MVE165/MMG630, Applied Optimization
Lecture 3

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A general linear program in standard form

- A linear program with n non-negative variables, m equality constraints ($m < n$), and non-negative right hand sides:

$$\begin{array}{lrcll} \text{maximize} & z = \sum_{j=1}^{n} c_j x_j & & & \\ \text{subject to} & \sum_{j=1}^{n} a_{ij} x_j & = & b_i, & i = 1, \ldots, m, \\ & x_j & \geq & 0, & j = 1, \ldots, n. \end{array}$$

- On matrix form it is written as:

$$\begin{array}{lr} \text{maximize} & z = \mathbf{c}^{\mathrm{T}}\mathbf{x}, \\ \text{subject to} & \mathbf{A}\mathbf{x} = \mathbf{b}, \\ & \mathbf{x} \geq \mathbf{0}^n, \end{array}$$

where $\mathbf{x} \in \Re^n$, $\mathbf{A} \in \Re^{m \times n}$, $\mathbf{b} \in \Re^m_+$ ($\mathbf{b} \geq \mathbf{0}^m$), and $\mathbf{c} \in \Re^n$.

Alternative optimal solutions

- Example:

$$\begin{array}{lrrrl} \color{red}{\text{maximize}} & z = & 2x_1 & +4x_2 & \\ \text{subject to} & & x_1 & +2x_2 & \leq 5 \\ & & x_1 & +x_2 & \leq 4 \\ & & & x_1, x_2 & \geq 0 \end{array}$$

Draw graph!!

- The extreme points $(0, \frac{5}{2})$ and $(3, 1)$ have the same optimal value $z = 10$
- All solutions that are positive linear (convex) combinations of these are optimal:

$$(x_1, x_2) = \alpha \cdot (0, \frac{5}{2}) + (1 - \alpha) \cdot (3, 1), \quad 0 \leq \alpha \leq 1$$

- Reduced cost of a non-basic variable is 0 in an optimal basis

General derivation of the simplex method

- B = set of basic variables, N = set of non-basic variables

$\Rightarrow$ $|B| = m$ and $|N| = n - m$

- Partition matrix/vectors: $\mathbf{A} = (\mathbf{B}, \mathbf{N})$, $\mathbf{x} = (\mathbf{x}_B, \mathbf{x}_N)$, $\mathbf{c} = (\mathbf{c}_B, \mathbf{c}_N)$
- The matrix $\mathbf{B}$ ($\mathbf{N}$) contains the columns of $\mathbf{A}$ corresponding to the index set B (N) — Analogously for $\mathbf{x}$ and $\mathbf{c}$
- Rewrite the linear program:

$$\left[\begin{array}{r} \text{maximize } z = \mathbf{c}^{\mathrm{T}}\mathbf{x} \\ \text{subject to } \mathbf{A}\mathbf{x} = \mathbf{b}, \\ \mathbf{x} \geq \mathbf{0}^n \end{array}\right] = \left[\begin{array}{r} \text{maximize } z = \mathbf{c}_B^{\mathrm{T}}\mathbf{x}_B + \mathbf{c}_N^{\mathrm{T}}\mathbf{x}_N \\ \text{subject to } \mathbf{B}\mathbf{x}_B + \mathbf{N}\mathbf{x}_N = \mathbf{b}, \\ \mathbf{x}_B \geq \mathbf{0}^m, \ \mathbf{x}_N \geq \mathbf{0}^{n-m} \end{array}\right]$$

- Substitute: $\mathbf{x}_B = \mathbf{B}^{-1}\mathbf{b} - \mathbf{B}^{-1}\mathbf{N}\mathbf{x}_N \Longrightarrow$

$$\begin{array}{ll} \text{maximize} & z = \mathbf{c}_B^{\mathrm{T}}\mathbf{B}^{-1}\mathbf{b} + [\mathbf{c}_N^{\mathrm{T}} - \mathbf{c}_B^{\mathrm{T}}\mathbf{B}^{-1}\mathbf{N}]\mathbf{x}_N \\ \text{subject to} & \mathbf{B}^{-1}\mathbf{b} - \mathbf{B}^{-1}\mathbf{N}\mathbf{x}_N \geq \mathbf{0}^m, \\ & \mathbf{x}_N \geq \mathbf{0}^{n-m} \end{array}$$

Optimality and feasibility

- **Optimality condition** (for maximization)

  The basis B is optimal if $\mathbf{c}_N^{\mathrm{T}} - \mathbf{c}_B^{\mathrm{T}}\mathbf{B}^{-1}\mathbf{N} \leq \mathbf{0}^{n-m}$
  (marginal values = reduced costs ≤ 0)

  If not, choose as entering variable $j \in N$ the one with the largest value of the reduced cost $c_j - \mathbf{c}_B^{\mathrm{T}}\mathbf{B}^{-1}\mathbf{A}_j$

- **Feasibility condition**

  For all $i \in B$ it holds that $x_i = (\mathbf{B}^{-1}\mathbf{b})_i - (\mathbf{B}^{-1}\mathbf{A}_j)_i x_j$

  Choose the leaving variable $i^* \in B$ according to

$$i^* = \arg\min_{i \in B} \left\{ \frac{(\mathbf{B}^{-1}\mathbf{b})_i}{(\mathbf{B}^{-1}\mathbf{A}_j)_i} \middle| (\mathbf{B}^{-1}\mathbf{A}_j)_i > 0 \right\}$$

Linear programming duality

- To each (primal) linear program corresponds a dual linear program:

$$\begin{array}{llrl} \text{[Primal]} & \text{minimize} & z = & \mathbf{c}^{\mathrm{T}}\mathbf{x}, \\ & \text{subject to} & \mathbf{A}\mathbf{x} = & \mathbf{b}, \\ & & \mathbf{x} \geq & \mathbf{0}^n, \end{array}$$

$$\begin{array}{llrl} \text{[Dual]} & \text{maximize} & w = & \mathbf{b}^{\mathrm{T}}\mathbf{y}, \\ & \text{subject to} & \mathbf{A}^{\mathrm{T}}\mathbf{y} \leq & \mathbf{c}, \end{array}$$

In the simplex tableau we have

basis	$-z$	$\mathbf{x}_B$	$\mathbf{x}_N$	$\mathbf{s}$	RHS
$-z$	1	$\mathbf{0}$	$\mathbf{c}_N^{\mathrm{T}} - \mathbf{c}_B^{\mathrm{T}}\mathbf{B}^{-1}\mathbf{N}$	$-\mathbf{c}_B^{\mathrm{T}}\mathbf{B}^{-1}$	$-\mathbf{c}_B^{\mathrm{T}}\mathbf{B}^{-1}\mathbf{b}$
$\mathbf{x}_B$	$\mathbf{0}$	$\mathbf{I}$	$\mathbf{B}^{-1}\mathbf{N}$	$\mathbf{B}^{-1}$	$\mathbf{B}^{-1}\mathbf{b}$

- $\mathbf{s}$ denotes possible slack variables (columns for $\mathbf{s}$ are copies of certain columns for $(\mathbf{x}_B, \mathbf{x}_N)$)
- The computations performed by the simplex algorithm involve matrix inversions and updates of these
- A non-basic (basic) variable enters (leaves) the basis $\Rightarrow$ one column, $\mathbf{A}_j$, of $\mathbf{B}$ is replaced by another, $\mathbf{A}_k$
- Row operations $\Leftrightarrow$ Updates of $\mathbf{B}^{-1}$ (and $\mathbf{B}^{-1}\mathbf{N}$, $\mathbf{B}^{-1}\mathbf{b}$, and $\mathbf{c}_B^{\mathrm{T}}\mathbf{B}^{-1}$)

$\Rightarrow$ Efficient numerical computations are crucial for the performance of the simplex algorithm

In practice ...

- A primal linear program

$$\begin{array}{llrrl} \text{minimize} & z = & 2x_1 & +3x_2 & \\ \text{subject to} & & 3x_1 & +2x_2 & = 14 \\ & & 2x_1 & -4x_2 & \geq 2 \\ & & 4x_1 & +3x_2 & \leq 19 \\ & & & x_1, x_2 & \geq 0 \end{array}$$

- The corresponding dual linear program

$$\begin{array}{llrrrl} \text{maximize} & w = & 14y_1 & +2y_2 & +19y_3 & \\ \text{subject to} & & 3y_1 & +2y_2 & +4y_3 & \leq 2 \\ & & 2y_1 & -4y_2 & +3y_3 & \leq 3 \\ & & y_1 & & & \text{free}, \\ & & & y_2 & & \geq 0, \\ & & & & y_3 & \leq 0 \end{array}$$

Rules for constructing the dual program (p. 327)

maximization	$\Leftrightarrow$	minimization
dual program	$\Leftrightarrow$	primal program
primal program	$\Leftrightarrow$	dual program
constraints		*variables*
$\geq$	$\Leftrightarrow$	≤ 0
$\leq$	$\Leftrightarrow$	≥ 0
$=$	$\Leftrightarrow$	free
variables		*constraints*
≥ 0	$\Leftrightarrow$	$\geq$
≤ 0	$\Leftrightarrow$	$\leq$
free	$\Leftrightarrow$	$=$

The dual of the dual of any linear program equals the primal

Relations between primal and dual optimal solutions

primal (dual) problem	$\Longleftrightarrow$	dual (primal) problem
unique and non-degenerate solution	$\Longleftrightarrow$	unique and non-degenerate solution
unbounded solution	$\Longrightarrow$	no feasible solutions
no feasible solutions	$\Longrightarrow$	unbounded solution **or** no feasible solutions
degenerate solution	$\Longleftrightarrow$	alternative solutions

Duality properties (Ch. 7.5)

- **Weak duality**: Let $\mathbf{x}$ be a feasible point in the primal and $\mathbf{y}$ be a feasible point in the dual. Then,

$$z = \mathbf{c}^{\mathrm{T}}\mathbf{x} \geq \mathbf{b}^{\mathrm{T}}\mathbf{y} = w$$

- **Strong duality**: In a pair of primal and dual linear programs, if one of them has an optimal solution, so does the other, and their optimal values are equal.
- **Complementary slackness**: If $\mathbf{x}$ is optimal in the primal and $\mathbf{y}$ is optimal in the dual, then $\mathbf{x}^{\mathrm{T}}(\mathbf{c} - \mathbf{A}^{\mathrm{T}}\mathbf{y}) = \mathbf{y}^{\mathrm{T}}(\mathbf{b} - \mathbf{A}\mathbf{x}) = 0$.

  If $\mathbf{x}$ is feasible in the primal, $\mathbf{y}$ is feasible in the dual, and $\mathbf{x}^{\mathrm{T}}(\mathbf{c} - \mathbf{A}^{\mathrm{T}}\mathbf{y}) = \mathbf{y}^{\mathrm{T}}(\mathbf{b} - \mathbf{A}\mathbf{x}) = 0$, then $\mathbf{x}$ and $\mathbf{y}$ are optimal for their respective problems.

Exercises on duality

- Formulate and solve graphically the dual of:

$$\begin{array}{rlrrrl}
\text{minimize} & z = & 6x_1 & +3x_2 & +x_3 & \\
\text{subject to} & & 6x_1 & -3x_2 & +x_3 & \geq 2 \\
 & & 3x_1 & +4x_2 & +x_3 & \geq 5 \\
 & & & & x_1, x_2, x_3 & \geq 0
\end{array}$$

- Then find the optimal primal solution
- Verify that the dual of the dual equals the primal

Sensitivity analysis

- How does the optimum change when the right hand sides (resources, e.g.) change?
- When the objective coefficients (prices, e.g.) change?
- Assume that the basis B is optimal:

$$\begin{array}{ll} \text{maximize} & z = \mathbf{c}_B^{\mathrm{T}}\mathbf{B}^{-1}\mathbf{b} + [\mathbf{c}_N^{\mathrm{T}} - \mathbf{c}_B^{\mathrm{T}}\mathbf{B}^{-1}\mathbf{N}]\mathbf{x}_N \\ \text{subject to} & \mathbf{B}^{-1}\mathbf{b} - \mathbf{B}^{-1}\mathbf{N}\mathbf{x}_N \geq \mathbf{0}^m, \\ & \mathbf{x}_N \geq \mathbf{0}^{n-m} \end{array}$$

- $\mathbf{x}_B = \mathbf{B}^{-1}\mathbf{b} - \mathbf{B}^{-1}\mathbf{N}\mathbf{x}_N$

Changes in the right hand side coefficients

- Consider the linear program

$$\begin{array}{lrrrl} \text{minimize} & z = & -x_1 & -2x_2 & \\ \text{subject to} & & -2x_1 & +x_2 & \leq 2 \\ & & -x_1 & +2x_2 & \leq 7 \\ & & x_1 & & \leq 3 \\ & & & x_1, x_2 & \geq 0 \end{array}$$

DRAW GRAPH!!

- The optimal solution is given by

basis	$-z$	x_1	x_2	s_1	s_2	s_3	RHS
$-z$	1	0	0	0	1	2	13
x_2	0	0	1	0	$\frac{1}{2}$	$\frac{1}{2}$	5
x_1	0	1	0	0	0	1	3
s_1	0	0	0	1	$-\frac{1}{2}$	$\frac{3}{2}$	3

Changes in the right hand side coefficients

- Suppose $\mathbf{b}$ changes to $\mathbf{b} + \Delta\mathbf{b}$

⇒ New optimal value:

$$z^{\text{new}} = \mathbf{c}_B^{\mathrm{T}}\mathbf{B}^{-1}(\mathbf{b} + \Delta\mathbf{b}) = z + \mathbf{c}_B^{\mathrm{T}}\mathbf{B}^{-1}\Delta\mathbf{b}$$

- The current basis is feasible if $\mathbf{B}^{-1}(\mathbf{b} + \Delta\mathbf{b}) \geq 0$
- If not: negative values will occur in the right hand side
- The reduced costs are unchanged (negative, at optimum) ⇒ this can be resolved using the *dual simplex method*

Changes in the right hand side coefficients

- Change the right hand side according to

$$\begin{array}{lrrrl} \text{minimize} & z = & -x_1 & -2x_2 & \\ \text{subject to} & & -2x_1 & +x_2 & \leq 2 \\ & & -x_1 & +2x_2 & \leq 7 + \delta \\ & & x_1 & & \leq 3 \\ & & x_1, x_2 & \geq 0 & \end{array}$$

- The change in the right hand side is given by $\mathbf{B}^{-1}(0, \delta, 0)^{\mathrm{T}} = (\frac{1}{2}\delta, 0, -\frac{1}{2}\delta)^{\mathrm{T}} \Rightarrow$ new optimal tableau:

basis	$-z$	x_1	x_2	s_1	s_2	s_3	RHS
$-z$	1	0	0	0	1	2	$13 + \delta$
x_2	0	0	1	0	$\frac{1}{2}$	$\frac{1}{2}$	$5 + \frac{1}{2}\delta$
x_1	0	1	0	0	0	1	3
s_1	0	0	0	1	$-\frac{1}{2}$	$\frac{3}{2}$	$3 - \frac{1}{2}\delta$

- The current basis is feasible if $-10 \leq \delta \leq 6$

Changes in the right hand side coefficients

- Suppose $\delta = 8$:

basis	$-z$	x_1	x_2	s_1	s_2	s_3	RHS
$-z$	1	0	0	0	1	2	21
x_2	0	0	1	0	$\frac{1}{2}$	$\frac{1}{2}$	9
x_1	0	1	0	0	0	1	3
s_1	0	0	0	1	$-\frac{1}{2}$	$\frac{3}{2}$	-1

- Dual simplex iteration:
- $s_1 = -1$ has to leave the basis
- Find the smallest ratio between reduced costs (for non-basic columns) and (negative) elements in the "s_1-row" (to stay optimal)
- s_2 will enter the basis — **New optimal** tableau:

basis	$-z$	x_1	x_2	s_1	s_2	s_3	RHS
$-z$	1	0	0	2	0	5	19
x_2	0	0	1	1	0	2	8
x_1	0	1	0	0	0	1	3
s_2	0	0	0	-2	1	-3	2

Changes in the objective coefficients

- Change the objective according to

$$\begin{array}{lrrl} \text{minimize} & z = -x_1 & +(-2+\delta)x_2 & \\ \text{subject to} & -2x_1 & +x_2 & \le 2 \\ & -x_1 & +2x_2 & \le 7 \\ & x_1 & & \le 3 \\ & x_1, x_2 & & \ge 0 \end{array}$$

- The changes in the reduced costs are given by $-(\delta, 0, 0)\mathbf{B}^{-1}\mathbf{N} = (-\frac{1}{2}\delta, -\frac{1}{2}\delta) \Rightarrow$ new optimal tableau:

basis	$-z$	x_1	x_2	s_1	s_2	s_3	RHS
$-z$	1	0	0	0	$1-\frac{1}{2}\delta$	$2-\frac{1}{2}\delta$	$13-5\delta$
x_2	0	0	1	0	$\frac{1}{2}$	$\frac{1}{2}$	5
x_1	0	1	0	0	0	1	3
s_1	0	0	0	1	$-\frac{1}{2}$	$\frac{3}{2}$	3

- The current basis is optimal if $\delta \le 2$

Changes in the objective coefficients

- Suppose $\mathbf{c}$ changes to $\mathbf{c} + \Delta\mathbf{c}$
- The new optimal value:

$$z^{\text{new}} = (\mathbf{c}_B + \Delta\mathbf{c}_B)^{\mathrm{T}}\mathbf{B}^{-1}\mathbf{b} = z + \Delta\mathbf{c}_B^{\mathrm{T}}\mathbf{B}^{-1}\mathbf{b}$$

- The current basis is optimal if $(\mathbf{c}_N + \Delta\mathbf{c}_N)^{\mathrm{T}} - (\mathbf{c}_B + \Delta\mathbf{c}_B)^{\mathrm{T}}\mathbf{B}^{-1}\mathbf{N} \le \mathbf{0}$
- If not: more simplex iterations to find the optimal solution

Changes in the objective coefficients

- Suppose $\delta = 4$: new tableau:

basis	$-z$	x_1	x_2	s_1	s_2	s_3	RHS
$-z$	1	0	0	0	-1	0	-7
x_2	0	0	1	0	$\frac{1}{2}$	$\frac{1}{2}$	5
x_1	0	1	0	0	0	1	3
s_1	0	0	0	1	$-\frac{1}{2}$	$\frac{3}{2}$	3

- Let s_2 enter and x_2 leave the basis. New optimal tableau:

basis	$-z$	x_1	x_2	s_1	s_2	s_3	RHS
$-z$	1	0	2	0	0	1	3
s_2	0	0	2	0	1	1	10
x_1	0	1	0	0	0	1	3
s_1	0	0	1	1	0	2	8