

DM545/DM871
Linear and Integer Programming

Lecture 4
Exception Handling and Initialization

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Simplex: Exception Handling, Overview

Solution of an LP problem:

- a. $F \neq \emptyset$ and \nexists solution
- b. $F \neq \emptyset$ and \exists solution
 - i) **one solution**
 - ii) infinite solutions
- c. $F = \emptyset$

Handling exceptions in the Simplex Method

1. Unboundedness
2. More than one solution
3. Degeneracies
 - benign
 - cycling
4. Infeasible starting
Phase I + Phase II

Outline

Exception Handling
Initialization

1. Exception Handling

2. Initialization

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Exception Handling
Initialization

1. Exception Handling

2. Initialization

$$\begin{aligned} \max \quad & 2x_1 + x_2 \\ & x_2 \leq 5 \\ -x_1 + x_2 & \leq 1 \\ x_1, x_2 & \geq 0 \end{aligned}$$

- Initial tableau

	x1	x2	x3	x4	-z	b
x3	0	1	1	0	0	5
x4	-1	1	0	1	0	1
	2	1	0	0	1	0

- x_2 entering, x_4 leaving

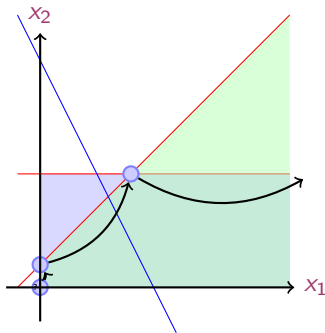
	x1	x2	x3	x4	-z	b
II'=II-I'	1	0	1	-1	0	4
I'=I	-1	1	0	1	0	1
III'=III-I'	3	0	0	-1	1	-1

$-x_1 + x_2 + x_4 = 1$, x_1 can increase without restriction, $\theta = \min\left\{\frac{b_i}{a_{is}} : a_{is} > 0, i = 1 \dots, n\right\}$

- x_1 entering, x_3 leaving

	x_1	x_2	x_3	x_4	$-z$	b
I'=I	1	0	1	-1	0	4
II'=II+I'	0	1	1	0	0	5
III'=III-3I'	0	0	-3	2	1	-13

x_4 was already in basis but for both I and II ($x_2 + x_3 + 0x_4 = 5$), x_4 can increase arbitrarily



$$\begin{aligned}
 \max \quad & x_1 + x_2 \\
 & 5x_1 + 10x_2 \leq 60 \\
 & 4x_1 + 4x_2 \leq 40 \\
 & x_1, x_2 \geq 0
 \end{aligned}$$

- Initial tableau

	x1	x2	x3	x4	-z	b
x3	5	10	1	0	0	60
x4	4	4	0	1	0	40
	1	1	0	0	1	0

- x_2 enters, x_3 leaves

	x1	x2	x3	x4	-z	b
I'=I/10	1/2	1	1/10	0	0	6
II'=II-4Ix4	2	0	-2/5	1	0	16
III'=III-I	1/2	0	-1/6	0	1	-6

- x_1 enters, x_4 leaves

	x_1	x_2	x_3	x_4	$-z$	b
I' = I - II'/2	0	1	1/5	-1/4	0	2
II' = II/2	1	0	-1/5	1/2	0	8
III' = III - II'/2	0	0	0	-1/4	1	-10

$$\mathbf{x} = (8, 2, 0, 0), z = 10$$

nonbasic variables typically have reduced costs $\neq 0$. Here x_3 has r.c. = 0. Let's make it enter the basis

- x_3 enters, x_2 leaves

	x_1	x_2	x_3	x_4	$-z$	b
I' = 5I	0	5	1	-5/4	0	10
II' = II + I'/5	1	1	0	4	0	10
III' = III	0	0	0	-1/4	1	-10

$$\mathbf{x} = (10, 0, 10, 0), z = 10$$

There are 2 optimal solutions \rightsquigarrow all their convex combinations are optimal solutions (from the proof of the fundamental theorem of LP) \rightsquigarrow

$$\mathbf{x} = \sum_{i=1}^2 \alpha_i \mathbf{x}_i$$

$$\alpha_i \geq 0$$

$$\sum_{i=1}^2 \alpha_i = 1$$

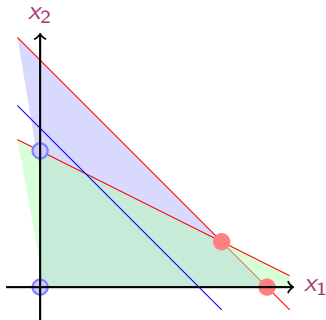
$$\mathbf{x}_1^T = [8, 2, 0, 0]$$

$$\mathbf{x}_2^T = [10, 0, 10, 0]$$

$$\alpha_1 = \alpha$$

$$\alpha_2 = 1 - \alpha$$

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \alpha \begin{bmatrix} 8 \\ 2 \\ 0 \\ 0 \end{bmatrix} + (1 - \alpha) \begin{bmatrix} 10 \\ 0 \\ 10 \\ 0 \end{bmatrix}$$



$$x_1 = 8\alpha + 10(1 - \alpha)$$

$$x_2 = 2\alpha$$

$$x_3 = 10(1 - \alpha)$$

$$x_4 = 0$$

$$\begin{aligned} \max \quad & x_2 \\ -x_1 + x_2 \leq & 0 \\ x_1 \leq & 2 \\ x_1, x_2 \geq & 0 \end{aligned}$$

- Initial tableau

	x1	x2	x3	x4	-z	b
x3	-1	1	1	0	0	0
x4	1	0	0	1	0	2
	0	1	0	0	1	0

$b_i = 0$ (one basic var. is zero) might lead to cycling

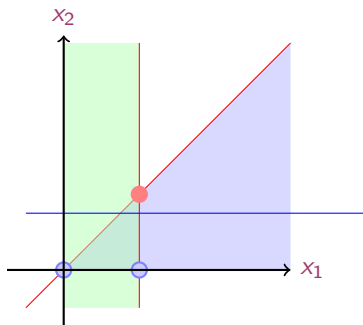
- degenerate pivot step: not improving, the entering variable stays at zero

	x1	x2	x3	x4	-z	b
	-1	1	1	0	0	0
	1	0	0	1	0	2
	1	0	-1	0	1	0

- now nondegenerate:

	x_1	x_2	x_3	x_4	$-z$	b
	0	1	0	1	0	2
	1	0	0	1	0	2
	0	0	-1	-1	1	-2

$$x_1 = 2, x_2 = 2, z = 2$$



$\geq n + 1$ constraints meet at a vertex

Def: An **improving variable** is one with positive reduced cost

Def: A **degenerate iteration** is one in which the objective function does not increase.

Def: The simplex method **cycles** if the same tableau appears in two iterations.

Degenerate conditions may appear often in practice but cycling is rare.
(see compendium for the smallest possible example)

Theorem

If the simplex fails to terminate, then it must cycle.

Proof:

- there is a finite number of basis and simplex chooses to always increase the objective value
- hence the only situation for not terminating is that a basis appears again and iterations in between are degenerate. Two tableaux with the same basis are the same (related to uniqueness of basic solutions)

Some pivoting rules can prevent the occurrence of cycling altogether.

So far we chose an **arbitrary improving variable** to enter. Rules for breaking ties in selecting **entering** improving variables (more important than selecting leaving variables)

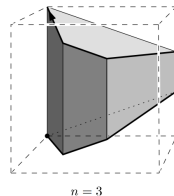
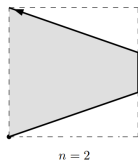
- **Largest Coefficient**: the improving var with largest coefficient in last row of the tableau.
Original Dantzig's rule, can cycle
- **Largest increase**: absolute improvement: $\operatorname{argmax}_j \{c_j \theta_j\}$
computationally more costly
- **Steepest edge** the improving var that if entering in the basis moves the current basic feasible sol in a direction closest to the direction of the vector \mathbf{c} (ie, maximizes the cosine of the angle between the two vectors):

$$\mathbf{a} \cdot \mathbf{b} = \|\mathbf{a}\| \|\mathbf{b}\| \cos \theta \quad \Rightarrow \quad \max_{\mathbf{x}_{\text{new}}} \frac{\mathbf{c}^T (\mathbf{x}_{\text{new}} - \mathbf{x}_{\text{old}})}{\|\cancel{\mathbf{e}}\| \|\mathbf{x}_{\text{new}} - \mathbf{x}_{\text{old}}\|}$$

- **Bland's rule (smallest-subscript rule)** chooses the improving var with the lowest index and, if there are more than one leaving variable, the one with the lowest index.
Prevents cycling but is slow (no smart choice for entering variable)
- **Random edge** select var uniformly at random among the improving ones and the leaving ones among those selected by the ratio test
- **Perturbation method**: perturb values of b_i terms to avoid $b_i = 0$, which must occur for cycling.
To avoid cancellations: $0 < \epsilon_m \ll \epsilon_{m-1} \ll \dots \ll \epsilon_1 \ll 1$
It affects the choice of the leaving variable
Can be shown to be the same as lexicographic method, which prevents cycling

Efficiency of Simplex Method

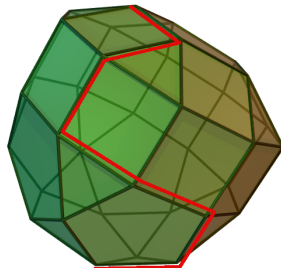
- Trying all points is $\approx 4^m$
- In practice between $2m$ and $3m$ iterations
- Klee and Minty 1978 constructed an example that requires $2^n - 1$ iterations in \mathbb{R}^n :



- random shuffle of indexes + lowest index for entering + lexicographic for leaving: expected iterations $< e^{C\sqrt{n \ln n}}$

Efficiency of Simplex Method

- unknown if there exists a pivot rule that leads to polynomial time.
- Clairvoyant's rule: shortest possible sequence of steps
Hirsh conjecture $O(n - d)$ for an n -facet polytope in d -dimensional Euclidean space but best known $n^{1+\ln n}$



- smoothed complexity: slight random perturbations of worst-case inputs
D. Spielman and S. Teng (2001), *Smoothed analysis of algorithms: why the simplex algorithm usually takes polynomial time*
 $O(\max(n^5 \log^2 m, n^9 \log^4 n, n^3 \sigma^{-4}))$

Outline

Exception Handling
Initialization

1. Exception Handling

2. Initialization

Initial Infeasibility

$$\begin{aligned} \max \quad & x_1 - x_2 \\ & x_1 + x_2 \leq 2 \\ & 2x_1 + 2x_2 \geq 5 \\ & x_1, x_2 \geq 0 \end{aligned}$$

$$\begin{aligned} \max \quad & x_1 - x_2 \\ & x_1 + x_2 + x_3 = 2 \\ & -2x_1 - 2x_2 + x_4 = -5 \\ & x_1, x_2, x_3, x_4 \geq 0 \end{aligned}$$

- Initial tableau

	x1	x2	x3	x4	-z	b
x3	1	1	1	0	0	2
x4	-2	-2	0	1	0	-5
	1	-1	0	0	1	0

~> we do not have an initial basic feasible solution!!

In general finding any feasible solution is difficult as finding an optimal solution, otherwise we could do binary search

Auxiliary Problem (I Phase of Simplex)

We introduce auxiliary variables:

$$\begin{aligned}
 w^* &= \max -x_5 \equiv \min x_5 \\
 x_1 + x_2 + x_3 &= 2 \\
 2x_1 + 2x_2 - x_4 + x_5 &= 5 \\
 x_1, x_2, x_3, x_4, x_5 &\geq 0
 \end{aligned}$$

if $w^* = 0$ then $x_5 = 0$ and the two problems are equivalent

if $w^* > 0$ then not possible to set x_5 to zero.

- Initial tableau

	x1	x2	x3	x4	x5	-z	-w	b
	1	1	1	0	0	0	0	2
	2	2	0	-1	1	0	0	5
z	1	-1	0	0	0	1	0	0
w	0	0	0	0	-1	0	1	0

Keep z always in basis

- we reach a canonical form simply by letting x_5 enter the basis:

	x_1	x_2	x_3	x_4	x_5	$-z$	$-w$	b
I	1	1	1	0	0	0	0	2
II	2	2	0	-1	1	0	0	5
z	1	-1	0	0	0	1	0	0
IV+II	2	2	0	-1	0	0	1	5

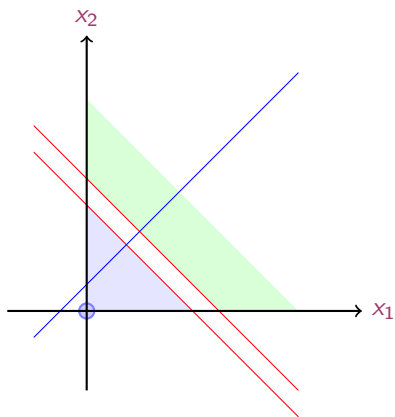
now we have a basic feasible solution!

- x_1 enters, x_3 leaves

	x_1	x_2	x_3	x_4	x_5	$-z$	$-w$	b
I	1	1	1	0	0	0	0	2
II-2I'	0	0	-2	-1	1	0	0	1
III-I'	0	-2	-1	0	0	1	0	-2
IV-2I'	0	0	-2	-1	0	0	1	1

$w^* = -1$ then no solution with $x_5 = 0$ exists then no feasible solution to initial problem

$$\begin{aligned} \max \quad & x_1 - x_2 \\ \text{s.t.} \quad & x_1 + x_2 \leq 2 \\ & 2x_1 + 2x_2 \geq 5 \\ & x_1, x_2 \geq 0 \end{aligned}$$



Initial Infeasibility - Another Example

$$\begin{aligned}\max \quad & x_1 - x_2 \\ & x_1 + x_2 \leq 2 \\ & 2x_1 + 2x_2 \geq 2 \\ & x_1, x_2 \geq 0\end{aligned}$$

$$\begin{aligned}\max \quad & x_1 - x_2 \\ & x_1 + x_2 + x_3 = 2 \\ & 2x_1 + 2x_2 - x_4 = 2 \\ & x_1, x_2, x_3, x_4 \geq 0\end{aligned}$$

Auxiliary problem (I phase):

$$\begin{aligned}w = \max \quad & -x_5 \equiv \min x_5 \\ & x_1 + x_2 + x_3 = 2 \\ & 2x_1 + 2x_2 - x_4 + x_5 = 2 \\ & x_1, x_2, x_3, x_4, x_5 \geq 0\end{aligned}$$

- Initial tableau

	x1	x2	x3	x4	x5	-z	-w	b
	1	1	1	0	0	0	0	2
	2	2	0	-1	1	0	0	2
z	1	-1	0	0	0	1	0	0
w	0	0	0	0	-1	0	1	0

↪ we do not have an initial basic feasible solution.

- set in canonical form:

	x1	x2	x3	x4	x5	-z	-w	b
	1	1	1	0	0	0	0	2
	2	2	0	-1	1	0	0	2
z	1	-1	0	0	0	1	0	0
IV+II	2	2	0	-1	0	0	1	2

- x_1 enters, x_5 leaves

	x1	x2	x3	x4	x5	-z	-w	b
	0	0	1	1/2	-1/2	0	0	1
	1	1	0	-1/2	1/2	0	0	1
z	0	-2	0	1/2	-1/2	1	0	-1
w	0	0	0	0	-1	0	1	0

$w^* = 0$ hence $x_5 = 0$ we have a starting feasible solution for the initial problem.

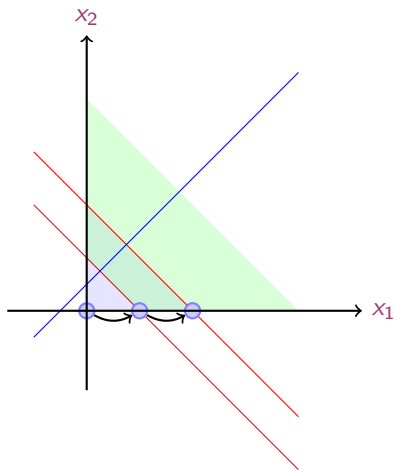
- (II phase) We keep only what we need:

	x1	x2	x3	x4	-z	b
	0	0	1	1/2	0	1
	1	1	0	-1/2	0	1
	z	0	-2	0	1/2	1

-
- | | x1 | x2 | x3 | x4 | -z | b |
|--|----|----|----|----|----|---|
| | | | | | | |
| | 0 | 0 | 2 | 1 | 0 | 2 |
| | 1 | 1 | 1 | 0 | 0 | 2 |
| | z | 0 | -2 | -1 | 0 | 1 |

Optimal solution: $x_1 = 2, x_2 = 0, x_3 = 0, x_4 = 2, z = 2$.

$$\begin{aligned} \max \quad & x_1 - x_2 \\ \text{s.t.} \quad & x_1 + x_2 \leq 2 \\ & 2x_1 + 2x_2 \geq 2 \\ & x_1, x_2 \geq 0 \end{aligned}$$



In Dictionary Form

$$\begin{aligned} \max \quad & x_1 - x_2 \\ & x_1 + x_2 \leq 2 \\ & 2x_1 + 2x_2 \geq 5 \\ & x_1, x_2 \geq 0 \end{aligned}$$

$$\begin{array}{rcl} x_3 & = & 2 - x_1 - x_2 \\ x_4 & = & -5 + 2x_1 + 2x_2 \\ \hline z & = & x_1 + x_2 \end{array}$$

sol. infeasible

We introduce corrections of infeasibility

$$\begin{aligned} \max \quad & -x_0 \equiv \min \quad x_0 \\ & x_1 + x_2 \leq 2 \\ & 2x_1 + 2x_2 - x_0 \geq 5 \\ & x_1, x_2, x_0 \geq 0 \end{aligned}$$

$$\begin{array}{rcl} x_3 & = & 2 - x_1 - x_2 \\ x_4 & = & -5 + 2x_1 + 2x_2 + x_0 \\ \hline z & = & - x_0 \end{array}$$

It is still infeasible but it can be made feasible by letting x_0 enter the basis

which variable should leave?

the most infeasible: the var with the b term whose negative value has the largest magnitude

Simplex: Exception Handling, Summary

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- b. $F \neq \emptyset$ and \exists solution
 - i) **one solution**
 - ii) infinite solutions
- c. $F = \emptyset$

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Phase I + Phase II