Linear Program Duality

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Motivation

- Finding bounds on the optimal solution. Provides a measure of the "goodness" of a solution.
- Provide certificate of optimality.
- Economic interpretation of the dual problem.

** Introduction to Duality **

Duality Theorem: introduction

$$
\begin{array}{lrcrcrcrcl}
\text{Maximize} & 4x_1 & + & x_2 & + & 5x_3 & + & 3x_4 & & \\
\text{Subject to :} & & & & & & & & & \\
 & x_1 & - & x_2 & - & x_3 & + & 3x_4 & \leq & 1 \\
 & 5x_1 & + & x_2 & + & 3x_3 & + & 8x_4 & \leq & 55 \\
 & -x_1 & + & 2x_2 & + & 3x_3 & - & 5x_4 & \leq & 3 \\
 & & & & & & & x_1, x_2, x_3, x_4 & \geq & 0.
\end{array}
$$

Lower bound: a feasible solution, e.g. $(0,0,1,0) \Rightarrow z^* \geq 5$.

What if we want an upper bound?

Duality Theorem: introduction

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\end{array}$$

Second Inequation $\times 5/3$:

$$\frac{25}{3}x_1 + \frac{5}{3}x_2 + 5x_3 + \frac{40}{3}x_4 \leq \frac{275}{3}.$$

Note that (all variables are positive),

$$4x_1 + x_2 + 5x_3 + 3x_4 \leq \frac{25}{3}x_1 + \frac{5}{3}x_2 + 5x_3 + \frac{40}{3}x_4$$

Hence, a first bound:

$$z^* \leq \frac{275}{3}.$$

Duality Theorem: introduction

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\end{array}
$$

Similarly, $2^d + 3^d$ constraints:

$$4x_1 + 3x_2 + 6x_3 + 3x_4 \leq 58.$$

Hence, a second bound:

$$z^* \leq 58.$$

$\longrightarrow$ need for a systematic strategy.

Duality Theorem: introduction

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\text{Maximize} & 4x_1 & + & x_2 & + & 5x_3 & + & 3x_4 & & \\
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& -x_1 & + & 2x_2 & + & 3x_3 & - & 5x_4 & \leq & 3 \qquad \boxed{\times y_3} \\
& & & & & & x_1, & x_2, x_3, x_4 & \geq & 0.
\end{array}$$

Build linear combinations of the constraints. Summing:

$$(y_1 + 5y_2 - y_3)x_1 + (-y_1 + y_2 + 2y_3)x_2 + (-y_1 + 3y_2 + 3y_3)x_3$$
$$+(3y_1 + 8y_2 - 5y_3)x_4 \leq y_1 + 55y_2 + 3y_3.$$

We want left part upper bound of z. We need coefficient of $x_j \geq$ coefficient in z:

$$\begin{array}{rcrcrcr}
y_1 & + & 5y_2 & - & y_3 & \geq & 4 \\
-y_1 & + & y_2 & + & 2y_3 & \geq & 1 \\
-y_1 & + & 3y_2 & + & 3y_3 & \geq & 5 \\
3y_1 & + & 8y_2 & - & 5y_3 & \geq & 3.
\end{array}$$

Duality Theorem: introduction

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$$(y_1 + 5y_2 - y_3)x_1 + (-y_1 + y_2 + 2y_3)x_2 + (-y_1 + 3y_2 + 3y_3)x_3$$
$$+ (3y_1 + 8y_2 - 5y_3)x_4 \leq y_1 + 55y_2 + 3y_3.$$

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$$\begin{array}{rcrcrcr} y_1 & + & 5y_2 & - & y_3 & \geq & 4 \\ -y_1 & + & y_2 & + & 2y_3 & \geq & 1 \\ -y_1 & + & 3y_2 & + & 3y_3 & \geq & 5 \\ 3y_1 & + & 8y_2 & - & 5y_3 & \geq & 3. \end{array}$$

If the $y_i \geq 0$ and satisfy theses inequations, then

$$4x_1 + x_2 + 5x_3 + 3x_4 \leq y_1 + 55y_2 + 3y_3.$$

In particular,

$$z^* \leq y_1 + 55y_2 + 3y_3.$$

Duality Theorem: introduction

Objective: smallest possible upper bound. Hence, we solve the following PL:

$$
\begin{array}{lrcrcrcr}
\text{Minimize} & y_1 & + & 55y_2 & + & 3y_3 & & \\
\text{Subject to:} & & & & & & & \\
& y_1 & + & 5y_2 & - & y_3 & \geq & 4 \\
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& -y_1 & + & 3y_2 & + & 3y_3 & \geq & 5 \\
& 3y_1 & + & 8y_2 & - & 5y_3 & \geq & 3 \\
& & & & & y_1, y_2, y_3 & \geq & 0.
\end{array}
\tag{1}
$$

It is the dual problem of the problem.

** Duality **

The Dual Problem

Primal problem:

$$
\begin{array}{lrcll}
\text{Maximize} & \sum_{j=1}^{n} c_j x_j & & & \\
\text{Subject to:} & \sum_{j=1}^{n} a_{ij} x_j & \leq & b_i & (i = 1, 2, \cdots, m) \\
 & x_j & \geq & 0 & (j = 1, 2, \cdots, n)
\end{array}
\tag{2}
$$

Its dual problem is defined by the LP problem:

$$
\begin{array}{lrcll}
\text{Minimize} & \sum_{i=1}^{m} b_i y_i & & & \\
\text{Subject to:} & \sum_{i=1}^{m} a_{ij} y_i & \geq & c_j & (j = 1, 2, \cdots, n) \\
 & y_i & \geq & 0 & (i = 1, 2, \cdots, m)
\end{array}
\tag{3}
$$

Weak Duality Theorem

Theorem: If $(x_1, x_2, ..., x_n)$ is feasible for the primal and $(y_1, y_2, ...y_n)$ is feasible for the dual, then

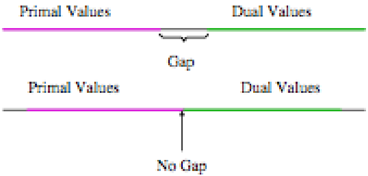
$$\sum_j c_j x_j \leq \sum_i b_i y_i.$$

Proof:

$$\begin{aligned} \textstyle\sum_j c_j x_j &\leq \textstyle\sum_j (\sum_i y_i a_{ij}) x_j && \text{dual definition: } \textstyle\sum_i y_i a_{ij} \geq c_j \\ &= \textstyle\sum_i (\sum_j a_{ij} x_j) y_i && \\ &\leq \textstyle\sum_i b_i y_i && \text{primal definition: } \textstyle\sum_i x_i a_{ij} \leq b_j \end{aligned}$$

Gap or No Gap?

An important question:
Is there a gap between the largest primal value and the smallest dual value?



Strong Duality Theorem

Theorem: If the primal problem has an optimal solution,

$$x^* = (x_1^*, ..., X_n^*),$$

then the dual also has an optimal solution,

$$y^* = (y_1^*, ..., y_n^*),$$

and

$$\sum_j c_j x_j^* = \sum_i b_i y_i^*.$$

Relationship between the Primal and Dual Problems

Lemma: The dual of the dual is always the primal problem.
Corollary: + (Strong Duality Theorem) $\Rightarrow$ Primal has an optimal solution iff dual has an optimal solution.
Weak duality: Primal unbounded $\Rightarrow$ dual unfeasible.

		Dual		
		Optimal	Unfeasible	Unbounded
	Optimal	X		
Primal	Unfeasible		X	X
	Unbounded		X	

Relationship between the Primal and Dual Problems

Lemma: The dual of the dual is always the primal problem.
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		Dual		
		Optimal	Unfeasible	Unbounded
	Optimal	X		
Primal	Unfeasible		X	X
	Unbounded		X	

**** Certificate of Optimality ****

Complementary Slackness

Theorem: Let $x_1^*, ...x_n^*$ be a feasible solution of the primal and $y_1^*, ...y_n^*$ be a feasible solution of the dual. Then,

$$\sum_{i=1}^{m} a_{ij} y_i^* = c_j \quad \text{or} \quad x_j^* = 0 \quad \text{or both} (j = 1, 2, ...n)$$

$$\sum_{j=1}^{n} a_{ij} x_j^* = b_i \quad \text{or} \quad y_i^* = 0 \quad \text{or both} (i = 1, 2, ...m)$$

are necessary and sufficient conditions to have the optimality of x^* and y^*.

Complementary Slackness - Proof

x^* feasible $\Rightarrow b_i - \sum_j a_{ij}x_j \geq 0$.
y^* dual feasible, hence non negative.

Thus

$$(b_i - \sum_j a_{ij}x_j)y_i \geq 0.$$

Similarly,
y^* dual feasible $\Rightarrow \sum_i a_{ij}y_i - c_j \geq 0$.
x^* feasible, hence non negative.

$$(\sum_i a_{ij}y_i - c_j)x_j \geq 0.$$

Complementary Slackness - Proof

$$(b_i - \sum_j a_{ij}x_j)y_i \geq 0 \qquad \text{and} \qquad (\sum_i a_{ij}y_i - c_j)x_j \geq 0$$

By summing, we get:

$$\sum_i (b_i - \sum_j a_{ij}x_j)y_i \geq 0 \qquad \text{and} \qquad \sum_j (\sum_i a_{ij}y_i - c_j)x_j \geq 0$$

Summing + strong duality theorem:

$$\sum_i b_i y_i - \sum_{i,j} a_{ij}x_j y_i + \sum_{j,i} a_{ij} y_i x_j - \sum_j c_j x_j = \sum_i b_i y_i - \sum c_j x_j = 0.$$

Implies: inequalities must be equalities:

$$\forall i, (b_i - \sum_j a_{ij}x_j)y_i = 0 \qquad \text{and} \qquad \forall j (\sum_i a_{ij}y_i - c_j)x_j = 0.$$

$XY = 0$ if $X = 0$ or $Y = 0$. Done.

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$XY = 0$ if $X = 0$ or $Y = 0$. Done.

Theorem [Optimality Certificate]: A feasible solution $x_1^*, \dots x_n^*$ of the primal is optimal iif there exist numbers $y_1^*, \dots y_n^*$ such that

1. they satisfy the complementary slackness condition:

$$\begin{array}{rll} \sum_{i=1}^m a_{ij} y_i^* & = c_j & \text{when } x_j^* > 0 \\ y_j^* & = 0 & \text{when } \sum_{j=1}^n a_{ij} x_j^* < b_i \end{array}$$

2. and $y_1^*, \dots y_n^*$ feasible solution of the dual, that is

$$\begin{array}{rll} \sum_{i=1}^m a_{ij} y_i^* & \geq c_j & \forall j = 1, \dots n \\ y_i^* & \geq 0 & \forall i = 1, \dots, m. \end{array}$$

Example: Verify that $(2,4,0,0,7,0)$ optimal solution of

$$\begin{array}{lcccccccccccccc}
\text{Max} & 18x_1 & - & 7x_2 & + & 12x_3 & + & 5x_4 & & & + & 8x_6 & & \\
\text{st:} & 2x_1 & - & 6x_2 & + & 2x_3 & + & 7x_4 & + & 3x_5 & + & 8x_6 & \leq & 1 \\
& -3x_1 & - & x_2 & + & 4x_3 & - & 3x_4 & + & x_5 & + & 2x_6 & \leq & -2 \\
& 8x_1 & - & 3x_2 & + & 5x_3 & - & 2x_4 & & & + & 2x_6 & \leq & 4 \\
& 4x_1 & & & + & 8x_3 & + & 7x_4 & - & x_5 & + & 3x_6 & \leq & 1 \\
& 5x_1 & + & 2x_2 & - & 3x_3 & + & 6x_4 & - & 2x_5 & - & x_6 & \leq & 5 \\
& & & & & & & & & & & x_1, x_2, \cdots, x_6 & \geq & 0
\end{array}$$

First step: Existence of $y_1^*, \ldots, y_5^*$, such as

$$\begin{array}{rcl}
\sum_{i=1}^m a_{ij} y_i^* & = c_j & \text{when } x_j^* > 0 \\
y_i^* & = 0 & \text{when } \sum_{j=1}^n a_{ij} x_j^* < b_i
\end{array}$$

That is

$$\begin{array}{rcrcrcrcrcr}
2y_1^* & - & 3y_2^* & + & 8y_3^* & + & 4y_4^* & + & 5y_5^* & = & 18 \\
-6y_1^* & - & y_2^* & - & 3y_3^* & & & + & 2y_5^* & = & -7 \\
3y_1^* & + & y_2^* & & & - & y_4^* & - & 2y_5^* & = & 0 \\
& & y_2^* & & & & & & & = & 0 \\
& & & & & & & & y_5^* & = & 0
\end{array}$$

$\left(\frac{1}{3}, 0, \frac{5}{3}, 1, 0\right)$ is solution.

Example: Verify that $(2,4,0,0,7,0)$ optimal solution of

$$\begin{array}{lrcrcrcrcrcrcr}
\text{Max} & 18x_1 & - & 7x_2 & + & 12x_3 & + & 5x_4 & & & + & 8x_6 & & \\
\text{st:} & 2x_1 & - & 6x_2 & + & 2x_3 & + & 7x_4 & + & 3x_5 & + & 8x_6 & \leq & 1 \\
 & -3x_1 & - & x_2 & + & 4x_3 & - & 3x_4 & + & x_5 & + & 2x_6 & \leq & -2 \\
 & 8x_1 & - & 3x_2 & + & 5x_3 & - & 2x_4 & & & + & 2x_6 & \leq & 4 \\
 & 4x_1 & & & + & 8x_3 & + & 7x_4 & - & x_5 & + & 3x_6 & \leq & 1 \\
 & 5x_1 & + & 2x_2 & - & 3x_3 & + & 6x_4 & - & 2x_5 & - & x_6 & \leq & 5 \\
 & & & & & & & & & & x_1, x_2, \cdots, & x_6 & \geq & 0
\end{array}$$

Second step: Verify $(\frac{1}{3}, 0, \frac{5}{3}, 1, 0)$ is a solution of the dual.

$$\begin{array}{rll}
\sum_{i=1}^{m} a_{ij} y_i^* & \geq c_j & \forall j = 1, \ldots n \\
y_j^* & \geq 0 & \forall i = 1, \ldots, m.
\end{array}$$

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$$
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 & 4x_1 & & & + & 8x_3 & + & 7x_4 & - & x_5 & + & 3x_6 & \leq & 1 \\
 & 5x_1 & + & 2x_2 & - & 3x_3 & + & 6x_4 & - & 2x_5 & - & x_6 & \leq & 5 \\
 & & & & & & & & & & & x_1, x_2, \cdots, x_6 & \geq & 0
\end{array}
$$

Second step: Verify $(\frac{1}{3}, 0, \frac{5}{3}, 1, 0)$ is a solution of the dual.

$$
\begin{array}{rll}
\sum_{i=1}^{m} a_{ij} y_i^* & \geq c_j & \forall j = 1, \ldots n \\
y_j^* & \geq 0 & \forall i = 1, \ldots, m.
\end{array}
$$

That is, we check

$$
\begin{array}{rcrcrcrcrcr}
2y_1^* & - & 3y_2^* & + & 8y_3^* & + & 4y_4^* & + & 5y_5^* & \geq & 18 \\
-6y_1^* & - & y_2^* & - & 3y_3^* & & & + & 2y_5^* & \geq & -7 \\
2y_1^* & + & 4y_2^* & + & 5y_3^* & + & 8y^4 & + & 3y_5^* & \geq & 12 \\
7y_1^* & - & 3y_2^* & - & 2y_3^* & + & 7y^4 & + & 6y_5^* & \geq & 5 \\
3y_1^* & + & y_2^* & & & - & y_4^* & - & 2y_5^* & \geq & 0 \\
8y_1^* & + & 2y_2^* & + & 2y_3^* & + & 3y^4 & 1 & y_5^* & \geq & 8
\end{array}
$$

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$$
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 & -3x_1 & - & x_2 & + & 4x_3 & - & 3x_4 & + & x_5 & + & 2x_6 & \leq & -2 \\
 & 8x_1 & - & 3x_2 & + & 5x_3 & - & 2x_4 & & & + & 2x_6 & \leq & 4 \\
 & 4x_1 & & & + & 8x_3 & + & 7x_4 & - & x_5 & + & 3x_6 & \leq & 1 \\
 & 5x_1 & + & 2x_2 & - & 3x_3 & + & 6x_4 & - & 2x_5 & - & x_6 & \leq & 5 \\
 & & & & & & & & & & & x_1, x_2, \cdots, x_6 & \geq & 0
\end{array}
$$

Second step: Verify $(\frac{1}{3}, 0, \frac{5}{3}, 1, 0)$ is a solution of the dual.

$$
\begin{array}{rll}
\sum_{i=1}^{m} a_{ij} y_i^* & \geq c_j & \forall j = 1, \ldots n \\
y_j^* & \geq 0 & \forall i = 1, \ldots, m.
\end{array}
$$

That is, we check

$$
\begin{array}{rcrcrcrcrcl}
2y_1^* & - & 3y_2^* & + & 8y_3^* & + & 4y_4^* & + & 5y_5^* & \geq & 18 & \textit{OK} \\
-6y_1^* & - & y_2^* & - & 3y_3^* & & & + & 2y_5^* & \geq & -7 & \textit{OK} \\
2y_1^* & + & 4y_2^* & + & 5y_3^* & + & 8y^4 & + & 3y_5^* & \geq & 12 & \\
7y_1^* & - & 3y_2^* & - & 2y_3^* & + & 7y^4 & + & 6y_5^* & \geq & 5 & \\
3y_1^* & + & y_2^* & & & - & y_4^* & - & 2y_5^* & \geq & 0 & \textit{OK} \\
8y_1^* & + & 2y_2^* & + & 2y_3^* & + & 3y^4 & 1 & y_5^* & \geq & 8 &
\end{array}
$$

Only three equations to check.

Example: Verify that $(2,4,0,0,7,0)$ optimal solution of

$$
\begin{array}{llllllllllllll}
\text{Max} & 18x_1 & - & 7x_2 & + & 12x_3 & + & 5x_4 & & & + & 8x_6 & & \\
\text{st:} & 2x_1 & - & 6x_2 & + & 2x_3 & + & 7x_4 & + & 3x_5 & + & 8x_6 & \leq & 1 \\
 & -3x_1 & - & x_2 & + & 4x_3 & - & 3x_4 & + & x_5 & + & 2x_6 & \leq & -2 \\
 & 8x_1 & - & 3x_2 & + & 5x_3 & - & 2x_4 & & & + & 2x_6 & \leq & 4 \\
 & 4x_1 & & & + & 8x_3 & + & 7x_4 & - & x_5 & + & 3x_6 & \leq & 1 \\
 & 5x_1 & + & 2x_2 & - & 3x_3 & + & 6x_4 & - & 2x_5 & - & x_6 & \leq & 5 \\
 & & & & & & & & & & & x_1, x_2, \cdots, x_6 & \geq & 0
\end{array}
$$

Second step: Verify $(\frac{1}{3}, 0, \frac{5}{3}, 1, 0)$ is a solution of the dual.

$$
\begin{array}{lll}
\sum_{i=1}^{m} a_{ij} y_i^* & \geq c_j & \forall j = 1, \dots n \\
y_j^* & \geq 0 & \forall i = 1, \dots, m.
\end{array}
$$

That is, we check

$$
\begin{array}{lllllllllllll}
2y_1^* & - & 3y_2^* & + & 8y_3^* & + & 4y_4^* & + & 5y_5^* & \geq & 18 & & \color{red}{OK} \\
-6y_1^* & - & y_2^* & - & 3y_3^* & & & + & 2y_5^* & \geq & -7 & & \color{red}{OK} \\
2y_1^* & + & 4y_2^* & + & 5y_3^* & + & 8y^4 & + & 3y_5^* & \geq & 12 & & \\
7y_1^* & - & 3y_2^* & - & 2y_3^* & + & 7y^4 & + & 6y_5^* & \geq & 5 & & \\
3y_1^* & + & y_2^* & & & - & y_4^* & - & 2y_5^* & \geq & 0 & & \color{red}{OK} \\
8y_1^* & + & 2y_2^* & + & 2y_3^* & + & 3y^4 & 1 & y_5^* & \geq & 8 & &
\end{array}
$$

Only three equations to check.

OK. The solution $(\frac{1}{3}, 0, \frac{5}{3}, 1, 0)$ is optimal.

**** Economical Interpretation ****

Signification of Dual Variables

Maximize	$\sum_{j=1}^{n} c_j x_j$			
Subject to:	$\sum_{j=1}^{n} a_{ij} x_j$	$\leq$	b_i	$(i = 1, 2, \cdots, m)$
	x_j	$\geq$	0	$(j = 1, 2, \cdots, n)$

Minimize	$\sum_{i=1}^{m} b_i y_i$			
Subject to:	$\sum_{i=1}^{m} a_{ij} y_i$	$\geq$	c_j	$(j = 1, 2, \cdots, n)$
	y_i	$\geq$	0	$(i = 1, 2, \cdots, m)$

Signification can be given to variables of the dual problem (dimension analysis):

- x_j: production of a product j (chair, ...)
- b_i: available quantity of resource i (wood, metal, ...)
- a_{ij}: unit of resource i per unit of product j
- c_j: net benefit of the production of a unit of product j

Signification of Dual Variables

$$\begin{array}{llcll} \text{Maximize} & \sum_{j=1}^{n} c_j x_j & & & \\ \text{Subject to:} & \sum_{j=1}^{n} a_{ij} x_j & \leq & b_i & (i = 1, 2, \cdots, m) \\ & x_j & \geq & 0 & (j = 1, 2, \cdots, n) \end{array} \qquad \begin{array}{llcll} \text{Minimize} & \sum_{i=1}^{m} b_i y_i & & & \\ \text{Subject to:} & \sum_{i=1}^{m} a_{ij} y_i & \geq & c_j & (j = 1, 2, \cdots, n) \\ & y_i & \geq & 0 & (i = 1, 2, \cdots, m) \end{array}$$

Signification can be given to variables of the dual problem (dimension analysis):

- x_j: production of a product j (chair, ...)
- b_i: available quantity of resource i (wood, metal, ...)
- a_{ij}: unit of resource i per unit of product j
- c_j: net benefit of the production of a unit of product j

unit of resource i/unit of product j **euros/unit of product j** **euros/unit of resource i**

$$a_{1j} y_1 + \ldots + a_{nj} y_n > c_j$$

$\longrightarrow$ y_i euro by unit of resource i.

Marginal cost of resource i.

Signification of Dual Variables

Theorem: If the LP admits at least one optimal solution, then there exists $\varepsilon > 0$, with the property: If $|t_i| \leq \varepsilon \ \forall i = 1, 2, \cdots, m$, then the LP

$$\begin{array}{rrcll} \text{Max} & \sum_{j=1}^{n} c_j x_j & & & \\ \text{Subject to:} & \sum_{j=1}^{n} a_{ij} x_j & \leq & b_i + t_i & (i = 1, 2, \cdots, m) \\ & x_j & \geq & 0 & (j = 1, 2, \cdots, n). \end{array} \qquad (4)$$

has an optimal solution and the optimal value of the objective is

$$z^* + \sum_{i=1}^{m} y_i^* t_i$$

with z^* the optimal solution of the initial LP and $(y_1^*, y_2^*, \cdots, y_m^*)$ the optimal solution of its dual.