15.081J/6.251J Introduction to Mathematical Programming

Lecture 5: The Simplex Method I

1 Outline

Slide 1

- Reduced Costs
- Optimality conditions
- Improving the cost
- Unboundness
- The Simplex algorithm
- The Simplex algorithm on degenerate problems

2 Matrix View

Slide 2

$$\begin{aligned} \min \quad & \boldsymbol{c}'\boldsymbol{x} \\ \text{s.t.} \quad & \boldsymbol{A}\boldsymbol{x} = \boldsymbol{b} \\ & \boldsymbol{x} \geq \boldsymbol{0} \end{aligned}$$

$\boldsymbol{x} = (\boldsymbol{x}_B, \boldsymbol{x}_N)$ $\quad$ $\boldsymbol{x}_B$ basic variables
$\boldsymbol{x}_N$ non-basic variables

$\boldsymbol{A} = [\boldsymbol{B}, \boldsymbol{N}]$
$\boldsymbol{A}\boldsymbol{x} = \boldsymbol{b} \Rightarrow \quad \boldsymbol{B} \cdot \boldsymbol{x}_B + \boldsymbol{N} \cdot \boldsymbol{x}_N = \boldsymbol{b}$
$\Rightarrow \boldsymbol{x}_B + \boldsymbol{B}^{-1}\boldsymbol{N}\boldsymbol{x}_N = \boldsymbol{B}^{-1}\boldsymbol{b}$
$\Rightarrow \boldsymbol{x}_B = \boldsymbol{B}^{-1}\boldsymbol{b} - \boldsymbol{B}^{-1}\boldsymbol{N}\boldsymbol{x}_N$

2.1 Reduced Costs

Slide 3

$$\begin{aligned} z &= \boldsymbol{c}_B'\boldsymbol{x}_B + \boldsymbol{c}_N'\boldsymbol{x}_N \\ &= \boldsymbol{c}_B'(\boldsymbol{B}^{-1}\boldsymbol{b} - \boldsymbol{B}^{-1}N\boldsymbol{x}_N) + \boldsymbol{c}_N'\boldsymbol{x}_N \\ &= \boldsymbol{c}_B'\boldsymbol{B}^{-1}\boldsymbol{b} + (\boldsymbol{c}_N' - \boldsymbol{c}_B'\boldsymbol{B}^{-1}\boldsymbol{N})\boldsymbol{x}_N \end{aligned}$$

$$\boxed{\overline{c}_j = c_j - \boldsymbol{c}_B'\boldsymbol{B}^{-1}\boldsymbol{A}_j \quad \text{reduced cost}}$$

2.2 Optimality Conditions

Slide 4

Recall Theorem:

- $\boldsymbol{x}$ BFS associated with basis B
- $\overline{\boldsymbol{c}}$ reduced costs
  Then
- If $\overline{\boldsymbol{c}} \geq \boldsymbol{0} \Rightarrow \boldsymbol{x}$ optimal
- $\boldsymbol{x}$ optimal and non-degenerate $\Rightarrow \overline{\boldsymbol{c}} \geq \boldsymbol{0}$

3 Improving the Cost

SLIDE 5

- Suppose $\overline{c}_j = c_j - \boldsymbol{c}'_B \boldsymbol{B}^{-1} \boldsymbol{A}_j < 0$
  Can we improve the cost?
- Let $\boldsymbol{d}_B = -\boldsymbol{B}^{-1} \boldsymbol{A}_j$
  $d_j = 1, \; d_i = 0, \; i \neq B(1), \ldots, B(m), j.$
- Let $\boldsymbol{y} = \boldsymbol{x} + \theta \cdot \boldsymbol{d}, \quad \theta > 0$ scalar

SLIDE 6

$$
\begin{array}{rcl}
\boldsymbol{c}'\boldsymbol{y} - \boldsymbol{c}'\boldsymbol{x} & = & \theta \cdot \boldsymbol{c}'\boldsymbol{d} \\
& = & \theta \cdot (\boldsymbol{c}'_B \boldsymbol{d}_B + c_j d_j) \\
& = & \theta \cdot (c_j - \boldsymbol{c}'_B \boldsymbol{B}^{-1} \boldsymbol{A}_j) \\
& = & \theta \cdot \overline{c}_j
\end{array}
$$

Thus, if $\overline{c}_j < 0$ cost will decrease.

4 Unboundness

SLIDE 7

- Is $\boldsymbol{y} = \boldsymbol{x} + \theta \cdot \boldsymbol{d}$ feasible?
  Since $\boldsymbol{A}\boldsymbol{d} = 0 \Rightarrow \boldsymbol{A}\boldsymbol{y} = \boldsymbol{A}\boldsymbol{x} = \boldsymbol{b}$
- $\boldsymbol{y} \geq \boldsymbol{0}$?
  If $\boldsymbol{d} \geq \boldsymbol{0} \Rightarrow \boldsymbol{x} + \theta \cdot \boldsymbol{d} \geq \boldsymbol{0} \quad \forall \; \theta \geq 0$
  $\Rightarrow$ objective unbounded.

5 Improvement

SLIDE 8

If $d_i < 0$, then

$$x_i + \theta d_i \geq 0 \Rightarrow \theta \leq -\frac{x_i}{d_i}$$

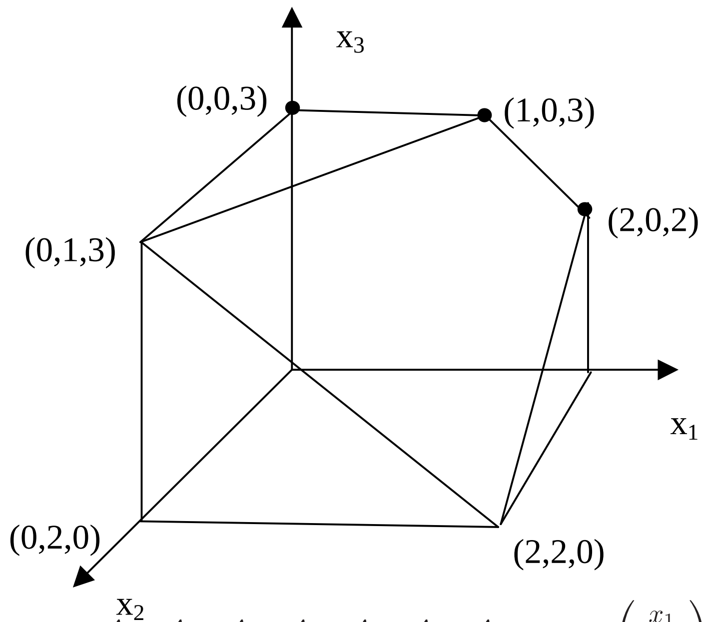
$\Rightarrow \theta^* = \min\limits_{\{i \mid d_i < 0\}} \left(-\dfrac{x_i}{d_i} \right)$

$\Rightarrow \theta^* = \min\limits_{\{i=1,\ldots,m \mid d_{B(i)} < 0\}} \left(-\dfrac{x_{B(i)}}{d_{B(i)}} \right)$

5.1 Example

SLIDE 9

$$
\begin{array}{rllll}
\min & x_1 + & 5x_2 & -2x_3 & \\
\text{s.t.} & x_1 + & x_2 + & x_3 & \leq 4 \\
& x_1 & & & \leq 2 \\
& & & x_3 & \leq 3 \\
& & 3x_2 + & x_3 & \leq 6 \\
& x_1, & x_2, & x_3 & \geq 0
\end{array}
$$



Slide 10

Slide 11

$$\begin{array}{ccccccc} \boldsymbol{A}_1 & \boldsymbol{A}_2 & \boldsymbol{A}_3 & \boldsymbol{A}_4 & \boldsymbol{A}_5 & \boldsymbol{A}_6 & \boldsymbol{A}_7 \end{array}$$
$$\left[\begin{array}{ccccccc} 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 3 & 1 & 0 & 0 & 0 & 1 \end{array}\right] \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{pmatrix} = \begin{pmatrix} 4 \\ 2 \\ 3 \\ 6 \end{pmatrix}$$

B $= [\boldsymbol{A}_1, \boldsymbol{A}_3, \boldsymbol{A}_6, \boldsymbol{A}_7]$

BFS: $\boldsymbol{x} = (2, 0, 2, 0, 0, 1, 4)'$

Slide 12

$$\boldsymbol{B} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix}, \quad \boldsymbol{B}^{-1} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ -1 & 1 & 1 & 0 \\ -1 & 1 & 0 & 1 \end{bmatrix} \quad \overline{\boldsymbol{c}}' = (0, 7, 0, 2, -3, 0, 0)$$

$$d_5 = 1, d_2 = d_4 = 0, \quad \begin{pmatrix} d_1 \\ d_3 \\ d_6 \\ d_7 \end{pmatrix} = -\boldsymbol{B}^{-1}\boldsymbol{A}_5 = \begin{pmatrix} -1 \\ 1 \\ -1 \\ -1 \end{pmatrix}$$

Slide 13

$$\boldsymbol{y}' = \boldsymbol{x}' + \theta \boldsymbol{d}' = (2 - \theta, 0, 2 + \theta, 0, \theta, 1 - \theta, 4 - \theta)$$

What happens as θ increases?

$\theta^* = \min_{\{i=1,\ldots,m | d_{B(i)} < 0\}} \left(-\frac{x_{B(i)}}{d_i}\right) =$

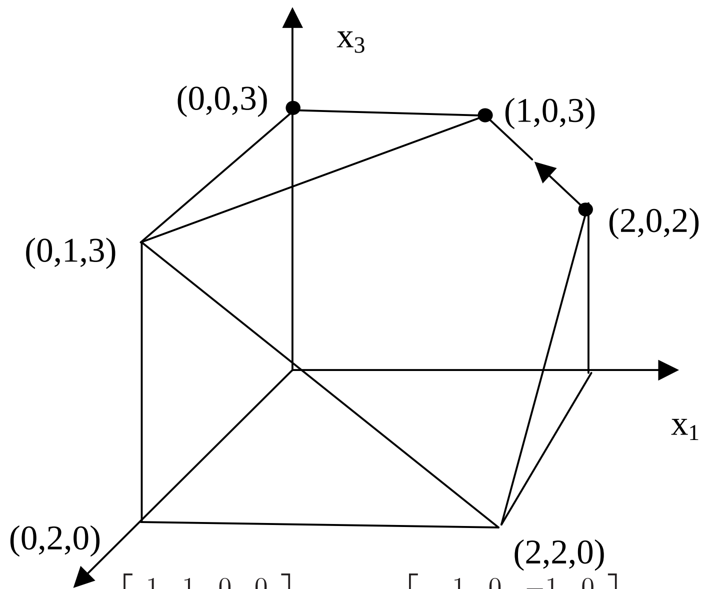
$\quad \min\left(-\frac{2}{(-1)}, -\frac{1}{(-1)}, -\frac{4}{(-1)}\right) = 1.$

$l = 6$ ($\boldsymbol{A}_6$ exits the basis).

New solution

$\boldsymbol{y} = (1, 0, 3, 0, 1, 0, 3)'$ Slide 14

New basis $\overline{\boldsymbol{B}} = (\boldsymbol{A}_1, \boldsymbol{A}_3, \boldsymbol{A}_5, \boldsymbol{A}_7)$ Slide 15



$$\overline{\boldsymbol{B}} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix}, \overline{B}^{-1} = \begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 \\ -1 & 1 & 1 & 0 \\ 0 & 0 & -1 & 1 \end{bmatrix}$$

$\overline{\boldsymbol{c}}' = \boldsymbol{c}' - \boldsymbol{c}'_{\overline{B}} \overline{\boldsymbol{B}}^{-1} \boldsymbol{A} = (0, 4, 0, -1, 0, 3, 0)$
Need to continue, column $\boldsymbol{A}_4$ enters the basis.

6 Correctness

SLIDE 16

$$-\frac{x_{B(l)}}{d_{B(l)}} = \min_{i=1,\ldots,m, d_{B(i)<0}} \left(-\frac{x_{B(i)}}{d_{B(i)}} \right) = \theta^*$$

Theorem

- $\overline{\boldsymbol{B}} = \{\boldsymbol{A}_{B_{(i)}, i \neq l}, \boldsymbol{A}_j\}$ basis
- $\boldsymbol{y} = \boldsymbol{x} + \theta^* \boldsymbol{d}$ is a BFS associated with basis $\overline{\boldsymbol{B}}$.

7 The Simplex Algorithm

SLIDE 17

1. Start with basis $\boldsymbol{B} = [\boldsymbol{A}_{B(1)}, \ldots, \boldsymbol{A}_{B(m)}]$
   and a BFS $\boldsymbol{x}$.
2. Compute $\overline{c}_j = c_j - \boldsymbol{c}'_B \boldsymbol{B}^{-1} \boldsymbol{A}_j$
   - If $\overline{c}_j \geq 0$; x optimal; stop.
   - Else select $j : \overline{c}_j < 0$.

3. Compute $\boldsymbol{u} = -\boldsymbol{d} = \boldsymbol{B}^{-1}\boldsymbol{A}_j$.
   - If $\boldsymbol{u} \leq \boldsymbol{0} \Rightarrow$ cost unbounded; stop
   - Else
4. $\theta^* = \min_{1 \leq i \leq m, u_i > 0} \frac{x_{B(i)}}{u_i} = \frac{u_{B(l)}}{u_l}$
5. Form a new basis by replacing $\boldsymbol{A}_{B(l)}$ with $\boldsymbol{A}_j$.
6. $y_j = \theta^*$
   $y_{B(i)} = x_{B(i)} - \theta^* u_i$

7.1 Finite Convergence

Slide 19

Theorem:

- $P = \{\boldsymbol{x} \mid \boldsymbol{A}\boldsymbol{x} = \boldsymbol{b}, \ \ \boldsymbol{x} \geq \boldsymbol{0}\} \neq \emptyset$
- Every BFS non-degenerate
  Then
- Simplex method terminates after a finite number of iterations
- At termination, we have optimal basis $\boldsymbol{B}$ or we have a direction $\boldsymbol{d} : \boldsymbol{A}\boldsymbol{d} = \boldsymbol{0}, \boldsymbol{d} \geq \boldsymbol{0}, \boldsymbol{c}'\boldsymbol{d} < \boldsymbol{0}$ and optimal cost is $-\infty$.

7.2 Degenerate problems

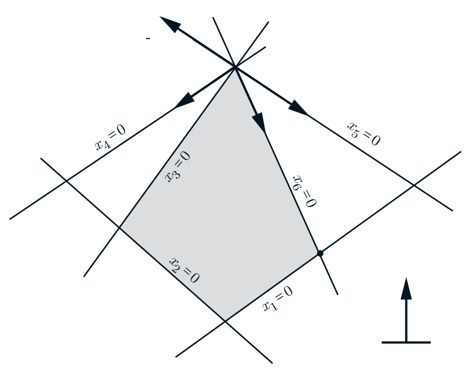
Slide 20

- θ^* can equal zero (why?) $\Rightarrow \boldsymbol{y} = \boldsymbol{x}$, although $\overline{\boldsymbol{B}} \neq \boldsymbol{B}$.
- Even if $\theta^* > 0$, there might be a tie

$$\min_{1 \leq i \leq m, u_i > 0} \frac{x_{B(i)}}{u_i} \Rightarrow$$

  next BFS degenerate.
- Finite termination not guaranteed; cycling is possible.

Slide 21



7.3 Pivot Selection

SLIDE 22

- Choices for the entering column:

  (a) Choose a column $\boldsymbol{A}_j$, with $\overline{c}_j < 0$, whose reduced cost is the most negative.

  (b) Choose a column with $\overline{c}_j < 0$ for which the corresponding cost decrease $\theta^*|\overline{c}_j|$ is largest.

- Choices for the exiting column:
  smallest subscript rule: out of all variables eligible to exit the basis, choose one with the smallest subscript.

7.4 Avoiding Cycling

SLIDE 23

- Cycling can be avoided by carefully selecting which variables enter and exit the basis.

- Example: among all variables $\overline{c}_j < 0$, pick the smallest subscript;
  among all variables eligible to exit the basis, pick the one with the smallest subscript.

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