(\hat{f})D_1}{\sigma_1 \cdot (N+1)^2}$.

Corollary. Let $L(\hat{f}) = 0$. For getting an ϵ-solution, we choose

$$\mu = \frac{\epsilon}{2D_2}, \quad L = \frac{D_2}{2\sigma_2} \cdot \frac{\|A\|^2_{1,2}}{\epsilon}, \quad N \geq 4\|A\|_{1,2}\sqrt{\frac{D_1 D_2}{\sigma_1\sigma_2}} \cdot \frac{1}{\epsilon}.$$

Example: Equilibrium in matrix games (1)

Denote $\Delta_n = \{x \in R^n : \; x \geq 0, \; \sum\limits_{i=1}^{n} x^{(i)} = 1\}$. Consider the problem

$\min\limits_{x\in\Delta_n} \max\limits_{u\in\Delta_m} \{\langle Ax, u\rangle_2 + \langle c, x\rangle_1 + \langle b, u\rangle_2\}$.

Minimization form:

$$\min_{x\in\Delta_n} f(x), \quad f(x) = \langle c, x\rangle_1 + \max_{1\leq j\leq m} [\langle a_j, x\rangle_1 + b_j],$$
$$\max_{u\in\Delta_m} \phi(u), \quad \phi(u) = \langle b, u\rangle_2 + \min_{1\leq i\leq n} [\langle \hat{a}_i, u\rangle_2 + c_i],$$

where a_j are the rows and $\hat{a}_i$ are the columns of A.

1. Euclidean distance: Let us take

$$\|x\|_1^2 = \sum_{i=1}^{n} x_i^2, \quad \|u\|_2^2 = \sum_{j=1}^{m} u_j^2,$$
$$d_1(x) = \tfrac{1}{2}\|x - \tfrac{1}{n} e_n\|_1^2, \quad d_2(u) = \tfrac{1}{2}\|u - \tfrac{1}{m} e_m\|_2^2.$$

Then $\|A\|_{1,2} = \lambda_{\max}^{1/2}(A^T A)$ and $f(\hat{x}) - \phi(\hat{u}) \leq \frac{4\lambda_{\max}^{1/2}(A^T A)}{N+1}$.

Example: Equilibrium in matrix games (2)

2. Entropy distance. Let us choose

$$\|x\|_1 = \sum_{i=1}^{n} |x_i|, \quad d_1(x) = \ln n + \sum_{i=1}^{n} x_i \ln x_i,$$

$$\|u\|_2 = \sum_{j=1}^{m} |u_j|, \quad d_2(u) = \ln m + \sum_{j=1}^{m} u_j \ln u_j.$$

LM: $\sigma_1 = \sigma_2 = 1$. (Hint: $\langle d_1''(x)h, h\rangle = \sum_{i=1}^{n} \frac{h_i^2}{x_i} \to \min_{x \in \Delta_n} = \|h\|_1^2$.)

Moreover, since $D_1 = \ln n$, $D_2 = \ln m$, and

$$\|A\|_{1,2} = \max_x \{ \max_{1 \leq j \leq m} |\langle a_j, x\rangle| : \ \|x\|_1 = 1\} = \max_{i,j} |A_{i,j}|,$$

we have $f(\hat{x}) - \phi(\hat{u}) \leq \frac{4\sqrt{\ln n \ln m}}{N+1} \cdot \max_{i,j} |A_{i,j}|$.

NB: 1. Usually $\max_{i,j} |A_{i,j}| << \lambda_{\max}^{1/2}(A^T A)$.

2. We have $\bar{f}_\mu(x) = \langle c, x\rangle_1 + \mu \ln \left(\frac{1}{m} \sum_{j=1}^{m} e^{[\langle a_j, x\rangle + b_j]/\mu} \right)$.

Part II: Interior Point Methods

Black-Box Methods: Main assumptions represent the bounds for the size of certain derivatives.

Example

Consider the function $f(x_1, x_2) = \begin{cases} \frac{x_2^2}{x_1}, & x_1 > 0, \\ 0, & x_1 = x_2 = 0. \end{cases}$

It is closed, convex, but discontinuous at the origin.

However, its epigraph $\{x \in R^3 : x_1 x_3 \geq x_2^2\}$ is a simple convex set:

$x_1 = u_1 + u_3,\ x_2 = u_2,\ x_3 = u_1 - u_3 \ \Rightarrow \ u_1 \geq \sqrt{u_2^2 + u_3^2}.$

(Lorentz cone)

Question: Can we always replace the functional components by convex sets?

Standard formulation

Problem: $f^* = \min\limits_{x \in Q} \langle c, x \rangle,$

where $Q \subset E$ is a closed convex set with nonempty interior.

How we can measure the quality of $x \in Q$?

1. The residual $\langle c, x \rangle - f^*$ is not very informative since it does not depend on *position* of x inside Q.

2. The boundary of a convex set can be very complicated.

3. It is easy to travel inside provided that we keep a sufficient distance to the boundary.

Conclusion: we need a barrier function $f(x)$:

- $\mathrm{dom}\, f = \mathrm{int}\, Q$,
- $f(x) \to \infty$ as $t \to \partial Q$.

Path-following method

Central path: for $t > 0$ define $x^*(t)$, $\quad tc + f'(x^*(t)) = 0$

$\Big($hence $x^*(t) = \arg\min\limits_x \Big[\Psi_t(x) \stackrel{\mathrm{def}}{=} t\langle c, x\rangle + f(x)\Big].\Big)$

Lemma. Suppose $\langle f'(x), y - x\rangle \leq A$ for all $x, y \in \mathrm{dom}\, Q$. Then

$$\langle c, x^*(t) - x^*\rangle = \langle f'(x^*(t)), x^* - x^*(t)\rangle \leq \frac{1}{t}A.$$

Method: $t_k > 0$, $x^k \approx x^*(t_k) \quad \Rightarrow \quad t_{k+1} > t_k$, $x^{k+1} \approx x^*(t_{k+1})$.

For approximating $x^*(t^{k+1})$, we need a powerful minimization scheme.

Main candidate: Newton Method.
(Very good local convergence.)

Classical results on the Newton Method

Method: $x^{k+1} = x^k - [f''(x^k)]^{-1} f'(x^k)$.

Assume that:

- $f''(x^*) \geq \ell \cdot I_n$
- $\| f''(x) - f''(y) \| \leq M \| x - y \|$, $\forall x, y \in R^n$.
- The starting point x^0 is close to x^*: $\| x^0 - x^* \| < \bar{r} = \frac{2\ell}{3M}$.

Then $\| x^k - x^* \| < \bar{r}$ for all k, and the Newton method converges quadratically: $\| x^{k+1} - x^* \| \leq \frac{M \| x^k - x^* \|^2}{2(\ell - M \| x^k - x^* \|)}$.

Note:

- The description of the *region of quadratic convergence* is given in terms of the metric $\langle \cdot, \cdot \rangle$.
- This region is changing when we choose another metric.

Simple observation

Let $f(x)$ satisfy our assumptions. Consider $\phi(y) = f(Ay)$, where A is a non-degenerate $(n \times n)$-matrix.

Lemma: Let $\{x^k\}$ be a sequence, generated by Newton Method for function f.
Consider the sequence $\{y^k\}$, generated by the Newton Method for function ϕ with $y^0 = A^{-1}x^0$.
Then $y^k = A^{-1}x^k$ for all $k \geq 0$.
Proof: Assume $y_k = A^{-1}x_k$ for some $k \geq 0$. Then

$$\begin{aligned} y^{k+1} &= y^k - [\phi''(y^k)]^{-1}\phi'(y^k) \\ &= y^k - [A^T f''(Ay^k)A]^{-1}A^T f'(Ay^k) \\ &= A^{-1}x^k - A^{-1}[f''(x^k)]^{-1}f'(x^k) = A^{-1}x^{k+1}. \quad \square \end{aligned}$$

Conclusion: The method is *affine invariant*. Its region of quadratic convergence *does not depend on the metric*!

What was wrong?

Old assumption: $\| f''(x) - f''(y) \| \leq M \| x - y \|$.

Let $f \in C^3(R^n)$. Denote $f'''(x)[u] = \lim\limits_{\alpha \to 0} \frac{1}{\alpha}[f''(x + \alpha u) - f''(x)]$. This is a matrix!

Then the old assumption is equivalent to: $\| f'''(x)[u] \| \leq M \| u \|$.

Hence, at any point $x \in R^n$ we have

$$(*) : \quad | \langle f'''(x)[u]v, v \rangle | \leq M \| u \| \cdot \| v \|^2 \text{ for all } u, v \in R^n.$$

Note:

- The LHS of $(*)$ is an *affine invariant* directional derivative.
- The norm $\| \cdot \|$ has nothing common with our particular f.
- However, there exists a local norm, which is closely related to f. This is $\| u \|_{f''(x)} = \langle f''(x)u, u \rangle^{1/2}$.
- Let us make a similar assumption in terms of $\| \cdot \|_{f''(x)}$.

Definition of Self-Concordant Function

Let $f(x) \in C^3(\mathrm{dom}\, f)$ be a *closed and convex*, with *open* domain. Let us fix a point $x \in \mathrm{dom}\, f$ and a direction $u \in R^n$.

Consider the function $\phi(x;t) = f(x+tu)$. Denote

$$Df(x)[u] = \phi'_t(x;0) = \langle f'(x), u \rangle,$$

$$D^2 f(x)[u,u] = \phi''_{tt}(x;0) = \langle f''(x)u, u \rangle = \| u \|^2_{f''(x)},$$

$$D^3 f(x)[u,u,u] = \phi'''_{ttt}(x;0) = \langle f'''[u]u, u \rangle.$$

Def. We call function f *self-concordant* if the inequality $| D^3 f(x)[u,u,u] | \leq 2 \| u \|^3_{f''(x)}$ holds for any $x \in \mathrm{dom}\, f$, $u \in R^n$.

Note:

- We cannot expect that these functions are very common.
- We hope that they are good for the Newton Method.

Examples

1. Linear function is s.c. since $f''(x) \equiv 0$, $f'''(x) \equiv 0$

2. Convex quadratic function is s.c. $(f'''(x) \equiv 0)$.

3. Logarithmic barrier for a ray $\{x > 0\}$:

$$f(x) = -\ln x, \quad f'(x) = -\frac{1}{x}, \quad f''(x) = \frac{1}{x^2}, \quad f'''(x) = -\frac{2}{x^3}.$$

4. Logarithmic barrier for a quadratic region. Consider a *concave* function $\phi(x) = \alpha + \langle a, x \rangle - \frac{1}{2}\langle Ax, x \rangle$. Define $f(x) = -\ln \phi(x)$.

$$Df(x)[u] = -\frac{1}{\phi(x)}[\langle a, u \rangle - \langle Ax, u \rangle] \stackrel{\mathrm{def}}{=} \omega_1,$$

$$D^2 f(x)[u]^2 = \frac{1}{\phi^2(x)}[\langle a, u \rangle - \langle Ax, u \rangle]^2 + \frac{1}{\phi(x)}\langle Au, u \rangle,$$

$$D^3 f(x)[u]^3 = -\frac{2}{\phi^3(x)}[\langle a, u \rangle - \langle Ax, u \rangle]^3 - \frac{3\langle Au,u \rangle}{\phi^2(x)}[\langle a, u \rangle - \langle Ax, u \rangle].$$

$D_2 = \omega_1^2 + \omega_2$, $D_3 = 2\omega_1^3 - 3\omega_1\omega_2$. Hence, $|D_3| \le 2|D_2|^{3/2}$.

Simple properties

1. If f_1, f_2 are s.c.f., then $f_1 + f_2$ is s.c. function.

2. If $f(y)$ is s.c.f., then $\phi(x) = f(Ax + b)$ is also a s.c. function.

Proof: Denote $y = y(x) = Ax + b$, $v = Au$. Then

$$D\phi(x)[u] = \langle f'(y(x)), Au\rangle = \langle f'(y), v\rangle,$$
$$D^2\phi(x)[u]^2 = \langle f''(y(x))Au, Au\rangle = \langle f''(y)v, v\rangle,$$
$$D^3\phi(x)[u]^3 = D^3 f(y(x))[Au]^3 = D^3 f(y)[v]^3.\Box$$

Example: $f(x) = -\sum\limits_{i=1}^{m} \ln(a_i - \|A_i x - b_i\|^2)$ is a s.c.-function.

Main properties

Let $x \in \mathrm{dom}\, f$ and $u \in R^n$, $u \neq 0$. For $x + tu \in \mathrm{dom}\, f$, consider

$$\phi(t) = \frac{1}{\langle f''(x+tu)u,u\rangle^{1/2}}.$$

Lemma. For all feasible t we have: $|\ \phi'(t)\ | \leq 1$.

Proof: Indeed, $\phi'(t) = -\frac{f'''(x+tu)[u]^3}{2\langle f''(x+tu)u,u\rangle^{3/2}}$. □

Corollary 1: $\mathrm{dom}\, \phi$ contains the interval $(-\phi(0), \phi(0))$.

Proof: Since $f(x+tu) \to \infty$ as $x + tu \to \partial \mathrm{dom}\, f$, the same is true for $\langle f''(x+tu)u, u\rangle$. Hence $\mathrm{dom}\, \phi(t) \equiv \{t \mid \ \phi(t) > 0\}$. □

Denote $W^0(x;r) = \{y \in R^n \mid \| \ y - x \ \|_{f''(x)} < r\}$. Then

$$W^0(x;r) \subseteq \mathrm{dom}\, f \text{ for } r < 1.$$

Main Theorem: for any $y \in W(x;r)$, $r \in [0,1)$, we have

$$(1-r)^2 F''(x) \preceq F''(y) \preceq \frac{1}{(1-r)^2} F''(x).$$

Local convergence

For x close to x^*, $f'(x^*) = 0$, function $f(x)$ is almost quadratic:

$$f(x) \approx f^* + \frac{1}{2}\langle f''(x^*)(x - x^*), x - x^* \rangle.$$

Therefore, $f(x) - f^* \approx \frac{1}{2}\|x - x^*\|^2_{f''(x^*)} \approx \frac{1}{2}\|x - x^*\|^2_{f''(x)}$

$$\approx \frac{1}{2}\langle f'(x), [f''(x)]^{-1} f'(x) \rangle \stackrel{\mathrm{def}}{=} \frac{1}{2}(\|f'(x)\|^*_x)^2 \stackrel{\mathrm{def}}{=} \lambda_f^2(x).$$

The last value is the *local norm* of the gradient. It is computable!

Theorem: Let $x \in \mathrm{dom}\, f$ and $\lambda_f(x) < 1$.

Then the point $x_+ = x - [f''(x)]^{-1} f'(x)$ belongs to $\mathrm{dom}\, f$ and

$$\lambda_f(x_+) \leq \left(\frac{\lambda_f(x)}{1 - \lambda_f(x)} \right)^2.$$

NB: Region of quadratic convergence is $\lambda_f(x) < \bar{\lambda}$, $\frac{\bar{\lambda}}{(1-\bar{\lambda})^2} = 1$.

It is affine-invariant!

Following the cental path

Consider $\Psi_t(x) = t\langle c, x\rangle + f(x)$ with s.c. function f.

- For Ψ_t, Newton Method has local quadratic convergence.
- The region of quadratic convergence (RQC) is given by
$$\lambda_{\Psi_t}(x) \leq \beta < \bar{\lambda}.$$

Assume we know $x = x^*(t)$. We want to update t, $t_+ = t + \Delta$, keeping x in RQC of function $\Psi_{t+\Delta}$: $\lambda_{\Psi_{t+\Delta}}(x) \leq \beta$.

Question: How large can be Δ? Since $tc + f'(x) = 0$, we have:

$$\lambda_{\Psi_{t+\Delta}}(x) = \| t_+ c + f'(x) \|_x^* = |\Delta| \cdot \| c \|_x^* = \frac{|\Delta|}{t} \| f'(x) \|_x^* \leq \beta.$$

Conclusion: for the *linear rate*, we need to assume that

$$\langle [f''(x)]^{-1} f'(x), f'(x)\rangle \text{ is } \textit{uniformly bounded} \text{ on } \operatorname{dom} f.$$

Thus, we come to the definition of *self-concordant barrier*.

Definition of Self-Concordant Barrier

Let $F(x)$ be a s.c.-function. It is a *ν-self-concordant barrier*, if

$$\max_{u \in R^n} [2\langle F'(x), u\rangle - \langle F''(x)u, u\rangle] \leq \nu \text{ for all } x \in \mathrm{dom}\, F.$$

The value ν is called the *parameter* of the barrier.

If $F''(x)$ is non-degenerate, then $\langle [F''(x)]^{-1}F'(x), F'(x)\rangle \leq \nu$.

Another form: $\langle F'(x), u\rangle^2 \leq \nu \langle F''(x)u, u\rangle$.

Main property: $\langle F'(x), y - x\rangle \leq \nu$, $x, y \in \mathrm{int}\, Q$.

NB: ν is responsible for the rate of p.-f. method: $t_+ = t \pm \frac{\alpha \cdot t}{\nu^{1/2}}$.

Complexity: $O\left(\sqrt{\nu} \ln \frac{\nu}{\epsilon}\right)$ iterations of the Newton method.

Calculus: **1.** Affine transformations do not change ν.

2. Restriction on a subspace can only decrease ν.

3. $F = F_1 + F_2 \quad \Rightarrow \quad \nu = \nu_1 + \nu_2$.

Examples

1. Barrier for a ray: $F(t) = -\ln t$, $F'(t) = -\frac{1}{t}$, $F''(t) = \frac{1}{t^2}$, $\nu = 1$.

2. Polytop $\{x : \langle a_i, x\rangle \leq b_i\}$, $F(x) = -\sum\limits_{i=1}^{m} \ln(b_i - \langle a_i, x\rangle)$, $\nu = m$.

3. l_2-ball: $F(x) = -\ln(1 - \|x\|^2)$, $D_1 = \omega_1$, $D_2 = \omega_1^2 + \omega_2$, $\nu = 1$.

4. Intersection of ellipsoids: $F(x) = -\sum\limits_{i=1}^{m} \ln(r_i^2 - \|A_i x - b_i\|^2)$, $\nu = m$.

5. Lorentz cone $\{t \geq \|x\|\}$, $F(x,t) = -\ln(t^2 - \|x\|^2)$, $\nu = 2$.

6. LMI-cone $\{X = X^T \succeq 0\}$, $F(X) = -\ln\det X$, $\nu = n$.

7. Epigraph $\{t \geq e^x\}$, $F(x,t) = -\ln(t - e^x) - \ln(\ln t - x)$, $\nu = 4$.

8. **Universal barrier.** Define the *polar set*

$$P(x) = \{s : \langle s, y - x\rangle \leq 1, \; y \in Q\}.$$

Then $F(x) = -\ln \mathrm{vol}_n P(x)$ is an $O(n)$-s.c. barrier for Q.

Further directions: specification of the model description

Path-following methods

- Conic problems. Gain: primal-dual IPM.
- Self-scaled cones: $F_*(F''(x)u) \equiv F(u) - 2F(x) - \nu$. Gain: long-step methods, very good search directions.
- Positive polynomials: $p(t) \geq 0$, $t \in R$ iff $p_k = \sum\limits_{i+j=k} Y^{i,j}$, $Y \succeq 0$.

  Gain: very cheap computation of determinants.

Black-box methods

- Composite functions: $f(x) + h(x)$, where f is smooth but complex, and h is nonsmooth and simple. Gain: rate $O(\frac{1}{k^2})$.
- Huge-scale problem: very sparse linear operators. Gain: extremely cheap iterations. (Next Lecture.)