CME 307 / MS&E 311 / OIT 676: Optimization

LP geometry, modeling and solution techniques

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Course survey

you're interested in:

- modeling real-world problems, from political science and economics to energy and desalination!
- robustness and modeling under uncertainty
- understanding core optimization concepts like duality and KKT conditions
- ...

questions:

- recommended resource for linear algebra?
- how to ask questions in class?

Outline

Linear programming: standard form

standard form linear program (LP)

$$\begin{array}{ll} \text{minimize} & c^T x \\ \text{subject to} & Ax = b \\ & x \geq 0 \end{array}$$

optimal value $p^\star$, solution $x^\star$ (if it exists)

- any x with $Ax = b$ and $x \geq 0$ is called a **feasible point**
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A: otherwise infeasible or redundant rows; use gaussian elimination to check and remove

LP example: diet problem

- x_j servings of food j, $j = 1, \ldots, n$
- c_j cost per serving
- a_{ij} amount of nutrient i in food j
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- ranges of nutrients? $Ax + s = b, \; l \leq s \leq u$

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- LP is feasible if hyperplane $\{x \mid Ax = b\}$ intersects the positive orthant

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- the intersection of convex sets is convex
- the feasible set $\{x : Ax = b,\ x \geq 0\}$ is convex

Outline

LP standard form

LP inequality form

What kinds of points can be optimal?

Modeling

Solving LPs

LP inequality form

another useful form for LP is **inequality form**

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interpretation: halfspaces

- $a_i^T x \leq b_i$ defines a **halfspace**
- $Ax \leq b$ defines a **polyhedron**: intersection of halfspaces
- LP is feasible if polyhedron $\{x \mid Ax \leq b\}$ is nonempty

LP example: production planning

- x_i units of product i
- c_i cost per unit
- a_{ij} amount of resource j used by product i
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  $c^T x + f^T z$, $z_i \in \{0, 1\}$, $x_i \leq M z_i$ for M large

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$$\begin{array}{ll} \text{minimize} & c^T x \\ \text{subject to} & Ax \leq b \end{array} \qquad \rightarrow \qquad \begin{array}{ll} \text{minimize} & c^T (x_+ - x_-) \\ \text{subject to} & A(x_+ - x_-) + s = b \\ & s, x_+, x_- \geq 0 \end{array}$$

so both forms have the same expressive power, and feasible sets are polyhedra

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for nonnegative variable $x \ge 0$, x_i is **active** if $x_i > 0$

example: active slack variables are dual to active constraints

$$\begin{aligned} Ax \le b \quad &\Longleftrightarrow \quad Ax + s = b,\ \ s \ge 0 \\ a_i^T x = b_i \quad &\Longleftrightarrow \quad s_i = 0 \\ \text{constraint } i \text{ is active} \quad &\Longleftrightarrow \quad \text{slack variable } s_i \text{ is inactive} \end{aligned}$$

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Q: Does there always exist an extreme solution?

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x is the unique optimum of this problem, so the proof of this statement follows from the previous proof.

Basic feasible solution

recall the standard form LP

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Q: how to find a BFS?

A: choose m linearly independent columns of A and set $x = A_S^{-1} b$; check $x \geq 0$.

Extreme point $\iff$ vertex $\iff$ BFS

fact. consider the feasible set $F = \{x \mid Ax = b,\ x \geq 0\}$ in $\mathbf{R}^n$. the following are equivalent:

- x is an extreme point of F
- x is a vertex of F
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we have already shown that vertex $\Longrightarrow$ extreme point. need to show

- extreme point $\Longrightarrow$ BFS
- BFS $\Longrightarrow$ vertex

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we will show the contrapositive: x is not a BFS $\implies$ x is not an extreme point

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consider $I = \{i : x^\star_i > 0\}$, the active set of variables in $x^\star$.

- if A_I were full rank $|I|$, we could complete A_I to an invertible A_S,
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extend this vector to $d \in \mathbf{R}^n$ with $d_{\bar{I}} = 0$, so $Ad = A_I d_I = 0$.
now for $\epsilon \leq \min_i x_i^\star / \max_i |d_i|$, define $x^+, x^- \in \mathbf{R}^n$ as

$$x^+ = x^\star + \epsilon d, \qquad x^- = x^\star - \epsilon d.$$

these are feasible:

- $x^+, x^- \geq 0$ by our choice of ϵ,
- $Ax^+ = Ax^- = b$ since $Ad = 0$.

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so $x^\star = \frac{1}{2}x^+ + \frac{1}{2}x^-$ is not extreme in F.

BFS $\implies$ vertex

suppose $x^\star$ is a BFS of F with active set S and A_S invertible. define $c \in \mathbf{R}^n$ as

$$c_i = \begin{cases} 0 & \text{if } i \in S \\ 1 & \text{otherwise} \end{cases}$$

so $c^T x^\star = 0$.

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- $x^\star$ is the only point in F supported on S, as $\mathbf{nullspace}(A_S) = 0$,
- so any other feasible point $x \in F$ has a positive objective value $c^T x > 0$.

hence $x^\star$ is a vertex of F with defining vector c.

Outline

Let's do some modeling!

practical solvers for MILP:

- Gurobi and COPT (cardinal optimizer) are the state-of-the-art commercial solvers
- GLPK is a free solver that is not as fast
- gurobipy is a python interface to Gurobi
- CVX* (including CVXPY in python) are modeling languages that call solvers like Gurobi with good support for convex problems
- OptiMUS is a LLM-based modeling tool for MILP that produces gurobipy code https://optimus-solver.com/dashboard
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demos:

- power systems https://jump.dev/JuMP.jl/stable/tutorials/applications/power_systems/
- multicast routing https://colab.research.google.com/drive/

Modeling challenges

model the following as standard form LPs:

1. **inequality constraints.** $Ax \leq b$
2. **free variable.** $x \in \mathbf{R}$
3. **absolute value.** constraint $|x| \leq 10$
4. **piecewise linear.** objective $\max(x_1, x_2)$
5. **assignment.** *e.g.*, every class is assigned exactly one classroom
6. **logic.** *e.g.*, class enrollment $\leq$ capacity of assigned room
7. **flow.** *e.g.*, the least cost way to ship an item from s to t

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(see chapter 1 of Bertsimas and Tsitsiklis for more details on 1–6. see https://colab.research.google.com/drive/1iOn1T1Muh51KaA7mf7UlQOdhSFZhZyry?usp=sharing for a detailed treatment of a flow problem.)

Use slack variables to represent inequality constraints

to represent the following problem in standard form,

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introduce slack variable $s \in \mathbf{R}^m$: $Ax + s = b$, $s \geq 0 \iff Ax \leq b$

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Split variable into parts to represent free variables

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introduce positive variables x_+, x_- so $x = x_+ - x_-$:

$$\begin{array}{ll} \text{minimize} & c^T x_+ - c^T x_- \\ \text{subject to} & Ax_+ - Ax_- = b \\ & x_+, x_- \geq 0 \end{array}$$

Use epigraph variables to handle absolute value

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verify these constraints ensure $|x_i| \leq t_i$.

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Q: Why does this work? For what kinds of functions can we use this trick?

Use binary variables to handle assignment

every class is assigned exactly one classroom:
define variable $X_{ij} \in \{0, 1\}$ for each class $i = 1, \ldots, n$ and room $j = 1, \ldots, m$

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now solve the problem

$$\begin{array}{ll} \text{minimize} & \sum_{i=1}^{n} \sum_{j=1}^{n} C_{ij} X_{ij} \\ \text{subject to} & \sum_{i=1}^{n} X_{ij} = 1, \ \forall j \quad \text{(every class assigned one room)} \\ & \sum_{j=1}^{m} X_{ij} \leq 1, \ \forall i \text{(no more than one class per room)} \\ & X_{ij} \in \{0, 1\} \qquad \text{(binary variables)} \end{array}$$

where C_{ij} is the cost of assigning class i to room j.

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model class enrollment $n_i \leq$ capacity c_j of assigned room:
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where C_{ij} is the cost of assigning class i to room j.

what if we want p to be a variable, too?

... or use a big-M relaxation!

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Outline

Solving LPs

algorithms:

- enumerate all vertices and check
- fourier-motzkin elimination
- simplex method
- ellipsoid method
- interior point methods
- first-order methods
- ...

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remarks:

- enumeration and elimination are simple but not practical
- simplex was the first practical algorithm; still used today
- ellipsoid method is the first polynomial-time algorithm; not practical
- interior point methods are polynomial-time and practical
- first-order methods are practical and scale to large problems

Enumerate vertices of LP

can generate all extreme points of LP: for each $S \subseteq \{1, \ldots, n\}$ with $|S| = m$,

- $A_S \in \mathbf{R}^{m \times m}$, submatrix of A with columns in S, is invertible
- solve $A_S x_S = b$ for x_S and set $x_{\bar{S}} = 0$
- if $x_S \geq 0$, then x is a BFS
- evaluate objective $c^T x$

the best BFS is optimal!

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problem: how many BFSs are there?
n choose m is $\binom{n}{m} = \frac{n!}{m!(n-m)!}$ ("exponentially many")

Simplex algorithm

basic idea: local search on the vertices of the feasible set

- start at BFS x and evaluate objective $c^T x$
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discuss in groups:

- how to find an initial BFS?
- how to find a neighboring BFS with better objective?
- how to prove optimality?

Finding an initial BFS

solve an auxiliary problem for which a BFS is known:

$$\begin{array}{ll} \text{minimize} & \sum_{i=1}^{m} z_i \\ \text{subject to} & Ax + Dz = b \\ & x, z \geq 0 \end{array}$$

where $D \in \mathbf{R}^{m \times m}$ is a diagonal matrix with $D_{ii} = \mathbf{sign}(b_i)$ for $i = 1, \ldots, m$.

- $x = 0$, $z = |b|$ is a BFS of this problem
- $(x, z) = (x, 0)$ is a BFS of this problem $\iff$ x is a BFS of the original problem

Find a better neighboring BFS

start with BFS x with active set S and turn on variable $j \notin S$

$$x^+ \leftarrow x + \theta d, \qquad \theta > 0$$

where $d_j = 1$ and $d_i = 0$ for $i \notin S \cup \{j\}$. need to solve for d_S.

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$$Ad = A_S d_S + A_j = 0 \implies d_S = -A_S^{-1} A_j$$

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- if $x_S > 0$ is **non-degenerate**, then $\exists \theta > 0$ st $x^+ \geq 0$
- how does objective change?

$$c^T x^+ = c^T x + \theta c^T d = c^T x + \theta c_j - \theta c_S^T A_S^{-1} A_j$$

Reduced cost

define **reduced cost** $\bar{c}_j = c_j - c_S^T A_S^{-1} A_j$, $j \notin S$

Reduced cost

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fact:

- if $\bar{c} \geq 0$, x is optimal
- if x is optimal and nondegenerate ($x_S > 0$), then $\bar{c} \geq 0$