Linear Programming *

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Outline

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An Example : Profit Maximization

Suppose that a factory produces two products **1** and **2**, using resources **A**, **B**, and **C**, under following settings :

- We have 200 units of **A**, 300 units of **B**, and 400 units of **C**.
- Making a unit of product **1** requires a unit of **A** and **C**.
- Making a unit of product **2** requires a unit of **B** and **C**.
- The price for product **1** and **2** are respectively 1 and 6.

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The factory aims to achieve the **maximum** profit, so how many units of product **1** and **2** the factory should produce ?

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According to the settings, we have

- 200 units **A**, one for each product **1** : $x_1 \leq 200.$
- 300 units **B**, one for each product **2** : $x_2 \leq 300.$
- 400 units **C**, one for both **1** and **2** : $x_1 + x_2 \leq 400.$
- Nonnegative Production : $x_1, x_2 \geq 0.$

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- Nonnegative Production : $x_1, x_2 \geq 0.$

Maximizing Profits : $\max \quad f(x_1, x_2) = x_1 + 6x_2.$

Formulation of Linear Programming

$$\begin{aligned} \max \quad & f(x_1, x_2) = x_1 + 6x_2 \\ s.t. \quad & x_1 + x_2 \le 400, \\ & x_1 \le 200, \\ & x_2 \le 300, \\ & x_1, x_2 \ge 0. \end{aligned}$$

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Linear Programming (LP) :
Both objective function and constraints are linear.

Outline

Standard Form of LP

Given

- n real numbers $c_1, c_2, \cdots, c_n$;
- m real numbers $b_1, b_2, \cdots, b_m$;
- $m \times n$ real numbers $\{a_{ij}\}_{i=1,2,\cdots,m;\ j=1,2,\cdots,n}$.

We wish to find n real numbers $x_1, x_2, \cdots, x_n$ such that

$$\begin{aligned} \max \quad & \sum_{j=1}^{n} c_j x_j \\ s.t. \quad & \sum_{j=1}^{n} a_{ij} x_j \le b_i, \quad i = 1, 2, \cdots, m \\ & x_j \ge 0. \quad j = 1, 2, \cdots, n \end{aligned}$$

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Example :

$$
\begin{aligned}
\min \quad & -2x_1 + 3x_2 \\
s.t. \quad & x_1 + x_2 = 7, \\
& x_1 - 2x_2 \leq 4, \\
& x_1 \geq 0.
\end{aligned}
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However, we can equivalently transform different LP variants to the standard form.

Transformation to Standard Form

1. From min **to** max **:**

$$\min \quad \sum_{j=1}^{n} c_j x_j \quad \Rightarrow \quad \max \quad -\sum_{j=1}^{n} c_j x_j$$

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Transformation to Standard Form

2. Equality Constraint :

$$\sum_{j=1}^{n} a_{ij}x_j = b_i \quad \Rightarrow \quad \begin{cases} \sum_{j=1}^{n} a_{ij}x_j \leq b_i \\ \sum_{j=1}^{n} a_{ij}x_j \geq b_i \end{cases}$$

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3. Inequality Constraint with $\geq$:

$$\sum_{j=1}^{n} a_{ij}x_j \geq b_i \quad \Rightarrow \quad -\sum_{j=1}^{n} a_{ij}x_j \leq -b_i$$

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\max \quad & 2x_1 - 3x_2 \\
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4. Variables without Constraints :

x_2 is without constraints. $\Rightarrow$ Introducing x_2^+ and x_2^-

$$x_2 = x_2^+ - x_2^-, x_2^+, x_2^- \geq 0.$$

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Standard Form

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Key : Introducing slack variables : s_i

$$\sum_{j=1}^{n} a_{ij}x_j \leq b_i \quad \Rightarrow \quad \sum_{j=1}^{n} a_{ij}x_j + s_i = b_i, s_i \geq 0$$

Slack Form of LP

Example : Profit Maximization

$$\begin{aligned} \max \quad & x_1 + 6x_2 \\ s.t. \quad x_1 + x_2 & \leq 400, \\ x_1 & \leq 200, \\ x_2 & \leq 300, \\ x_1, x_2 & \geq 0. \end{aligned}$$

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\end{aligned}
\quad \Rightarrow \quad
\begin{aligned}
\max \quad & x_1 + 6x_2 \\
s.t. \quad & x_1 + x_2 + x_3 = 400, \\
& x_1 + x_4 = 200, \\
& x_2 + x_5 = 300, \\
& x_1, x_2, x_3, x_4, x_5 \ge 0.
\end{aligned}
$$

x_3, x_4, x_5 are slack variables.

Slack Form of LP

We can use a tuple $(N, B, \mathbf{A}, \mathbf{b}, \mathbf{c}, v)$ to represent a slack form.

- N : Nonbasic Variable Set. $\{x_1, x_2\}$
- B : Basic Variable Set. $\{x_3, x_4, x_5\}$
- $\mathbf{A}$, $\mathbf{b}$, $\mathbf{c}$: Constant Terms and Coefficients.
- v : Optional Constant Term in Objective Function.

$$\mathbf{A} = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{b} = \begin{bmatrix} 400 & 200 & 300 \end{bmatrix}^T$$

$$\mathbf{c} = \begin{bmatrix} 1 & 6 \end{bmatrix}^T$$

Matrix-Vector Form of LP

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If we create

- an $m \times n$ matrix $\mathbf{A} = (a_{ij})_{m \times n}$;
- an m vector $\mathbf{b} = (b_1, b_2, \cdots, b_m)^T$;
- an n vector $\mathbf{c} = (c_1, c_2, \cdots, c_n)^T$;
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- an n vector $\mathbf{x} = (x_1, x_2, \cdots, x_n)^T$,

then we can equivalently transform the standard form as

$$
\begin{array}{ll}
\max & \displaystyle\sum_{j=1}^{n} c_j x_j \\
s.t. & \displaystyle\sum_{j=1}^{n} a_{ij} x_j \le b_i, \quad i = 1, 2, \cdots, m \\
 & x_j \ge 0. \quad j = 1, 2, \cdots, n
\end{array}
\quad \Rightarrow \quad
\begin{array}{ll}
\max & \mathbf{c}^T \mathbf{x} \\
s.t. & \mathbf{A}\mathbf{x} \le \mathbf{b}, \\
 & \mathbf{x} \ge \mathbf{0}.
\end{array}
$$

Outline

General Form of Programming

The general form of a programming is

$$
\begin{aligned}
\max \quad & f(\mathbf{x}) \\
s.t. \quad & g_i(\mathbf{x}) \leq 0, \quad i = 1, 2, \cdots, m \\
& h_i(\mathbf{x}) = 0. \quad i = m+1, m+2, \cdots, n
\end{aligned}
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\end{aligned}
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Linear Programming should satisfy that $f(\mathbf{x})$, $\{g_i(\mathbf{x})\}$, $\{h_i(\mathbf{x})\}$ are all linear functions.

Classification of Programming

$$
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We can classify programming as

- $\begin{cases} \text{Programming } \textbf{with} \text{ constraints ; (We only study this.)} \\ \text{Programming } \textbf{without} \text{ constraints.} \end{cases}$

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- $\begin{cases} \textbf{Linear} \text{ programming ;} \\ \textbf{Nonlinear} \text{ programming. (including quadratic)} \end{cases}$

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We can classify programming as

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- $\begin{cases} \textbf{Linear} \text{ programming ;} \\ \textbf{Nonlinear} \text{ programming. (including quadratic)} \end{cases}$
- $\begin{cases} \textbf{Single}\text{-objective programming ; (We only study this.)} \\ \textbf{Multiple}\text{-objective programming.} \end{cases}$
- $\cdots$

Integer Linear Programming (ILP)

ILP is an LP problem with an additional constraint that variables $\mathbf{x} = (x_1, x_2, \cdots, x_n)$ must take on integral values.

$$
\begin{aligned}
\max \quad & \sum_{j=1}^{n} c_j x_j \\
s.t. \quad & \sum_{j=1}^{n} a_{ij} x_j \leq b_i, \quad i = 1, 2, \cdots, m \\
& x_j \in \mathbb{Z}. \quad j = 1, 2, \cdots, n.
\end{aligned}
$$

Examples : the amount of products, people, data packets,...

Note : ILP is an **NP** problem, which no efficient algorithms can solve *directly*.

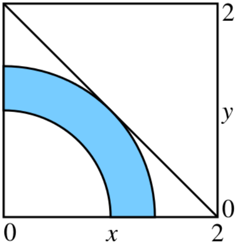
Nonlinear Programming

Nonlinear Programming : At least one of f_i, g_i, and h_i is nonlinear.

$$
\begin{aligned}
\max \quad & f(\mathbf{x}) \\
s.t. \quad & g_i(\mathbf{x}) \leq 0, \quad i = 1, 2, \cdots, m \\
& h_i(\mathbf{x}) = 0. \quad i = m+1, m+2, \cdots, n.
\end{aligned}
$$

Example :

$$
\begin{aligned}
\max \quad & x + y \\
s.t. \quad & x^2 + y^2 \geq 1, \\
& x^2 + y^2 \leq 2, \\
& x, y \geq 0.
\end{aligned}
$$



Quadratic Programming

Quadratic Programming (QP) is a special case of nonlinear programming in the form of

$$\begin{aligned} \max \quad & \frac{1}{2}\mathbf{x}^T\mathbf{Q}\mathbf{x} + \mathbf{c}^T\mathbf{x} \\ s.t. \quad & \mathbf{A}\mathbf{x} \leq \mathbf{b} \end{aligned}$$

where

- $\mathbf{Q}$: an $n \times n$ real symmetric matrix ;
- $\mathbf{c}$: an n vector ;
- $\mathbf{A}$: an $m \times n$ real matrix ;
- $\mathbf{b}$: an m vector.

Brief History of LP

- First formal application to problems in economics by Leonid Kantorovich in the 1930s, however the work was ignored ;
- Rediscovered by Tjalling Koopmans in the 1940s, along with applications to economics ;
- First algorithm (Simplex Algorithm) to solve linear programs by George Dantzig in 1947 ;
- Kantorovich and Koopmans receive Nobel Prize for economics in 1975 ; Dantzig, however, was ignored.
- LP was first shown to be solvable in polynomial time via Ellipsoid Method by Leonid Khachiyan in 1979, but a larger breakthrough came in 1984 when Narendra Karmarkar introduced a novel Interior-Point Method to solve LP.

Outline

Duality

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Try to find the optimum.

(x_1, x_2)	$f(x_1, x_2)$
$(100, 200)$	1300
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$(\mathbf{100}, \mathbf{300})$	**1900**

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$(\mathbf{100}, \mathbf{300})$	**1900**

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Duality enables us to prove that a solution is indeed optimal.

Intuitive Way to Show Optimality

Whether $(100, 300)$ is optimal ? (The objective value is 1900)

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When $(y_1, y_2, y_3) = (0, 1, 6)$, $x_1 + 6x_2 \leq 2000$;

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y_1	$x_1 + x_2 \leq 400$
y_2	$x_1 \leq 200$
y_3	$x_2 \leq 300$

When $(y_1, y_2, y_3) = (0, 1, 6)$, $x_1 + 6x_2 \leq 2000$;
When $(y_1, y_2, y_3) = (1, 0, 5)$, $x_1 + 6x_2 \leq 1900$! Optimal !

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Whether $(100, 300)$ is optimal ? (The objective value is 1900)

Upper bounding $x_1 + 6x_2$ by linearly combining constraints.

$$\begin{aligned} \max \quad & x_1 + 6x_2 \\ s.t. \quad & x_1 + x_2 \leq 400, \\ & x_1 \leq 200, \\ & x_2 \leq 300, \\ & x_1, x_2 \geq 0. \end{aligned}$$

Multiplier	Constraint
y_1	$x_1 + x_2 \leq 400$
y_2	$x_1 \leq 200$
y_3	$x_2 \leq 300$

When $(y_1, y_2, y_3) = (0, 1, 6)$, $x_1 + 6x_2 \leq 2000$;
When $(y_1, y_2, y_3) = (1, 0, 5)$, $x_1 + 6x_2 \leq 1900$! Optimal !

However, it is only a coincidence...

Rational Way to Show Optimality

$(y_1, y_2, y_3) = (1, 0, 5)$ serves as a certificate of the optimality, but how can we find it rationally ?

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y_1	$x_1 + x_2 \leq 400$
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y_3	$x_2 \leq 300$

Multiply horizontally and add vertically, we obtain

$(y_1 + y_2)x_1 + (y_1 + y_3)x_2 \leq 400y_1 + 200y_2 + 300y_3.$

$y_1, y_2, y_3 \geq 0$ to ensure no flipping from $\leq$ to $\geq$ in constraints.

Rational Way to Show Optimality

$$(y_1 + y_2)x_1 + (y_1 + y_3)x_2 \leq 400y_1 + 200y_2 + 300y_3$$

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We want the left-hand side to look like our objective function $x_1 + 6x_2$, so that the right-hand side becomes an upper bound on the objective function.

$$x_1 + 6x_2 \leq 400y_1 + 200y_2 + 300y_3 \text{ if } \left\{ \begin{array}{c} y_1, y_2, y_3 \geq 0 \\ y_1 + y_2 \geq 1 \\ y_1 + y_3 \geq 6 \end{array} \right\}$$

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We should minimize $400y_1 + 200y_2 + 300y_3$ to get the tightest upper bound of $x_1 + 6x_2$. A new LP problem !

Dual LP

The new LP problem :

$$\begin{aligned} \min \quad & 400y_1 + 200y_2 + 300y_3 \\ s.t. \quad & y_1 + y_2 \geq 1, \\ & y_1 + y_3 \geq 6, \\ & y_1, y_2, y_3 \geq 0. \end{aligned}$$

We call it the dual form of the original LP problem.

Primal and Dual Form

Correspondingly, we call the original LP problem as primal form.

$$
\begin{aligned}
\max \quad & x_1 + 6x_2 \\
s.t. \quad & x_1 + x_2 \leq 400, \\
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Primal Form | Dual Form

Primal and Dual Form

Generally we have the primal and dual form of LP as

$$
\begin{aligned}
\max \quad & \sum_{j=1}^{n} c_j x_j \\
s.t. \quad & \sum_{j=1}^{n} a_{ij} x_j \leq b_i, \quad \forall i \\
& x_j \geq 0. \quad \forall j
\end{aligned}
\quad \Rightarrow \quad
\begin{aligned}
\min \quad & \sum_{i=1}^{m} b_i y_i \\
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\end{aligned}
$$

It is obvious that the dual of dual form is the primal form.

Matrix-Vector Form

More generally, we can write primal and dual form in matrices and vectors.

$$
\begin{aligned}
\max \quad & \mathbf{c}^T\mathbf{x} \\
s.t. \quad & \mathbf{A}\mathbf{x} \leq \mathbf{b}, \\
& \mathbf{x} \geq \mathbf{0}.
\end{aligned}
\qquad \Rightarrow \qquad
\begin{aligned}
\min \quad & \mathbf{y}^T\mathbf{b} \\
s.t. \quad & \mathbf{y}^T\mathbf{A} \geq \mathbf{c}^T, \\
& \mathbf{y} \geq \mathbf{0}.
\end{aligned}
$$

Primal Form Dual Form

Outline

Observations of Duality

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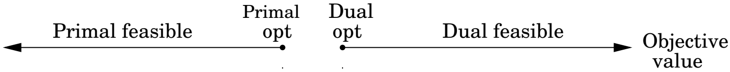
If we find a pair of primal and dual feasible objective values that are equal, then they must both be optimal.

One such pair, making the objective value both 1900, is :

Primal : $(x_1, x_2) = (100, 300)$; Dual : $(y_1, y_2, y_3) = (1, 0, 5)$.

Duality Theorem



Theorem (Weak Duality Theorem)

Let x be any feasible solution to the primal LP, and let y be any feasible solution to its dual LP. Then $\sum_{j=1}^{n} c_j x_j \leq \sum_{i=1}^{m} b_i y_i$.

Theorem (Strong Duality Theorem)

x and y are optimal solutions to primal and dual LPs respectively if and only if $\sum_{j=1}^{n} c_j x_j = \sum_{i=1}^{m} b_i y_i$.

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Proof.

$$\sum_{j=1}^{n} c_j x_j \le \sum_{j=1}^{n} \left(\sum_{i=1}^{m} a_{ij} y_i\right) x_j = \sum_{i=1}^{m} \left(\sum_{j=1}^{n} a_{ij} x_j\right) y_i \le \sum_{i=1}^{m} b_i y_i.$$

Proof of Strong Duality Theorem

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"$\Leftarrow$" : By **Weak Duality Theorem,** $\sum_{j=1}^{n} c_j x_j \leq \sum_{i=1}^{m} b_i y_i$. The primal LP is a maximization problem and the dual LP is a minimization problem. Thus, if feasible solutions x and y have the same objective value, neither can be improved.

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"$\Rightarrow$" : It involves using Simplex Method, which contains complex mathematical derivations. We omit here.

Outline

Recall : Profit Maximization–2D Case

Products : **1**, **2** ;

Resources : **A**, **B**, **C**.

- 200 **A** ; 300 **B** ; 400 **C**.
- Product **1** = 1**A** + 1**C**.
- Product **2** = 1**B** + 1**C**.
- Price(**1**)=1, Price(**2**)=6.

Goal : Maximum profit.

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Optimal Solution :

$$(x_1, x_2) = (100, 300)$$

2D Case : Where is the Optimum ?

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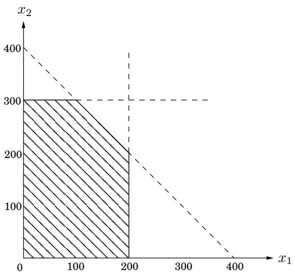

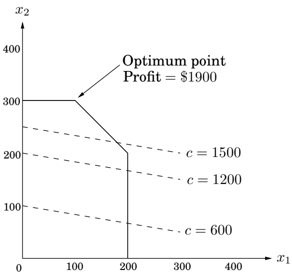

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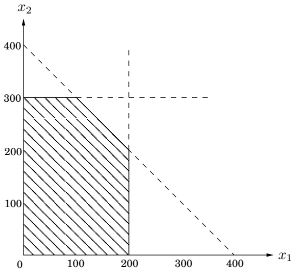

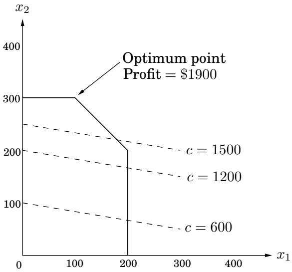

On the Vertex !

3D Case

Problem :

$$\begin{aligned} \max \quad & x_1 + 6x_2 + 13x_3 \\ s.t. \quad & x_1 + x_2 + x_3 \leq 400, \\ & x_2 + 3x_3 \leq 600, \\ & x_1 \leq 200, \\ & x_2 \leq 300, \\ & x_1, x_2, x_3 \geq 0. \end{aligned}$$

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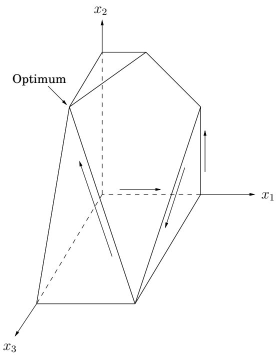
Feasible Region :



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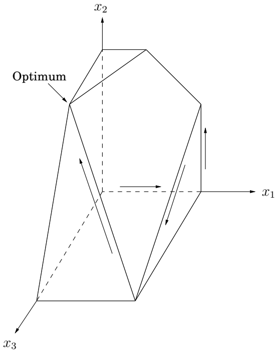
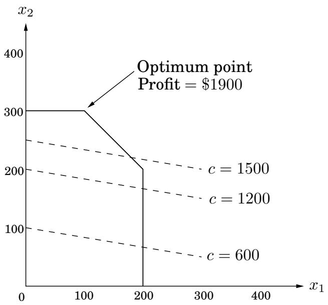
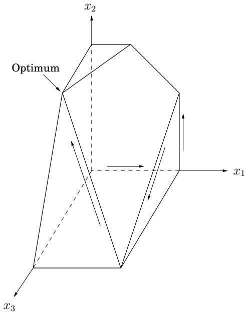


On the Vertex !

How to Find Optimum ?

Based on 2D and 3D situation, how can we find optimum of LP ?





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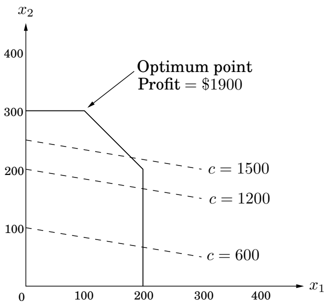

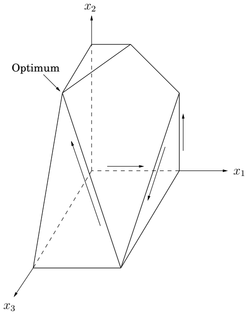

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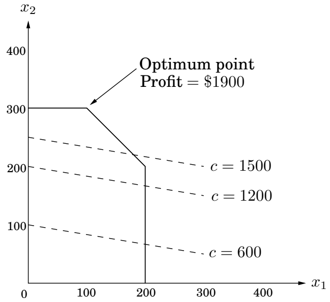

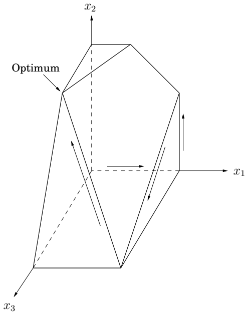

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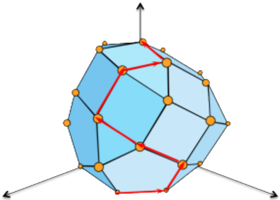
Simplex Algorithm : For LP with arbitrary n variables.

General Description of Simplex Algorithm



Definitions :

- Linear constraints form the boundary as a polyhedron, consisting of hyperplanes.

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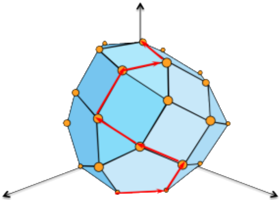

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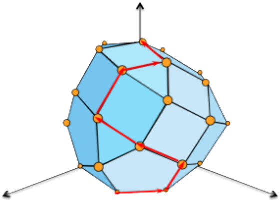

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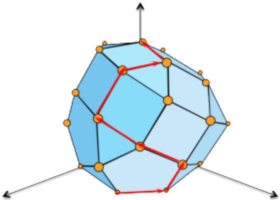

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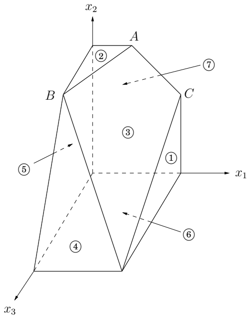
- Vertex is the point at which some hyperplanes meet.
- Two vertices are neighbors if they are adjacent on the polyhedron.

Observation : The optimal solution of LP exists on the vertex of the feasible region.

General Description of Simplex Algorithm

Example :

- A polyhedron defined by 7 inequalities (thus 7 hyperplanes).
- Vertices : A, B, C,...
- Neighbors : $\{A, B\}$, $\{A, C\}$,...



$$
\begin{array}{llr}
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s.t. & x_1 \leq 200, & ① \\
 & x_2 \leq 300, & ② \\
 & x_1 + x_2 + x_3 \leq 400, & ③ \\
 & x_2 + 3x_3 \leq 600, & ④ \\
 & x_1 \geq 0, & ⑤ \\
 & x_2 \geq 0, & ⑥ \\
 & x_3 \geq 0. & ⑦
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On each iteration, the Simplex Algorithm will do :

- Check whether the current vertex is optimal (if so, halt).
- Determine where to move next. → The one contributes to the increase of objective function.

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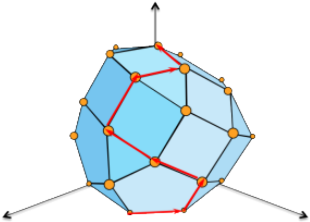
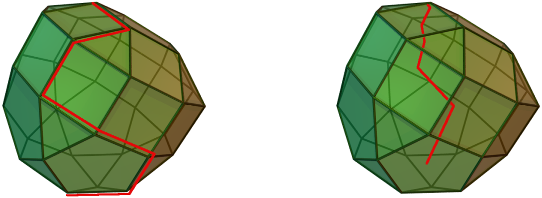
Initial Idea :

- Start at a vertex.
- Compare objective value with the neighbors.
- Move to neighbor that improves objective function, and repeat step 2.
- If no improving neighbor, stop.



Brief Overview of Algorithms for LP

- Simplex Algorithm
  - Efficient in practice, but exponential in worst case.
- Interior Point Algorithms
  - Ellipsoid Algorithm $O(n^4L)$ †
  - Karmarkar's Algorithm $O(n^{3.5}L)$
  - Path-Following Method (Barrier Function Method)



Simplex (Boundary) Interior Point (Inside)

† L is bit length.

Outline

An Introductory Example

How to perform simplex algorithm on a specific LP problem ?

Example : Profit Maximization

$$\begin{aligned}
\max \quad & f(x_1, x_2) = x_1 + 6x_2 \\
s.t. \quad & x_1 + x_2 \leq 400, \\
& x_1 \leq 200, \\
& x_2 \leq 300, \\
& x_1, x_2 \geq 0.
\end{aligned}$$

An Introductory Example

Step 1 : Converting LP into slack form

$$\begin{aligned} \max \quad & x_1 + 6x_2 \\ s.t. \quad & x_1 + x_2 \leq 400, \\ & x_1 \leq 200, \\ & x_2 \leq 300, \\ & x_1, x_2 \geq 0. \end{aligned} \qquad \Rightarrow$$

An Introductory Example

Step 1 : Converting LP into slack form

$$
\begin{array}{ll}
\max & x_1 + 6x_2 \\
s.t. & x_1 + x_2 \le 400, \\
& x_1 \le 200, \\
& x_2 \le 300, \\
& x_1, x_2 \ge 0.
\end{array}
\quad \Rightarrow \quad
\begin{array}{ll}
\max & x_1 + 6x_2 \\
s.t. & 400 - x_1 - x_2 = x_3, \\
& 200 - x_1 = x_4, \\
& 300 - x_2 = x_5, \\
& x_1, x_2, x_3, x_4, x_5 \ge 0.
\end{array}
$$

x_3, x_4, x_5 are slack variables.

An Introductory Example

Step 2 : Obtaining Basic Solution

$$
\begin{aligned}
\max \quad & x_1 + 6x_2 \\
s.t. \quad & 400 - x_1 - x_2 = x_3, \\
& 200 - x_1 = x_4, \\
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An Introductory Example

Step 2 : Obtaining Basic Solution

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Define :

- nonbasic variables : x_1, x_2 (in the objective)
- basic variables : x_3, x_4, x_5 (others in the constraints)

An Introductory Example

Step 2 : Obtaining Basic Solution

$$\begin{aligned} \max \quad & x_1 + 6x_2 \\ s.t. \quad & 400 - x_1 - x_2 = x_3, \\ & 200 - x_1 = x_4, \\ & 300 - x_2 = x_5, \\ & x_1, x_2, x_3, x_4, x_5 \geq 0. \end{aligned}$$

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- nonbasic variables : x_1, x_2 (in the objective)
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There are infinite number of feasible solutions for $x_1, \cdots, x_5$. The basic solution is obtained by setting all nonbasic variables to be 0.

An Introductory Example

Step 2 : Obtaining Basic Solution

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\begin{aligned}
\max \quad & x_1 + 6x_2 \\
s.t. \quad & 400 - x_1 - x_2 = x_3, \\
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Define :

- nonbasic variables : x_1, x_2 (in the objective)
- basic variables : x_3, x_4, x_5 (others in the constraints)

There are infinite number of feasible solutions for $x_1, \cdots, x_5$. The basic solution is obtained by setting all nonbasic variables to be 0.

In this example, the basic solution is

$$\bar{x} = (\bar{x}_1, \bar{x}_2, \cdots, \bar{x}_5) = (0, 0, 400, 200, 300)$$

An Introductory Example

Step 3 : Selecting Nonbasic Variable

Our goal, in each iteration, is to reformulate the linear program so that the basic solution gives a greater value of objective function.

An Introductory Example

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Currently for the basic solution $\bar{x} = (0, 0, 400, 200, 300)$, we have

$$f(\bar{x}_1, \bar{x}_2) = \bar{x}_1 + 6\bar{x}_2 = 0.$$

How to enhance $f(\bar{x}_1, \bar{x}_2)$?

An Introductory Example

Step 3 : Selecting Nonbasic Variable

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Currently for the basic solution $\bar{x} = (0, 0, 400, 200, 300)$, we have

$$f(\bar{x}_1, \bar{x}_2) = \bar{x}_1 + 6\bar{x}_2 = 0.$$

How to enhance $f(\bar{x}_1, \bar{x}_2)$?

- Select a nonbasic x_e with positive coefficient in $f(x_1, x_2)$;
- Increase the value of x_e without violating constraints.

An Introductory Example

Step 3 : Selecting Nonbasic Variable

$$
\begin{aligned}
\max \quad & x_1 + 6x_2 \\
s.t. \quad & 400 - x_1 - x_2 = x_3, \\
& 200 - x_1 = x_4, \\
& 300 - x_2 = x_5, \\
& x_1, x_2, x_3, x_4, x_5 \geq 0.
\end{aligned}
$$

An Introductory Example

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\begin{aligned}
\max \quad & x_1 + 6x_2 \\
s.t. \quad & 400 - x_1 - x_2 = x_3, \\
& 200 - x_1 = x_4, \\
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\end{aligned}
$$

$$\Downarrow$$

$$
\begin{aligned}
\max \quad & x_1 + 6x_2 \\
s.t. \quad & 400 - x_1 - x_2 = x_3, \\
& 200 - x_1 = x_4, \\
& 300 - {\color{red}x_5} = {\color{red}x_2}, \\
& x_1, x_2, x_3, x_4, x_5 \geq 0.
\end{aligned}
$$

An Introductory Example

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$$
\begin{aligned}
\max \quad & x_1 + 6x_2 \\
s.t. \quad & 400 - x_1 - x_2 = x_3, \\
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& x_1, x_2, x_3, x_4, x_5 \geq 0.
\end{aligned}
$$

- Choose the nonbasic variable x_2.

An Introductory Example

Step 3 : Selecting Nonbasic Variable

$$\begin{aligned} \max \quad & x_1 + 6x_2 \\ s.t. \quad & 400 - x_1 - x_2 = x_3, \\ & 200 - x_1 = x_4, \\ & 300 - x_2 = x_5, \\ & x_1, x_2, x_3, x_4, x_5 \geq 0. \end{aligned}$$

$$\Downarrow$$

$$\begin{aligned} \max \quad & x_1 + 6x_2 \\ s.t. \quad & 400 - x_1 - x_2 = x_3, \\ & 200 - x_1 = x_4, \\ & 300 - x_5 = x_2, \\ & x_1, x_2, x_3, x_4, x_5 \geq 0. \end{aligned}$$

- Choose the nonbasic variable x_2.
- When $x_2 \uparrow$, $x_3 \downarrow$ and $x_5 \downarrow$.
  However x_3 and x_5 should be nonnegative.
  - $x_3 \leq 0$ when $x_2 \geq 400$;
  - $x_5 \leq 0$ when $x_2 \geq 300$.

An Introductory Example

Step 3 : Selecting Nonbasic Variable

$$\begin{aligned} \max \quad & x_1 + 6x_2 \\ s.t. \quad & 400 - x_1 - x_2 = x_3, \\ & 200 - x_1 = x_4, \\ & 300 - x_2 = x_5, \\ & x_1, x_2, x_3, x_4, x_5 \geq 0. \end{aligned}$$

$$\Downarrow$$

$$\begin{aligned} \max \quad & x_1 + 6x_2 \\ s.t. \quad & 400 - x_1 - x_2 = x_3, \\ & 200 - x_1 = x_4, \\ & 300 - x_5 = x_2, \\ & x_1, x_2, x_3, x_4, x_5 \geq 0. \end{aligned}$$

- Choose the nonbasic variable x_2.
- When $x_2 \uparrow$, $x_3 \downarrow$ and $x_5 \downarrow$.

  However x_3 and x_5 should be nonnegative.
  - $x_3 \leq 0$ when $x_2 \geq 400$;
  - $x_5 \leq 0$ when $x_2 \geq 300$.
- $300 - x_2 = x_5$ is the tightest constraint for x_2.

  We transform it into $300 - x_5 = x_2$.

An Introductory Example

Step 4 : Pivoting

In **pivoting**, we exchange a nonbasic and a basic variable.

$$\begin{aligned} \max \quad & x_1 + 6x_2 \\ s.t. \quad & 400 - x_1 - x_2 = x_3, \\ & 200 - x_1 = x_4, \\ & 300 - x_2 = x_5, \\ & x_1, x_2, x_3, x_4, x_5 \geq 0. \end{aligned}$$

An Introductory Example

Step 4 : Pivoting

In **pivoting**, we exchange a nonbasic and a basic variable.

$$
\begin{array}{ll}
\max & x_1 + 6x_2 \\
s.t. & 400 - x_1 - x_2 = x_3, \\
& 200 - x_1 = x_4, \\
& 300 - x_2 = x_5, \\
& x_1, x_2, x_3, x_4, x_5 \geq 0.
\end{array}
\quad \Rightarrow \quad
\begin{array}{ll}
\max & x_1 + 6(300 - x_5) \\
s.t. & 100 - x_1 + x_5 = x_3, \\
& 200 - x_1 = x_4, \\
& 300 - x_5 = x_2, \\
& x_1, x_2, x_3, x_4, x_5 \geq 0.
\end{array}
$$

An Introductory Example

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\max & x_1 + 6x_2 \\
s.t. & 400 - x_1 - x_2 = x_3, \\
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& 300 - x_2 = x_5, \\
& x_1, x_2, x_3, x_4, x_5 \geq 0.
\end{array}
\quad \Rightarrow \quad
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\max & x_1 + 6(300 - x_5) \\
s.t. & 100 - x_1 + x_5 = x_3, \\
& 200 - x_1 = x_4, \\
& 300 - x_5 = x_2, \\
& x_1, x_2, x_3, x_4, x_5 \geq 0.
\end{array}
$$

$$
\bar{x} = \{0, 0, 400, 200, 300\} \quad \Rightarrow \quad \bar{x} = \{0, 300, 100, 200, 0\}.
$$

An Introductory Example

Step 4 : Pivoting

In **pivoting**, we exchange a nonbasic and a basic variable.

$$
\begin{array}{rr}
\max & x_1 + 6x_2 \\
s.t. & 400 - x_1 - x_2 = x_3, \\
 & 200 - x_1 = x_4, \\
 & 300 - x_2 = x_5, \\
 & x_1, x_2, x_3, x_4, x_5 \geq 0.
\end{array}
\quad \Rightarrow \quad
\begin{array}{rr}
\max & x_1 + 6(300 - x_5) \\
s.t. & 100 - x_1 + x_5 = x_3, \\
 & 200 - x_1 = x_4, \\
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\end{array}
$$

$$\bar{x} = \{0, 0, 400, 200, 300\} \quad \Rightarrow \quad \bar{x} = \{0, 300, 100, 200, 0\}.$$

- The nonbasic variables become x_1 and x_5.
- In next round we select a new nonbasic variable with positive coefficient. (x_1 in this example).

An Introductory Example

Step 5 : Repeat Step 2 to Step 4

- Repeat pivoting until all coefficients in the objective are negative.

An Introductory Example

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\max \quad & x_1 + 6(300 - x_5) \\
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& x_1, x_2, x_3, x_4, x_5 \geq 0.
\end{aligned}
\quad \Rightarrow \quad
\begin{aligned}
\max \quad & \boxed{1900 - x_3 - 5x_5} \\
s.t. \quad & 100 - x_3 + x_5 = x_1, \\
& 200 - x_1 = x_4, \\
& 300 - x_5 = x_2, \\
& x_1, x_2, x_3, x_4, x_5 \geq 0.
\end{aligned}
$$

An Introductory Example

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- Repeat pivoting until all coefficients in the objective are negative.

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\begin{array}{ll}
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\end{array}
\Rightarrow
\begin{array}{ll}
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 & 300 - x_5 = x_2, \\
 & x_1, x_2, x_3, x_4, x_5 \geq 0.
\end{array}
$$

$$\bar{x} = \{0, 300, 100, 200, 0\} \quad \Rightarrow \quad \bar{x} = \{100, 300, 0, 100, 0\}.$$

An Introductory Example

Step 5 : Repeat Step 2 to Step 4

- We can proved that when all coefficients are negative, the basic solution $\bar{x}$ is an optimal solution.

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$$

- The maximum of the objective function is 1900, when $x_3 = x_5 = 0$;

An Introductory Example

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- The maximum of the objective function is 1900, when $x_3 = x_5 = 0$;
- $\bar{x} = \{100, 300, 0, 100, 0\}$ is the optimal solution ;

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- The maximum of the objective function is 1900, when $x_3 = x_5 = 0$;
- $\bar{x} = \{100, 300, 0, 100, 0\}$ is the optimal solution ;

The optimal solution for original problem $f(x_1, x_2)$ is :

$$(x_1^*, x_2^*) = (100, 300)$$

Outline

Summarization and Further Topics

Summarization :

- Simplex Algorithm searches the optimal vertex on the boundary of feasible region ;
- Simplex Algorithm iteratively exchanges the nonbasic and basic variables until the objective function cannot be further enhanced.

Summarization and Further Topics

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- Simplex Algorithm searches the optimal vertex on the boundary of feasible region ;
- Simplex Algorithm iteratively exchanges the nonbasic and basic variables until the objective function cannot be further enhanced.

Further Topics :

- How to implement Simplex Algorithm ?
  - How to do the **pivoting** ?
  - How to find an initial **basic solution** ?
- Can Simplex Algorithm always find the optimal solution ?
- What will happen when the feasible region is unbounded ?

Please refer to Chapter 29.3 and 29.5 in “Introduction to Algorithms” (CLRS) for details.

Tools for Solving LP

Common Softwares and Toolboxes for solving LP :

MATLAB : Toolboxes

Mathematica : Toolboxes

Lingo : Large-scale LP (ILP)

Cplex : Large-scale ILP (Mixed ILP)

Gurobi : Similar to but better than Cplex synthetically.

Yalmip : Toolbox used by Matlab.