

A low-poly 3D rendering of a yellow duck and a brown dog, possibly a Corgi, sitting on a light gray surface. The duck is on the left, facing right, and the dog is on the right, facing left. Both are composed of many flat, triangular polygons. A semi-transparent white rectangular box is centered over the image, containing text.

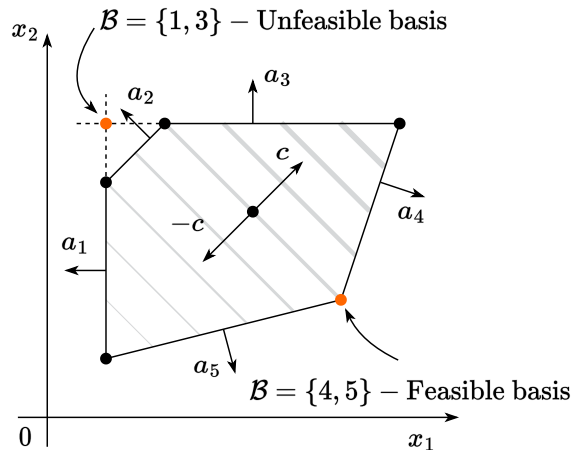
## Two-Phase Simplex Method. Duality in LP

**Daniil Merkulov**

Optimization methods. MIPT

## Simplex method

# Geometry of simplex method

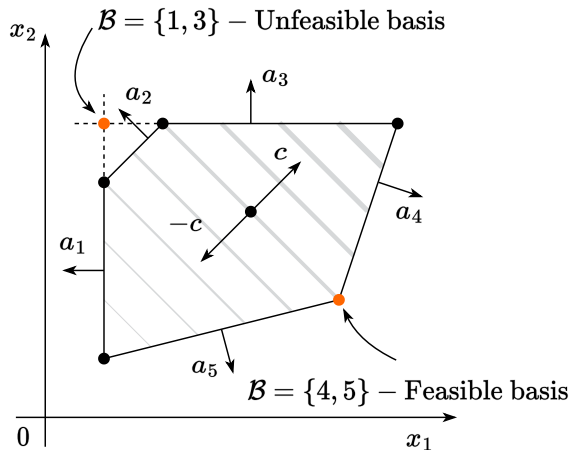


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$$\begin{aligned} \min_{x \in \mathbb{R}^n} \quad & c^\top x \\ \text{s.t.} \quad & Ax \leq b \end{aligned} \quad (\text{LP.Inequality})$$

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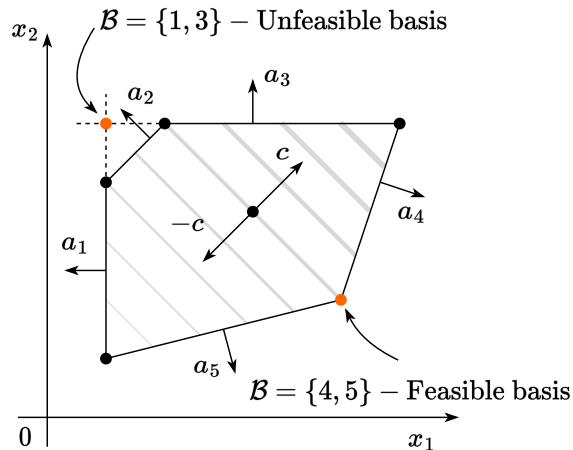


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- If  $Ax_{\mathcal{B}} \leq b$ , then basis  $\mathcal{B}$  is **feasible**.
- A basis  $\mathcal{B}$  is optimal if  $x_{\mathcal{B}}$  is an optimum of the LP.Inequality.

## The solution of LP if exists lies in the corner



### i Theorem

1. If Standard LP has a nonempty feasible region, then there is at least one basic feasible point

The high-level idea of the simplex method is following:



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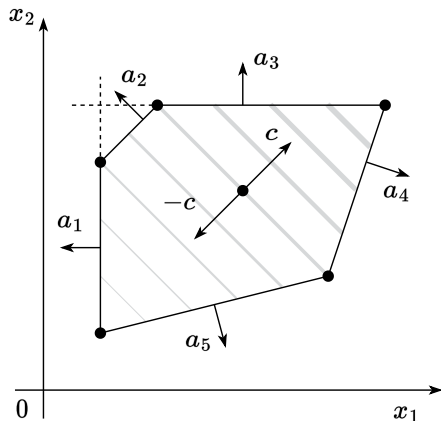


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The high-level idea of the simplex method is following:

- Ensure, that you are in the corner.
- Check optimality.
- If necessary, switch the corner (change the basis).
- Repeat until converge.

# Optimal basis



Since we have a basis, we can decompose our objective vector  $c$  in this basis and find the scalar coefficients  $\lambda_{\mathcal{B}}$ :

$$\lambda_{\mathcal{B}}^T A_{\mathcal{B}} = c^T \leftrightarrow \lambda_{\mathcal{B}}^T = c^T A_{\mathcal{B}}^{-1}$$

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If all components of  $\lambda_{\mathcal{B}}$  are non-positive and  $\mathcal{B}$  is feasible, then  $\mathcal{B}$  is optimal.

## Proof

$$\exists x^* : Ax^* \leq b, c^T x^* < c^T x_{\mathcal{B}}$$



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Suppose, some of the coefficients of  $\lambda_{\mathcal{B}}$  are positive. Then we need to go through the edge of the polytope to the new vertex (i.e., switch the basis)

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- Suppose, we have a basis  $B$ :  $\lambda_B^T = c^T A_B^{-1}$
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$$B' = B \setminus \{k\} \cup \{t\}$$

$$x_{B'} = x_B + \mu_t d = A_{B'}^{-1} b_{B'}$$

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- Note, that changing basis implies objective function decreasing

$$c^T x_{B'} = c^T (x_B + \mu_t d) = c^T x_B + \mu_t c^T d$$

## Finding an initial basic feasible solution

We aim to solve the following problem:

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The proposed algorithm requires an initial basic feasible solution and corresponding basis.

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We start by reformulating the problem:

$$\begin{aligned} \min_{y \in \mathbb{R}^n, z \in \mathbb{R}^n} \quad & c^\top (y - z) \\ \text{s.t.} \quad & Ay - Az \leq b \\ & y \geq 0, z \geq 0 \end{aligned} \tag{2}$$



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Given the solution of Problem 2 the solution of Problem 1 can be recovered and vice versa

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$$x = y - z \quad \Leftrightarrow \quad y_i = \max(x_i, 0), \quad z_i = \max(-x_i, 0)$$

Now we will try to formulate new LP problem, which solution will be basic feasible point for Problem 2. Which means, that we firstly run Simplex method for Phase-1 problem and run Phase-2 problem with known starting point. Note, that basic feasible solution for Phase-1 should be somehow easily established.

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**Proof:** trivial check.

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- Now we know, that if we can solve a Phase-1 problem then we will either find a starting point for the simplex method in the original method (if slacks are zero) or verify that the original problem was infeasible (if slacks are non-zero).

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- Now we know, that if we can solve a Phase-1 problem then we will either find a starting point for the simplex method in the original method (if slacks are zero) or verify that the original problem was infeasible (if slacks are non-zero).
- But how to solve Phase-1? It has basic feasible solution (the problem has  $2n + m$  variables and the point below ensures  $2n + m$  inequalities are satisfied as equalities (active).)

$$z = 0 \quad y = 0 \quad \xi_i = \max(0, -b_i)$$

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## Convergence of the Simplex method

## Unbounded budget set

In this case, all  $\mu_j$  will be negative.



# Degeneracy



One needs to handle degenerate corners carefully. If no degeneracy exists, one can guarantee a monotonic decrease of the objective function on each iteration.

# Exponential convergence



- A wide variety of applications could be formulated as linear programming.

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- Major breakthrough - Narendra Karmarkar's method for solving LP (1984) using interior point method.
- Interior point methods are the last word in this area. However, good implementations of simplex-based methods and interior point methods are similar for routine applications of linear programming.



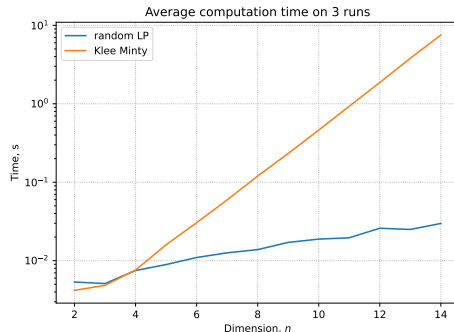
## Klee Minty example

Since the number of edge points is finite, the algorithm should converge (except for some degenerate cases, which are not covered here). However, the convergence could be exponentially slow, due to the high number of edges.

There is the following iconic example when the simplex method should perform exactly all vertexes.

In the following problem, the simplex method needs to check  $2^n - 1$  vertexes with  $x_0 = 0$ .

$$\begin{aligned} \max_{x \in \mathbb{R}^n} \quad & 2^{n-1}x_1 + 2^{n-2}x_2 + \dots + 2x_{n-1} + x_n \\ \text{s.t.} \quad & x_1 \leq 5 \\ & 4x_1 + x_2 \leq 25 \\ & 8x_1 + 4x_2 + x_3 \leq 125 \\ & \dots \\ & 2^n x_1 + 2^{n-1}x_2 + 2^{n-2}x_3 + \dots + x_n \leq 5^n \\ & x \geq 0 \end{aligned}$$



# Duality in Linear Programming

# Duality

Primal problem:

$$\begin{array}{ll} \min_{x \in \mathbb{R}^n} & c^\top x \\ \text{s.t.} & Ax = b \\ & x_i \geq 0, \ i = 1, \dots, n \end{array} \quad (3)$$

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KKT for optimal  $x^*, \nu^*, \lambda^*$ :

$$\begin{aligned} L(x, \nu, \lambda) &= c^\top x + \nu^\top (Ax - b) - \lambda^\top x \\ &\quad - A^\top \nu^* + \lambda^* = c \\ Ax^* &= b \\ x^* &\succeq 0 \\ \lambda^* &\succeq 0 \\ \lambda_i^* x_i^* &= 0 \end{aligned}$$

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Has the following dual:

$$(3) \quad \begin{aligned} \max_{\nu \in \mathbb{R}^m} \quad & -b^\top \nu \\ \text{s.t.} \quad & -A^\top \nu \preceq c \end{aligned} \quad (4)$$

Find the dual problem to the problem above (it should be the original LP). Also, write down KKT for the dual problem, to ensure, they are identical to the primal KKT.

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**PROOF.** For (i), suppose that Equation 3 has a finite optimal solution  $x^*$ . It follows from KKT that there are optimal vectors  $\lambda^*$  and  $\nu^*$  such that  $(x^*, \nu^*, \lambda^*)$  satisfies KKT. We noted above that KKT for Equation 3 and Equation 4 are equivalent. Moreover,  $c^T x^* = (-A^T \nu^* + \lambda^*)^T x^* = -(\nu^*)^T A x^* = -b^T \nu^*$ , as claimed.

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To prove (ii), suppose that the primal is unbounded, that is, there is a sequence of points  $x_k$ ,  $k = 1, 2, 3, \dots$  such that

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Suppose too that the dual Equation 4 is feasible, that is, there exists a vector  $\bar{\nu}$  such that  $-A^T \bar{\nu} \leq c$ . From the latter inequality together with  $x_k \geq 0$ , we have that  $-\bar{\nu}^T A x_k \leq c^T x_k$ , and therefore

$$-\bar{\nu}^T b = -\bar{\nu}^T A x_k \leq c^T x_k \downarrow -\infty,$$

yielding a contradiction. Hence, the dual must be infeasible. A similar argument can be used to show that the unboundedness of the dual implies the infeasibility of the primal.

## Max-flow min-cut

## Max-flow problem example



The nodes are routers, the edges are communications links; associated with each node is a capacity — node 1 can communicate to node 2 at as much as 6 Mbps, node 2 can communicate to node 4 at upto 2 Mbps, etc.

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### Capacity Matrix:

$$C = \begin{bmatrix} 0 & 6 & 0 & 0 & 6 & 0 \\ 0 & 0 & 2 & 2 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 & 7 \\ 0 & 0 & 0 & 0 & 0 & 3 \\ 0 & 0 & 0 & 5 & 0 & 2 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

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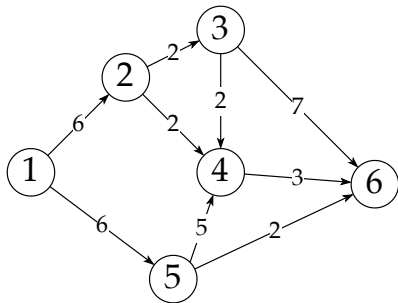
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### Constraints:

$$0 \preceq X \quad X \preceq C$$

$$\text{Flow Conservation: } \sum_{j=2}^N X(i, j) = \sum_{k=1}^{N-1} X(k, i), \quad i = 2, \dots, N-1$$

## Max-flow problem example



Given the setup, when everything, that is produced by source will go to the sink. the flow of the network, is simply the sum of everything coming out of the source:

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$$\text{maximize } \langle X, S \rangle$$

$$\text{s.t. } -X \preceq 0$$

$$X \preceq C$$

$$\langle X, L_n \rangle = 0, \quad n = 2, \dots, N-1,$$

(Max-Flow Problem)

$L_n$  consists of a single column ( $n$ ) of ones (except for the last row) minus a single row (also  $n$ ) of ones (except for the first column).

$$S = \begin{bmatrix} 0 & 1 & \dots & 1 \\ 0 & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 0 \end{bmatrix}, \quad L_2 = \begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & -1 & \dots & -1 \\ 0 & 1 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & 0 \end{bmatrix}.$$

# Deriving dual to the Max-flow

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$$\begin{aligned} & \text{minimize } \langle \Lambda, C \rangle \\ & \Lambda, \nu \\ \text{s.t. } & \Lambda + Q \succeq S \\ & \Lambda \succeq 0 \end{aligned} \quad (\text{Max-Flow Dual Problem})$$

where

$$Q = \begin{bmatrix} 0 & \nu_2 & \nu_3 & \cdots & \nu_{N-1} & 0 \\ 0 & 0 & \nu_3 - \nu_2 & \cdots & \nu_{N-1} - \nu_2 & -\nu_2 \\ 0 & \nu_2 - \nu_3 & 0 & \cdots & \nu_{N-1} - \nu_3 & -\nu_3 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & \nu_2 - \nu_{N-1} & \nu_3 - \nu_{N-1} & \cdots & 0 & -\nu_{N-1} \\ 0 & 0 & 0 & \cdots & 0 & 0 \end{bmatrix}.$$

## Min-cut problem example

A cut of the network separates the vertices into two sets: one containing the source (we call this set  $\mathcal{S}$ , and one containing the sink. The capacity of the cut is the total value of the edges coming out of  $\mathcal{S}$  — we are separating the sets by “cutting off the flow” along these edges.

$$\mathcal{S} = \{1, 4, 5\}$$



The edges in the cut are  $1 \rightarrow 2$ ,  $4 \rightarrow 6$ , and  $5 \rightarrow 6$  the capacity of this cut is  $6 + 3 + 2 = 11$ .

$$\mathcal{S} = \{1, 2, 4, 5\}$$



The edges in the cut are  $2 \rightarrow 3$ ,  $4 \rightarrow 6$ , and  $5 \rightarrow 6$  the capacity of this cut is  $2 + 3 + 2 = 7$ .



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What is the minimum value of the smallest cut? We will argue that it is same as the optimal value of the solution  $d^*$  of the dual program (Max-Flow Dual Problem).

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$$\nu_n = \begin{cases} 1, & n \in \mathcal{S}, \\ 0, & n \notin \mathcal{S}, \end{cases} \quad \text{and} \quad \lambda_{i,j} = \begin{cases} \max(\nu_i - \nu_j, 0), & i \neq 1, j \neq N, \\ 1 - \nu_j, & i = 1, \\ \nu_i, & j = N. \end{cases}$$

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Notice that these choices obey the constraints in the dual, and that  $\lambda_{i,j}$  will be 1 if  $i \rightarrow j$  is cut, and 0 otherwise, so

$$\text{capacity}(S) = \sum_{i,j} \lambda_{i,j} C_{i,j}.$$

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Every cut is feasible, so

$$d^* \leq \text{MINCUT}.$$

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Now we show that for every solution  $\nu^*, \lambda^*$  of the dual, there is a cut that has a capacity at most  $d^*$ . We generate a cut *at random*, and then show that the expected value of the capacity of the cut is less than  $d^*$  — this means there must be at least one with a capacity of  $d^*$  or less.

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Let  $Z$  be a uniform random variable on  $[0, 1]$ . Along with  $\lambda^*, \nu_2^*, \dots, \nu_{N-1}^*$  generated by solving (Max-Flow Dual Problem), take  $\nu_1 = 1$  and  $\nu_N = 0$ . Create a cut  $\mathcal{S}$  with the rule:

if  $\nu_n^* > Z$ , then take  $n \in \mathcal{S}$ .

. . . The probability that a particular edge  $i \rightarrow j$  is in this cut is

$$\begin{aligned} P(i \in \mathcal{S}, j \notin \mathcal{S}) &= P(\nu_j^* \leq Z \leq \nu_i^*) \\ &\leq \begin{cases} \max(\nu_i^* - \nu_j^*, 0), & 2 \leq i, j \leq N-1, \\ 1 - \nu_j^*, & i = 1; j = 2, \dots, N-1, \\ \nu_i^*, & i = 2, \dots, N-1; j = N, \\ 1, & i = 1; j = N. \end{cases} \\ &\leq \lambda_{i,j}^*, \end{aligned}$$

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The last inequality follows simply from the constraints in the dual program (Max-Flow Dual Problem). This cut is random, so its capacity is a random variable, and its expectation is

$$\begin{aligned}\mathbb{E}[\text{capacity}(\mathcal{S})] &= \sum_{i,j} C_{i,j} P(i \in \mathcal{S}, j \notin \mathcal{S}) \\ &\leq \sum_{i,j} C_{i,j} \lambda_{i,j}^* = d^*.\end{aligned}$$

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**i** Max-flow min-cut theorem.

The maximum value of an s-t flow is equal to the minimum capacity over all s-t cuts.

## Sensitivity analysis

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Let us switch from the original optimization problem

$$\begin{aligned} f_0(x) &\rightarrow \min_{x \in \mathbb{R}^n} \\ \text{s.t. } f_i(x) &\leq 0, \quad i = 1, \dots, m \\ h_i(x) &= 0, \quad i = 1, \dots, p \end{aligned} \quad (\text{P})$$

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Note, that we still have the only variable  $x \in \mathbb{R}^n$ , while treating  $u \in \mathbb{R}^m, v \in \mathbb{R}^p$  as parameters. It is obvious, that  $\text{Per}(u, v) \rightarrow \text{P}$  if  $u = 0, v = 0$ . We will denote the optimal value of Per as  $p^*(u, v)$ , while the optimal value of the original problem P is just  $p^*$ . One can immediately say, that  $p^*(u, v) = p^*$ .

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Speaking of the value of some  $i$ -th constraint we can say, that

- $u_i = 0$  leaves the original problem

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Speaking of the value of some  $i$ -th constraint we can say, that

- $u_i = 0$  leaves the original problem
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Let us switch from the original optimization problem

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One can even show, that when  $\text{P}$  is convex optimization problem,  $p^*(u, v)$  is a convex function.

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Suppose, that strong duality holds for the original problem and suppose, that  $x$  is any feasible point for the perturbed problem:

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And taking the optimal  $x$  for the perturbed problem, we have:

$$p^*(u, v) \geq p^*(0, 0) - \lambda^{*T} u - \nu^{*T} v \quad (5)$$

## Sensitivity analysis

In scenarios where strong duality holds, we can draw several insights about the sensitivity of optimal solutions in relation to the Lagrange multipliers. These insights are derived from the inequality expressed in equation above:

- **Impact of Tightening a Constraint (Large  $\lambda_i^*$ ):**

When the  $i$ th constraint's Lagrange multiplier,  $\lambda_i^*$ , holds a substantial value, and if this constraint is tightened (choosing  $u_i < 0$ ), there is a guarantee that the optimal value, denoted by  $p^*(u, v)$ , will significantly increase.

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These interpretations provide a framework for understanding how changes in constraints, reflected through their corresponding Lagrange multipliers, impact the optimal solution in problems where strong duality holds.

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The same idea can be used to establish the fact about  $v_i$ .

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The same idea can be used to establish the fact about  $v_i$ . The local sensitivity result Equation 6 provides a way to understand the impact of constraints on the optimal solution  $x^*$  of an optimization problem. If a constraint  $f_i(x^*)$  is negative at  $x^*$ , it's not affecting the optimal solution, meaning small changes to this constraint won't alter the optimal value. In this case, the corresponding optimal Lagrange multiplier will be zero, as per the principle of complementary slackness.

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Suppose now that  $p^*(u, v)$  is differentiable at  $u = 0, v = 0$ .

$$\lambda_i^* = -\frac{\partial p^*(0, 0)}{\partial u_i} \quad \nu_i^* = -\frac{\partial p^*(0, 0)}{\partial v_i} \quad (6)$$

To show this result we consider the directional derivative of  $p^*(u, v)$  along the direction of some  $i$ -th basis vector  $e_i$ :

$$\lim_{t \rightarrow 0} \frac{p^*(te_i, 0) - p^*(0, 0)}{t} = \frac{\partial p^*(0, 0)}{\partial u_i}$$

From the inequality Equation 5 and taking the limit  $t \rightarrow 0$  with  $t > 0$  we have

$$\frac{p^*(te_i, 0) - p^*}{t} \geq -\lambda_i^* \rightarrow \frac{\partial p^*(0, 0)}{\partial u_i} \geq -\lambda_i^*$$

For the negative  $t < 0$  we have:

$$\frac{p^*(te_i, 0) - p^*}{t} \leq -\lambda_i^* \rightarrow \frac{\partial p^*(0, 0)}{\partial u_i} \leq -\lambda_i^*$$

The same idea can be used to establish the fact about  $v_i$ . The local sensitivity result Equation 6 provides a way to understand the impact of constraints on the optimal solution  $x^*$  of an optimization problem. If a constraint  $f_i(x^*)$  is negative at  $x^*$ , it's not affecting the optimal solution, meaning small changes to this constraint won't alter the optimal value. In this case, the corresponding optimal Lagrange multiplier will be zero, as per the principle of complementary slackness.

However, if  $f_i(x^*) = 0$ , meaning the constraint is precisely met at the optimum, then the situation is different. The value of the  $i$ -th optimal Lagrange multiplier,  $\lambda_i^*$ , gives us insight into how 'sensitive' or 'active' this constraint is. A small  $\lambda_i^*$  indicates that slight adjustments to the constraint won't significantly affect the optimal value. Conversely, a large  $\lambda_i^*$  implies that even minor changes to the constraint can have a significant impact on the optimal solution.

# Mixed Integer Programming



## Complexity of MIP

Consider the following Mixed Integer Programming (MIP):

$$\begin{aligned} z = 8x_1 + 11x_2 + 6x_3 + 4x_4 &\rightarrow \max_{x_1, x_2, x_3, x_4} \\ \text{s.t. } 5x_1 + 7x_2 + 4x_3 + 3x_4 &\leq 14 \\ x_i &\in \{0, 1\} \quad \forall i \end{aligned} \quad (7)$$

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Optimal solution

$$x_1 = 0, x_2 = x_3 = x_4 = 1, \text{ and } z = 21.$$

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- General MIP is NP-hard.
- However, if the coefficient matrix of an MIP is a *totally unimodular matrix*, then it can be solved in polynomial time.

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# Hardware progress vs Software progress

What would you choose, assuming, that the question posed correctly (you can compile software for any hardware and the problem is the same for both options)? We will consider the time period from 1992 to 2023.

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Solving MIP with an old software on the modern hardware

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It turns out that if you need to solve a MILP, it is better to use an old computer and modern methods than vice versa, the newest computer and methods of the early 1990s!<sup>1</sup>

<sup>1</sup>

[R. Bixby report](#)

[Recent study](#)



# Sources

- Optimization Theory (MATH4230) course @ CUHK by Professor Tieyong Zeng