CSED700H: Convex Optimization

Convex optimization problems[1]

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POSTECH

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[1] slides credits to Prof. Lieven Vandenberghe

Contents

- standard form (convex) optimization problem
- quasiconvex optimization
- linear optimization
- quadratic optimization
- geometric programming
- semidefinite programming
- vector optimization

Optimization problem in standard form

$$\begin{array}{ll} \text{minimize} & f_0(x) \\ \text{subject to} & f_i(x) \leq 0, \quad i = 1, \ldots, m \\ & h_i(x) = 0, \quad i = 1, \ldots, p \end{array}$$

- $x \in \mathbb{R}^n$ is the optimization variable
- $f_0 : \mathbb{R}^n \to \mathbb{R}$ is the objective or cost function
- $f_i : \mathbb{R}^n \to \mathbb{R}$ for $i = 1, \ldots, m$ are the inequality constraint functions
- $h_i : \mathbb{R}^n \to \mathbb{R}$ for $i = 1, \ldots, p$ are the equality constraint functions

Optimal value

$$p^\star = \inf\{f_0(x) \mid f_i(x) \leq 0,\ i = 1, \ldots, m,\ h_i(x) = 0,\ i = 1, \ldots, p\}$$

- $p^\star = \infty$ if the problem is infeasible (no x satisfies the constraints)
- $p^\star = -\infty$ if the problem is unbounded below

Optimal and locally optimal points

- x is **feasible** if $x \in \mathrm{dom}\, f_0$ and it satisfies the constraints
- a feasible x is **optimal** if $f_0(x) = p^\star$
- x is **locally optimal** if there is an $R > 0$ such that x is optimal for

$$
\begin{array}{lll}
\text{minimize (over } z\text{)} & f_0(z) & \\
\text{subject to} & f_i(z) \le 0, & i = 1, \ldots, m \\
& h_i(z) = 0, & i = 1, \ldots, p \\
& \|z - x\|_2 \le R &
\end{array}
$$

Examples (with $n = 1, m = p = 0$)

- $f_0(x) = 1/x$ with $\mathrm{dom}\, f_0 = \mathbb{R}_{++}$: $p^\star = 0$, no optimal point
- $f_0(x) = -\log x$ with $\mathrm{dom}\, f_0 = \mathbb{R}_{++}$: $p^\star = -\infty$
- $f_0(x) = x \log x$ with $\mathrm{dom}\, f_0 = \mathbb{R}_{++}$: $p^\star = -1/e$, $x = 1/e$ is optimal
- $f_0(x) = x^3 - 3x$: $p^\star = -\infty$, local optimum at $x = 1$

Implicit constraints

the standard form optimization problem has an **implicit constraint**

$$x \in \mathcal{D} = \bigcap_{i=0}^{m} \operatorname{dom} f_i \;\cap\; \bigcap_{i=1}^{p} \operatorname{dom} h_i,$$

- we call $\mathcal{D}$ the **domain** of the problem
- the constraints $f_i(x) \leq 0, h_i(x) = 0$ are the explicit constraints
- a problem is **unconstrained** if it has no explicit constraints ($m = p = 0$)
- the distinction will be important when we discuss duality

Example

$$\text{minimize} \quad f_0(x) = -\sum_{i=1}^{k} \log(b_i - a_i^\top x)$$

this is an unconstrained problem with implicit constraints $a_i^\top x < b_i$

Feasibility problem

$$\begin{array}{ll} \text{find} & x \\ \text{subject to} & f_i(x) \leq 0, \quad i = 1, \ldots, m \\ & h_i(x) = 0, \quad i = 1, \ldots, p \end{array}$$

can be considered a special case of the general problem with $f_0(x) = 0$:

$$\begin{array}{ll} \text{minimize} & 0 \\ \text{subject to} & f_i(x) \leq 0, \quad i = 1, \ldots, m \\ & h_i(x) = 0, \quad i = 1, \ldots, p \end{array}$$

- $p^\star = 0$ if constraints are feasible; any feasible x is optimal
- $p^\star = \infty$ if constraints are infeasible

this formulation is not meant as a practical method for solving feasibility problems

Convex optimization problem in standard form

$$\begin{array}{ll} \text{minimize} & f_0(x) \\ \text{subject to} & f_i(x) \leq 0, \quad i = 1, \ldots, m \\ & a_i^\top x = b_i, \quad i = 1, \ldots, p \end{array}$$

- $f_0, f_1, \ldots, f_m$ are convex functions
- equality constraints are linear
- often written as

$$\begin{array}{ll} \text{minimize} & f_0(x) \\ \text{subject to} & f_i(x) \leq 0, \quad i = 1, \ldots, m \\ & Ax = b \end{array}$$

- important property: feasible set of a convex optimization problem is convex

Example

$$\begin{array}{ll} \text{minimize} & f_0(x) = x_1^2 + x_2^2 \\ \text{subject to} & f_1(x) = x_1/(1 + x_2^2) \leq 0 \\ & h_1(x) = (x_1 + x_2)^2 = 0 \end{array}$$

- f_0 is convex
- feasible set $\{(x_1, x_2) \mid x_1 = -x_2 \leq 0\}$ is convex
- not a convex problem (according to our definition): f_1 not convex, h_1 not affine
- the problem is equivalent (but not identical) to the convex problem

$$\begin{array}{ll} \text{minimize} & x_1^2 + x_2^2 \\ \text{subject to} & x_1 \leq 0 \\ & x_1 + x_2 = 0 \end{array}$$

Local and global optima

any local optimal point of a convex problem is (globally) optimal

- suppose x is locally optimal: there is an $R > 0$ such that

$$z \text{ feasible}, \quad \|z - x\|_2 \leq R \quad \Longrightarrow \quad f_0(z) \geq f_0(x)$$

- suppose if x is not globally optimal: there exists a feasible y with $f_0(y) < f_0(x)$
- convex combinations of x and y are feasible
- cost function at convex combination of x and y with $0 < \theta \leq 1$ satisfies

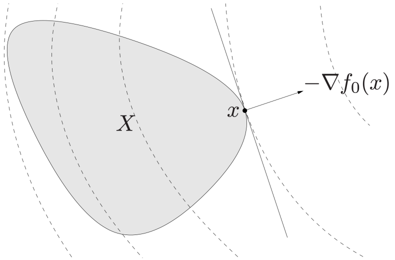
$$\begin{aligned} f_0((1-\theta)x + \theta y) &\leq (1-\theta)f_0(x) + \theta f_0(y) \\ &\leq (1-\theta)f_0(x) + \theta f_0(x) \\ &= f_0(x) \end{aligned}$$

- for $0 < \theta \leq R/\|y - x\|_2$ this contradicts the assumption of local optimality of x

Optimality criterion for differentiable f_0

x is optimal if and only if it is feasible and

$$\nabla f_0(x)^\top (y - x) \geq 0 \quad \text{for all feasible } y$$



if nonzero, $\nabla f_0(x)$ defines a supporting hyperplane to feasible set X at x

Proof (necessity)

- consider feasible $y \neq x$ and define line segment $I = \{x + t(y - x) \mid 0 \leq t \leq 1\}$
- by convexity of X, points in I are feasible
- let $g(t) = f_0(x + t(y - x))$ be the restriction of f_0 to I
- derivative at t is $g'(t) = \nabla f_0(x + t(y - x))^\top (y - x)$, so

$$g'(0) = \nabla f_0(x)^\top (y - x)$$

- if $g'(0) = \nabla f_0(x)^\top (y - x) < 0$, the point x is not even locally optimal

Proof (sufficiency)

if y is feasible and $\nabla f_0(x)^\top (y - x) \geq 0$, then, by convexity of f_0,

$$\begin{aligned} f_0(y) &\geq f_0(x) + \nabla f_0(x)^\top (y - x) \\ &\geq f_0(x) \end{aligned}$$

Examples

Unconstrained problem: x is optimal if and only if

$$x \in \mathbf{dom}\, f_0, \qquad \nabla f_0(x) = 0$$

(recall our assumption that $\mathbf{dom}\, f_0$ is an open set if f_0 is differentiable)

Minimization over nonnegative orthant

$$\begin{array}{ll} \text{minimize} & f_0(x) \\ \text{subject to} & x \succeq 0 \end{array}$$

x is optimal if and only if

$$x \in \mathbf{dom}\, f_0, \qquad x \succeq 0, \qquad \begin{cases} \nabla f_0(x)_i \geq 0 & x_i = 0 \\ \nabla f_0(x)_i = 0 & x_i > 0 \end{cases}$$

Equality constrained problem

$$\begin{array}{ll} \text{minimize} & f_0(x) \\ \text{subject to} & Ax = b \end{array}$$

x is optimal if and only if there exists a ν such that

$$x \in \operatorname{dom} f_0, \qquad Ax = b, \qquad \nabla f_0(x) + A^\top \nu = 0$$

- first two conditions are feasibility of x
- gradient $\nabla f_0(x)$ can always be decomposed as $\nabla f_0(x) + A^\top \nu = w$ with $Aw = 0$
- if $w = 0$, the optimality condition holds:

$$\nabla f_0(x)^\top (y - x) = -\nu^\top A(y - x) = 0 \quad \text{for all } y \text{ with } Ay = b$$

- if $w \neq 0$, condition does not hold: $y = x - tw$ is feasible for small $t > 0$,

$$\nabla f_0(x)^\top (y - x) = -t(w - A^\top \nu)^\top w = -t\|w\|_2^2 < 0$$

Equivalent convex problems

two problems are (informally) **equivalent** if the solution of one is readily obtained from the solution of the other, and vice-versa

Eliminating equality constraints

$$\begin{array}{ll} \text{minimize} & f_0(x) \\ \text{subject to} & f_i(x) \leq 0, \quad i = 1, \ldots, m \\ & Ax = b \end{array} \qquad \begin{array}{ll} \text{minimize} & f_0(Fz + x_0) \\ \text{subject to} & f_i(Fz + x_0) \leq 0, \quad i = 1, \ldots, m \end{array}$$

- x_0 is any solution of $Ax_0 = b$ and the columns of F span the nullspace of A
- variables in second problem are z

Introducing equality constraints

$$\begin{array}{ll} \text{minimize} & f_0(A_0 x + b_0) \\ \text{subject to} & f_i(A_i x + b_i) \leq 0, \quad i = 1, \ldots, m \end{array} \qquad \begin{array}{lll} \text{minimize} & f_0(y_0) & \\ \text{subject to} & f_i(y_i) \leq 0, & i = 1, \ldots, m \\ & y_i = A_i x + b_i, & i = 1, \ldots, m \end{array}$$

variables in second problem are $x, y_0, y_1, \ldots, y_m$

Equivalent convex problems

Epigraph form

$$
\begin{array}{ll}
\text{minimize} & f_0(x) \\
\text{subject to} & f_i(x) \leq 0, \quad i = 1, \dots, m \\
& Ax = b
\end{array}
\qquad
\begin{array}{ll}
\text{minimize} & t \\
\text{subject to} & f_0(x) - t \leq 0 \\
& f_i(x) \leq 0, \qquad i = 1, \dots, m \\
& Ax = b
\end{array}
$$

variables in second problem are x, t

Minimizing over some variables

$$
\begin{array}{ll}
\text{minimize} & f_0(x_1, x_2) \\
\text{subject to} & f_i(x_1) \leq 0, \quad i = 1, \dots, m
\end{array}
\qquad
\begin{array}{ll}
\text{minimize} & \tilde{f}_0(x_1) \\
\text{subject to} & f_i(x_1) \leq 0, \quad i = 1, \dots, m
\end{array}
$$

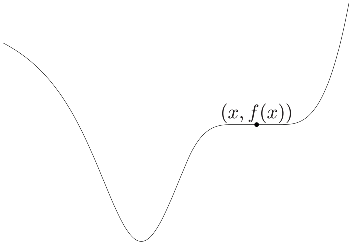
where $\tilde{f}_0(x_1) = \inf_{x_2} f_0(x_1, x_2)$

Quasiconvex optimization

$$\begin{array}{ll} \text{minimize} & f_0(x) \\ \text{subject to} & f_i(x) \leq 0, \quad i = 1, \ldots, m \\ & Ax = b \end{array}$$

- f_0 is quasiconvex
- $f_1, \ldots, f_m$ are convex

can have locally optimal points that are not (globally) optimal



Convex representation of sublevel sets of f_0

if f_0 is quasiconvex, there exists a family of functions ϕ_t such that:

- $\phi_t(x)$ is convex in x for fixed t
- t-sublevel set of f_0 is 0-sublevel set of ϕ_t, *i.e.*,

$$f_0(x) \leq t \quad \Longleftrightarrow \quad \phi_t(x) \leq 0$$

Example

$$f_0(x) = \frac{p(x)}{q(x)}$$

with p convex, q concave, and $p(x) \geq 0$, $q(x) > 0$ on $\mathrm{dom}\, f_0$

can take $\phi_t(x) = p(x) - tq(x)$:

- for $t \geq 0$, ϕ_t convex in x
- $p(x)/g(x) \leq t$ if and only if $\phi_t(x) \leq 0$

Quasiconvex optimization via convex feasibility problems

$$\phi_t(x) \le 0, \qquad f_i(x) \le 0, \quad i = 1, \ldots, m, \qquad Ax = b \tag{1}$$

- for fixed t, a convex feasibility problem in x
- if feasible, we can conclude that $t \ge p^\star$; if infeasible, $t \le p^\star$

Bisection method

given: $l \le p^\star$, $u \ge p^\star$, tolerance $\epsilon > 0$
repeat
1. $t := (l + u)/2$
2. solve the convex feasibility problem (1)
3. if (1) is feasible, $u := t$; else $l := t$

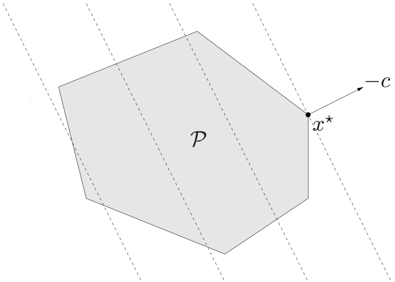
until $u - l \le \epsilon$

requires exactly $\lceil \log_2 \left(\frac{u-l}{\epsilon}\right) \rceil$ iterations

Linear program (LP)

$$
\begin{array}{ll}
\text{minimize} & c^\top x + d \\
\text{subject to} & Gx \preceq h \\
& Ax = b
\end{array}
$$

- convex problem with affine objective and constraint functions
- feasible set is a polyhedron



Examples

Diet problem: choose quantities $x_1, \ldots, x_n$ of n foods

- one unit of food j costs c_j, contains amount a_{ij} of nutrient i
- healthy diet requires nutrient i in quantity at least b_i

to find cheapest healthy diet,

$$\begin{array}{ll} \text{minimize} & c^\top x \\ \text{subject to} & Ax \succeq b, \quad x \succeq 0 \end{array}$$

Piecewise-linear minimization

$$\text{minimize} \quad \max_{i=1,\ldots,m} (a_i^\top x + b_i)$$

equivalent to LP

$$\begin{array}{ll} \text{minimize} & t \\ \text{subject to} & a_i^\top x + b_i \leq t, \quad i = 1, \ldots, m \end{array}$$

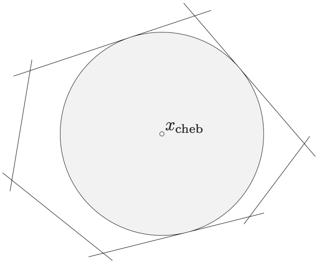
Chebyshev center of a polyhedron

Chebyshev center of

$$\mathcal{P} = \{x \mid a_i^\top x \le b_i,\ i = 1, \ldots, m\}$$

is center of largest inscribed ball

$$\mathcal{B} = \{x_c + u \mid \|u\|_2 \le r\}$$



- $a_i^\top x \le b_i$ for all $x \in \mathcal{B}$ if and only if

$$\sup\{a_i^\top (x_c + u) \mid \|u\|_2 \le r\} = a_i^\top x_c + r\|a_i\|_2 \le b_i$$

- hence, x_c, r can be determined by solving the LP

$$\begin{array}{ll} \text{maximize} & r \\ \text{subject to} & a_i^\top x_c + r\|a_i\|_2 \le b_i, \quad i = 1, \ldots, m \end{array}$$

Linear-fractional program

$$\begin{array}{ll} \text{minimize} & f_0(x) \\ \text{subject to} & Gx \preceq h \\ & Ax = b \end{array}$$

Linear-fractional program

$$f_0(x) = \frac{c^\top x + d}{e^\top x + f}, \qquad \mathrm{dom}\, f_0(x) = \{x \mid e^\top x + f > 0\}$$

- a quasiconvex optimization problem; can be solved by bisection
- also equivalent to the LP (variables y, z)

$$\begin{array}{ll} \text{minimize} & c^\top y + dz \\ \text{subject to} & Gy \preceq hz \\ & Ay = bz \\ & e^\top y + fz = 1 \\ & z \geq 0 \end{array}$$

Generalized linear-fractional program

$$f_0(x) = \max_{i=1,\dots,r} \frac{c_i^\top x + d_i}{e_i^\top x + f_i}, \qquad \mathrm{dom}\, f_0(x) = \{x \mid e_i^\top x + f_i > 0,\ i = 1, \dots, r\}$$

a quasiconvex optimization problem; can be solved by bisection

Example: Von Neumann model of a growing economy

$$\begin{array}{ll} \text{maximize (over } x,\ x^+) & \min_{i=1,\dots,n} x_i^+/x_i \\ \text{subject to} & x^+ \succeq 0, \quad Bx^+ \preceq Ax \end{array}$$

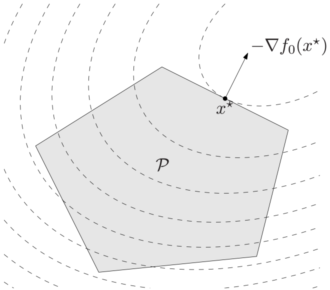
- $x,\ x^+ \in \mathbb{R}^n$: activity levels of n sectors, in current and next period
- $(Ax)_i,\ (Bx^+)_i$: produced, respectively, consumed, amounts of good i
- x_i^+/x_i: growth rate of sector i

allocate activity to maximize growth rate of slowest growing sector

Quadratic program (QP)

$$\begin{array}{ll} \text{minimize} & (1/2)x^\top P x + q^\top x + r \\ \text{subject to} & Gx \preceq h \\ & Ax = b \end{array}$$

- $P \in \mathbb{S}^n_+$, so objective is convex quadratic
- minimize a convex quadratic function over a polyheron



Examples

Least squares

$$\text{minimize} \quad \|Ax - b\|_2^2$$

- analytical solution $x^\star = A^\dagger b$ ($A^\dagger$ is pseudo-inverse)
- can add linear constraints, *e.g.*, $l \leq x \leq u$

Linear program with random cost

$$\begin{array}{ll} \text{minimize} & \bar{c}^\top x + \gamma x^\top \Sigma x = \mathbb{E} c^\top x + \gamma \mathrm{var}(c^\top x) \\ \text{subject to} & Gx \preceq h \\ & Ax = b \end{array}$$

- c is random vector with mean $\bar{c}$ and covariance Σ
- hence, $c^\top x$ is random variable with mean $\bar{c}^\top x$ and variance $x^\top \Sigma x$
- $\gamma > 0$ is risk aversion parameter
- γ controls trade-off between expected cost and variance (risk)

Quadratically constrained quadratic program (QCQP)

$$
\begin{array}{ll}
\text{minimize} & (1/2)x^\top P_0 x + q_0^\top x + r_0 \\
\text{subject to} & (1/2)x^\top P_i x + q_i^\top x + r_i \leq 0, \quad i = 1, \ldots, m \\
& Ax = b
\end{array}
$$

- $P_i \in \mathbb{S}^n_+$; objective and constraints are convex quadratic
- if $P_1, \ldots, P_m \in \mathbb{S}^n_{++}$, feasible set is intersection of m ellipsoids and an affine set

Second-order cone programming

$$\begin{array}{ll} \text{minimize} & f^\top x \\ \text{subject to} & \|A_i x + b_i\|_2 \leq c_i^\top x + d_i, \quad i = 1, \ldots, m \\ & Fx = g \end{array}$$

$(A_i \in \mathbb{R}^{n_i \times n},\ F \in \mathbb{R}^{p \times n})$

- inequalities are called second-order cone (SOC) constraints:

$$(A_i x + b_i,\ c_i^\top x + d_i) \in \text{ second-order cone in } \mathbb{R}^{n_i+1}$$

- for $n_i = 0$, reduces to an LP; if $c_i = 0$, reduces to a QCQP
- more general than QCQP and LP

Robust linear programming

the parameters in optimization problems are often uncertain, *e.g.*, in an LP

$$\begin{array}{ll} \text{minimize} & c^\top x \\ \text{subject to} & a_i^\top x \leq b_i, \quad i = 1, \ldots, m, \end{array}$$

there can be uncertainty in c, a_i, b_i

two common approaches to handling uncertainty (in a_i, for simplicity)

- deterministic model: constraints must hold for all $a_i \in \mathcal{E}_i$

$$\begin{array}{ll} \text{minimize} & c^\top x \\ \text{subject to} & a_i^\top x \leq b_i \text{ for all } a_i \in \mathcal{E}_i, \quad i = 1, \ldots, m \end{array}$$

- stochastic model: a_i is random variable; constraints must hold with probability η

$$\begin{array}{ll} \text{minimize} & c^\top x \\ \text{subject to} & \mathrm{prob}(a_i^\top x \leq b_i) \geq \eta, \quad i = 1, \ldots, m \end{array}$$

Deterministic approach via SOCP

choose an ellipsoide as $\mathcal{E}_i$:

$$\mathcal{E}_i = \{\bar{a}_i + P_i u \mid \|u\|_2 \leq 1\} \qquad (\bar{a}_i \in \mathbb{R}^n,\ P_i \in \mathbb{R}^{n \times n})$$

center is $\bar{a}_i$, semi-axes determined by singular values/vectors of P_i

SOCP formulation

$$\begin{array}{ll} \text{minimize} & c^\top x \\ \text{subject to} & a_i^\top x \leq b_i \ \ \forall a_i \in \mathcal{E}_i, \quad i = 1, \ldots, m \end{array}$$

this is equivalent to the SOCP

$$\begin{array}{ll} \text{minimize} & c^\top x \\ \text{subject to} & \bar{a}_i^\top x + \|P_i^\top x\|_2 \leq b_i, \quad i = 1, \ldots, m \end{array}$$

(follows from $\sup_{\|u\|_2 \leq 1} (\bar{a}_i + P_i u)^\top x = \bar{a}_i^\top x + \|P_i^\top x\|_2$)

Stochastic approach via SOCP

- assume $a_i \sim \mathcal{N}(\bar{a}_i, \Sigma_i)$: Gaussian with mean $\bar{a}_i$, covariance Σ_i
- $a_i^\top x$ is Gaussian random variable with mean $\bar{a}_i^\top x$, variance $x^\top \Sigma_i x$
- if we denote the CDF of $\mathcal{N}(0,1)$ by $\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-t^2/2} dt$,

$$\mathrm{prob}(a_i^\top x \le b_i) = \Phi\left(\frac{b_i - \bar{a}_i^\top x}{\|\Sigma_i^{1/2} x\|_2} \right)$$

SOCP formulation of robust LP

$$\begin{array}{ll} \text{minimize} & c^\top x \\ \text{subject to} & \mathrm{prob}(a_i^\top x \le b_i) \ge \eta, \quad i = 1, \dots, m \end{array}$$

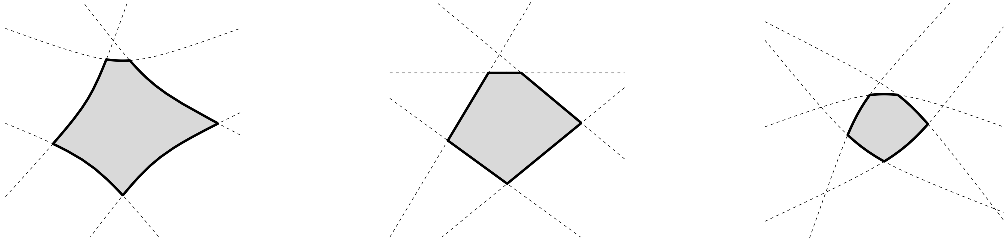
for $\eta \ge 1/2$, this is equivalent to the SOCP

$$\begin{array}{ll} \text{minimize} & c^\top x \\ \text{subject to} & \bar{a}_i^\top x + \Phi^{-1}(\eta) \|\Sigma_i^{1/2} x\|_2 \le b_i, \quad i = 1, \dots, m \end{array}$$

Example

$$\text{prob}(a_i^\top x \le b_i) \ge \eta, \quad i = 1, \ldots, 5$$

feasible set for three values of η



$\eta = 10\%$ $\quad$ $\Phi^{-1}(\eta) < 0$

$\eta = 50\%$ $\quad$ $\Phi^{-1}(\eta) = 0$

$\eta = 90\%$ $\quad$ $\Phi^{-1}(\eta) > 0$

Geometric programming

Monomial function

$$f(x) = c x_1^{a_1} x_2^{a_2} \cdots x_n^{a_n}, \qquad \operatorname{dom} f = \mathbb{R}^n_{++}$$

with $c > 0$; exponent a_i can be any real number

Posynomial function: sum of monomials

$$f(x) = \sum_{k=1}^{K} c_k x_1^{a_{1k}} x_2^{a_{2k}} \cdots x_n^{a_{nk}}, \qquad \operatorname{dom} f = \mathbb{R}^n_{++}$$

Geometric program (GP)

$$\begin{array}{ll} \text{minimize} & f_0(x) \\ \text{subject to} & f_i(x) \le 1, \quad i = 1, \ldots, m \\ & h_i(x) = 1, \quad i = 1, \ldots, p \end{array}$$

with f_i posynomial, h_i monomial

Geometric program in convex form

change variables to $y_i = \log x_i$, and take logarithm of cost, constraints

- monomial $f(x) = cx_1^{a_1} x_2^{a_2} \cdots x_n^{a_n}$ transforms to

$$\log f(e^{y_1}, \ldots, e^{y_n}) = a^\top y + b \qquad (b = \log c)$$

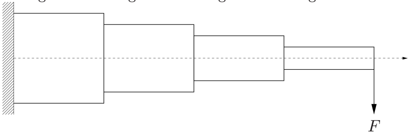
- posynomial $f(x) = \sum_{k=1}^{K} c_k x_1^{a_{1k}} x_2^{a_{2k}} \cdots x_n^{a_{nk}}$ transforms to

$$\log f(e^{y_1}, \ldots, e^{y_n}) = \log\left(\sum_{k=1}^{K} e^{a_k^\top y + b_k}\right) \qquad (\text{with } b_k = \log c_k)$$

- geometric program transforms to convex problem

$$\begin{array}{ll} \text{minimize} & \log\left(\sum_{k=1}^{K} \exp(a_{0k}^\top y + b_{0k})\right) \\ \text{subject to} & \log\left(\sum_{k=1}^{K} \exp(a_{ik}^\top y + b_{ik})\right) \leq 0, \quad i = 1, \ldots, m \\ & Gy + d = 0 \end{array}$$

Design of cantilever beam



- N segments with unit lengths, rectangular cross-sections of size $w_i \times h_i$
- given vertical force F applied at the right end

Design problem

$$\begin{array}{ll} \text{minimize} & \text{total weight} \\ \text{subject to} & \text{upper \& lower bounds on } w_i,\ h_i \\ & \text{upper bound \& lower bounds on aspect ratios } h_i/w_i \\ & \text{upper bound on stress in each segment} \\ & \text{upper bound on vertical deflection at the end of the beam} \end{array}$$

variables: $w_i,\ h_i$ for $i = 1, \ldots, N$

Objective and constraint functions

- total weight $w_1h_1 + \cdots + w_Nh_N$ is posynomial
- aspect ratio h_i/w_i and inverse aspect ratio w_i/h_i are monomials
- maximum stress in segment i is given by $6iF/(w_ih_i^2)$, a monomial
- vertical deflection y_i and slope v_i of central axis at the right end of segment i:

$$
\begin{aligned}
v_i &= 12(i-1/2)\frac{F}{Ew_ih_i^3} + v_{i+1} \\
y_i &= 6(i-1/3)\frac{F}{Ew_ih_i^3} + v_{i+1} + y_{i+1}
\end{aligned}
$$

for $i = N, N-1, \ldots, 1$, with $v_{N+1} = y_{N+1} = 0$ (E is Young's modulus)
v_i and y_i are posynomial functions of w, h

Formulation as a GP

$$\begin{array}{ll}\text{minimize} & w_1 h_1 + \cdots + w_N h_N \\ \text{subject to} & w_{\max}^{-1} w_i \leq 1, \quad w_{\min} w_i^{-1} \leq 1, \quad i = 1, \ldots, N \\ & h_{\max}^{-1} h_i \leq 1, \quad h_{\min} h_i^{-1} \leq 1, \quad i = 1, \ldots, N \\ & S_{\max}^{-1} w_i^{-1} h_i \leq 1, \quad S_{\min} w_i h_i^{-1} \leq 1, \quad i = 1, \ldots, N \\ & 6iF\sigma_{\max}^{-1} w_i^{-1} h_i^{-2} \leq 1, \quad i = 1, \ldots, N \\ & y_{\max}^{-1} y_1 \leq 1\end{array}$$

note

- we write $w_{\min} \leq w_i \leq w_{\max}$ and $h_{\min} \leq h_i \leq h_{\max}$

$$w_{\min}/w_i \leq 1, \quad w_i/w_{\max} \leq 1, \quad h_{\min}/h_i \leq 1, \quad h_i/h_{\max} \leq 1$$

- we write $S_{\min} \leq h_i/w_i \leq S_{\max}$

$$S_{\min} w_i/h_i \leq 1, \quad h_i/(w_i S_{\max}) \leq 1$$

Minimizing spectral radius of nonnegative matrix

Perron-Frobenius eigenvalue $\lambda_{\text{pf}}(A)$

- exists for (elementwise) positive $A \in \mathbb{R}^{n \times n}$
- a real, positive eigenvalue of A, equal to spectral radius $\max_i |\lambda_i(A)|$
- determines asymptotic growth (decay) rate of A^k: $A^k \sim \lambda_{\text{pf}}^k$ as $k \to \infty$
- alternative characterization: $\lambda_{\text{pf}}(A) = \inf\{\lambda \mid Av \preceq \lambda v \text{ for some } v \succ 0\}$

Minimizing spectral radius of matrix of posynomials

- minimize $\lambda_{\text{pf}}(A(x))$, where the elements $A(x)_{ij}$ are posynomials of x
- equivalent geometric program:

$$\begin{array}{ll} \text{minimize} & \lambda \\ \text{subject to} & \sum_{j=1}^{n} A(x)_{ij} v_j / (\lambda v_i) \leq 1, \quad i = 1, \ldots, n \end{array}$$

variables λ, v, x

Generalized inequality constraints

$$\begin{array}{ll} \text{minimize} & f_0(x) \\ \text{subject to} & f_i(x) \preceq_{K_i} 0, \quad i = 1, \ldots, m \\ & Ax = b \end{array}$$

- $f_0 : \mathbb{R}^n \to \mathbb{R}$ is convex
- $f_i : \mathbb{R}^n \to \mathbb{R}^{k_i}$ is K_i-convex with respect to proper cone K_i:

  $$f_i(\theta x + (1-\theta)y) \preceq_{K_i} \theta f_i(x) + (1-\theta) f_i(y) \qquad \text{for } 0 \le \theta \le 1 \text{ and } x, y \in \operatorname{dom} f_i$$
- same properties as standard convex problem (local optimum is global, etc.)

Conic linear program: special case with linear objective and constraints

$$\begin{array}{ll} \text{minimize} & c^\top x \\ \text{subject to} & Fx + g \prec_K 0 \\ & Ax = b \end{array}$$

extends linear programming ($K = \mathbb{R}^m_+$) to nonpolyhedral cones

Semidefinite program (SDP)

$$
\begin{array}{ll}
\text{minimize} & c^\top x \\
\text{subject to} & x_1 F_1 + x_2 F_2 + \cdots + x_n F_n + G \preceq 0 \\
& Ax = b
\end{array}
$$

with $F_i, G \in \mathbb{S}^k$

- inequality constraint is called *linear matrix inequality* (LMI)
- includes problems with multiple LMI constraints: for example,

$$
x_1 \hat{F}_1 + x_2 \hat{F}_2 + \cdots + x_n \hat{F}_n + \hat{G} \preceq 0, \qquad x_1 \tilde{F}_1 + x_2 \tilde{F}_2 + \cdots + x_n \tilde{F}_n + \tilde{G} \preceq 0
$$

  is equivalent to single LMI

$$
x_1 \begin{bmatrix} \hat{F}_1 & 0 \\ 0 & \tilde{F}_1 \end{bmatrix} + x_2 \begin{bmatrix} \hat{F}_2 & 0 \\ 0 & \tilde{F}_2 \end{bmatrix} + \cdots + x_n \begin{bmatrix} \hat{F}_n & 0 \\ 0 & \tilde{F}_n \end{bmatrix} + \begin{bmatrix} \hat{G} & 0 \\ 0 & \tilde{G} \end{bmatrix} \preceq 0
$$

LP and SOCP as SDP

LP and equivalent SDP

$$\text{LP}: \quad \begin{array}{ll} \text{minimize} & c^\top x \\ \text{subject to} & Ax \preceq b \end{array} \qquad\qquad \text{SDP}: \quad \begin{array}{ll} \text{minimize} & c^\top x \\ \text{subject to} & \operatorname{diag}(Ax - b) \preceq 0 \end{array}$$

(note different interpretation of generalized inequality $\preceq$)

SOCP and equivalent SDP

$$\text{SOCP}: \quad \begin{array}{ll} \text{minimize} & f^\top x \\ \text{subject to} & \|A_i x + b_i\|_2 \leq c_i^\top x + d_i, \quad i = 1, \ldots, m \end{array}$$

$$\text{SDP}: \quad \begin{array}{ll} \text{minimize} & f^\top x \\ \text{subject to} & \begin{bmatrix} (c_i^\top x + d_i) I & A_i x + b_i \\ (A_i x + b_i)^\top & c_i^\top x + d_i \end{bmatrix} \succeq 0, \quad i = 1, \ldots, m \end{array}$$

Eigenvalue minimization

$$\text{minimize} \quad \lambda_{\max}(A(x))$$

where $A(x) = A_0 + x_1 A_1 + \cdots x_n A_n$ (with given $A_i \in \mathbb{S}^k$)

Equivalent SDP

$$\begin{array}{ll} \text{minimize} & t \\ \text{subject to} & A(x) \preceq tI \end{array}$$

- variables $x \in \mathbb{R}^n$, $t \in \mathbb{R}$
- equivalence follows from

$$\lambda_{\max}(A) \leq t \quad \Longleftrightarrow \quad A \preceq tI$$

Matrix norm minimization

$$\text{minimize} \quad \|A(x)\|_2 = \left(\lambda_{\mathsf{max}}(A(x))^\top(A(x))\right)^{1/2}$$

where $A(x) = A_0(x) + x_1 A_1(x) + \cdots + x_n A_n(x)$ (with given $A_i \in \mathbb{R}^{p \times q}$)

Equivalent SDP

$$\begin{array}{ll} \text{minimize} & t \\ \text{subject to} & \begin{bmatrix} tI & A(x) \\ A(x)^\top & tI \end{bmatrix} \succeq 0 \end{array}$$

- variables $x \in \mathbb{R}^n$, $t \in \mathbb{R}$
- constraint follows from

$$\begin{aligned} \|A\|_2 \leq t \quad &\Longleftrightarrow \quad A^\top A \preceq t^2 I, \quad t \geq 0 \\ &\Longleftrightarrow \quad \begin{bmatrix} tI & A \\ A^\top & tI \end{bmatrix} \preceq 0 \end{aligned}$$

Vector optimization

General vector optimization problem

$$\begin{array}{ll} \text{minimize (w.r.t. } K) & f_0(x) \\ \text{subject to} & f_i(x) \leq 0, \quad i = 1, \dots, m \\ & h_i(x) = 0, \quad i = 1, \dots, p \end{array}$$

vector objective $f_0 : \mathbb{R}^n \to \mathbb{R}^q$, minimized with respect to proper cone $K \in \mathbb{R}^q$

Convex vector optimization problem

$$\begin{array}{ll} \text{minimize (w.r.t. } K) & f_0(x) \\ \text{subject to} & f_i(x) \leq 0, \quad i = 1, \dots, m \\ & Ax = b \end{array}$$

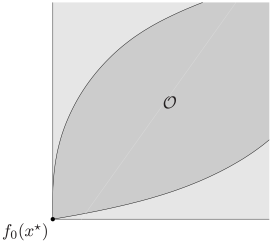
with f_0 K-convex, $f_1, \dots, f_m$ convex

Optimal and Pareto optimal points

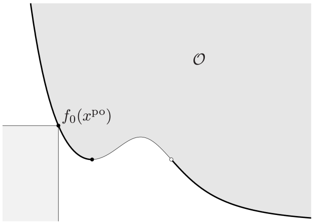
set of achievable objective values

$$\mathcal{O} = \{f_0(x) \mid x \text{ feasible}\}$$

- feasible x is **optimal** if $f_0(x)$ is the minimum value of $\mathcal{O}$
- feasible x is **Pareto optimal** if $f_0(x)$ is a minimum value of $\mathcal{O}$



$x^\star$ is optimal



x^{po} is Pareto optimal

Multicriterion optimization

vector optimization problem with $K = \mathbb{R}^q_+$

$$f_0(x) = (F_1(x), \ldots, F_q(x))$$

- q different objectives F_i; roughly speaking we want all F_i's to be small
- feasible $x^\star$ is *optimal* if

$$y \text{ feasible} \quad \Longrightarrow \quad f_0(x^\star) \preceq f_0(y)$$

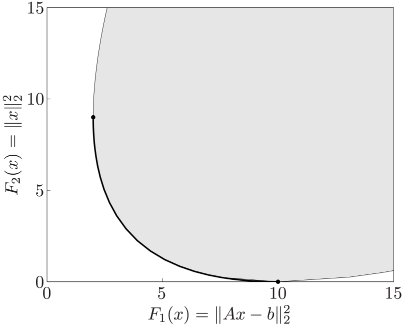
  if there exists an optimal point, the objectives are noncompeting
- feasible x^{po} is *Pareto optimal* if

$$y \text{ feasible}, \quad f_0(y) \preceq f_0(x^{\text{po}}) \quad \Longrightarrow \quad f_0(x^{\text{po}}) \preceq f_0(y)$$

  if Pareto optimal values are not unique, there is a trade-off between objectives
- f_0 is K-convex if $F_1, \ldots, F_q$ are convex (in the usual sense)

Regularized least-squares

$$\text{minimize (w.r.t. } \mathbb{R}^2_+) \quad (\|Ax - b\|_2^2, \|x\|_2^2)$$



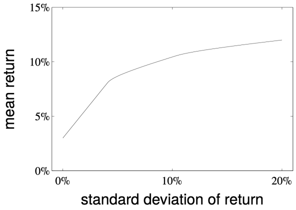
example for $A \in \mathbb{R}^{100\times 10}$; heavy line is formed by Pareto optimal points

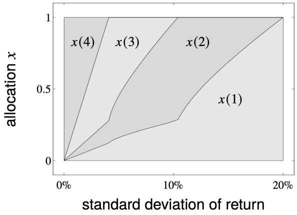
Risk-return trade-off in portfolio optimization

$$\begin{array}{ll} \text{minimize (w.r.t. } \mathbb{R}^2_+) & (-\bar{p}^\top x, x^\top \Sigma x) \\ \text{subject to} & \mathbf{1}^\top x = 1, \quad x \succeq 0 \end{array}$$

- $x \in \mathbb{R}^n$ is investment portfolio; x_i is fraction invested in asset i
- return is $r = p^\top x$ where $p \in \mathbb{R}^n$ is vector of relative asset price changes
- p is modeled as a random variable with mean $\bar{p}$, covariance Σ
- $\bar{p}^\top x = \mathbb{E} r$ is expected return; $x^\top \Sigma x = \mathbf{var}\ r$ is return variance (risk)

Example





Scalarization

to find Pareto optimal points: choose $\lambda \succ_{K^*} 0$ and solve scalar problem

$$\begin{array}{ll} \text{minimize} & \lambda^\top f_0(x) \\ \text{subject to} & f_i(x) \leq 0, \quad i = 1, \dots, m \\ & h_i(x) = 0, \quad i = 1, \dots, p \end{array}$$

- solutions x of scalar problem are Pareto-optimal for vector optimization problem

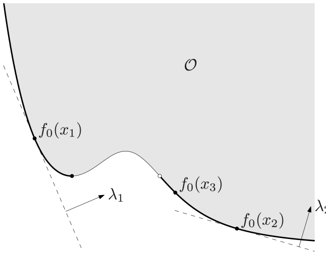
$$x \text{ not Pareto-optimal}$$

$$\Downarrow$$

$$\exists \text{ feasible } y : f_0(y) \preceq_K f_0(x), \; f_0(y) \neq f_0(x)$$

$$\Downarrow$$

$$\lambda^\top f_0(y) < \lambda^\top f_0(x) \text{ for } \lambda \succ_{K^*} 0$$



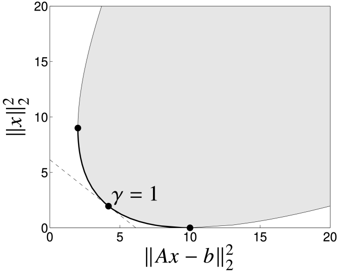
- partial converse for convex vector optimization problem (see later): can find (almost) all Pareto optimal points by varying $\lambda \succ_{K^*} 0$

Scalarization for multicriterion problems

to find Pareto optimal points, minimize positive weighted sum

$$\lambda^\top f_0(x) = \lambda_1 F_1(x) + \cdots + \lambda_q F_q(x)$$

- regularized least squares problem



take $\lambda = (1, \gamma)$ with $\gamma > 0$

$$\text{minimize} \quad \|Ax - b\|_2^2 + \gamma \|x\|_2^2$$

for fixed γ, a LS problem

- risk-return trade-off: with $\gamma > 0$,

$$\begin{array}{ll} \text{minimize} & -\bar{p}^\top x + \gamma x^\top \Sigma x \\ \text{subject to} & \mathbf{1}^\top x = 1, \quad x \succeq 0 \end{array}$$