Linear Programming and Primal-Dual Schema

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Example:Set Cover

Input:	A Universe $E = \{e_1, \ldots, e_n\}$; a family of subsets $S_1, \ldots, S_m$ where each $S_j \subseteq E$; a nonnegative weight $w_j \geq 0$ for each S_j.
Problem:	Find a minimum-weight collection of subsets that covers all of E

Integer Program

$$\begin{aligned} \text{minimize} \quad & \sum_{j=1}^{m} w_j x_j \\ \text{subject to} \quad & \sum_{j: e_i \in S_j} x_j \geq 1, \quad i = 1, \ldots, n, \\ & x_j \in \{0, 1\}, \quad j = 1, \ldots, m. \end{aligned}$$

$x_j \in \{0,1\}$: indicate whether S_j is in the solution.

Linear Program Relaxation

$$
\begin{aligned}
\text{minimize} \quad & \sum_{j=1}^{m} w_j x_j \\
\text{subject to} \quad & \sum_{j: e_i \in S_j} x_j \geq 1, \quad i = 1, \ldots, n, \\
& {\color{red} x_j \geq 0}, \qquad\quad j = 1, \ldots, m.
\end{aligned}
$$

Canonical Form

$$\begin{aligned} \text{maximize} \quad & \mathbf{c}^T\mathbf{x} \\ \text{subject to} \quad & A\mathbf{x} \le \mathbf{b} \\ & \mathbf{x} \ge 0 \end{aligned}$$

$$\begin{aligned} A = (a_{i,j}) : \quad & \text{An } m \times n \text{ matrix} \\ \mathbf{b} = (b_1, \ldots, b_m) : \quad & \text{A vector of } m \text{ entries} \\ \mathbf{c} = (c_1, \ldots, c_n) : \quad & \text{A vector of } n \text{ entries} \end{aligned}$$

Every LP can be transformed to canonical form efficiently.

Algorithms to Solve LP

- Simplex Algorithm
- Ellipsoid Method

Dual of Linear Program

Consider the following linear program:

$$\begin{aligned} \text{maximize} \quad & x_1 + 6x_2 \\ & x_1 \leq 200 & (1) \\ & x_2 \leq 300 & (2) \\ & x_1 + x_2 \leq 400 & (3) \\ & x_1, x_2 \geq 0 \end{aligned}$$

The optimal solution is at $(x_1, x_2) = (100, 300)$, with objective value 1900.

Dual of Linear Program (cont'd)

$$(1) + 6 \times (2): \quad x_1 + 6x_2 \leq 2000.$$
$$0 \times (1) + 5 \times (2) + 1 \times (3): \quad x_1 + 6x_2 \leq 1900$$

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

Dual of Linear Program (cont'd)

$$\begin{aligned} \text{minimize} \quad & 200y_1 + 300y_2 + 400y_3 \\ & y_1 + y_3 \geq 1 \\ & y_2 + y_3 \geq 6 \\ & y_1, y_2, y_3 \geq 0 \end{aligned}$$

Dual of Linear Program (cont'd)

Primal LP:

$$\begin{aligned} \text{maximize} \quad & \mathbf{c}^T\mathbf{x} \\ & A\mathbf{x} \le \mathbf{b} \\ & \mathbf{x} \ge 0 \end{aligned}$$

Dual LP:

$$\begin{aligned} \text{minimize} \quad & \mathbf{y}^T\mathbf{b} \\ & \mathbf{y}^T A \ge \mathbf{c}^T \\ & \mathbf{y} \ge 0 \end{aligned}$$

weakstrong duality property:

$$\mathbf{c}^T\mathbf{x} \le \mathbf{y}^T\mathbf{b}\mathbf{c}^T\mathbf{x}^* = (\mathbf{y}^*)^T\mathbf{b}$$

A Simple Rounding Algorithm for Set Cover

Recall the linear programming relaxation for set cover:

$$
\begin{aligned}
\text{minimize} \quad & \textstyle\sum_{j=1}^{m} w_j x_j \\
\text{subject to} \quad & \textstyle\sum_{j: e_i \in S_j} x_j \geq 1, \quad i = 1, \dots, n, \\
& x_j \geq 0, \qquad\qquad j = 1, \dots, m.
\end{aligned}
$$

Consider the optimal solution of the LP. Intuitively, the set with larger x_j is more likely to be in a good solution of set cover (or the IP).

A Simple Rounding Algorithm for Set Cover (cont'd)

1. Let $\mathbf{x}^*$ be the solution of LP.
2. Let $I = \{j \mid x_j^* \geq 1/f\}$, where $f = \max_{i=1,\ldots,n} |\{j \mid e_i \in S_j\}|$.
3. Output I.

Lemma

$\mathcal{S}$ is a set cover.

Analysis

Lemma

The rounding algorithm is an f-approximation algorithm for the set cover problem.

$$\begin{aligned}\sum_{j\in I} w_j &\leq \sum_{j=1}^{m} w_j \cdot (f \cdot x_j^*)\\ &= f\sum_{j=1}^{m} w_j x_j^*\\ &= f \cdot \mathrm{OPT}\end{aligned}$$

A Primal-Dual Algorithm for Set Cover

Recall the LP relaxation for Set Cover:

$$\begin{aligned} \text{minimize} \quad & \sum_{j=1}^{m} w_j x_j \\ \text{subject to} \quad & \sum_{j: e_i \in S_j} x_j \geq 1, \quad && i = 1, \ldots, n, \\ & x_j \geq 0, && j = 1, \ldots, m. \end{aligned}$$

and its dual:

$$\begin{aligned} \text{maximize} \quad & \sum_{i=1}^{n} y_i \\ \text{subject to} \quad & \sum_{i: e_i \in S_j} y_i \leq w_j, \quad && j = 1, \ldots, m, \\ & y_i \geq 0, && i = 1, \ldots, n. \end{aligned}$$

Vertex Cover

- Vertex cover problem is the special case of set cover problem when $f = 2$.
- The dual of vertex cover problem is maximum matching problem.
- The duality theorem implies

$$\text{maximum matching} \leq \text{minimum vertex cover}$$

Vertex Cover (cont'd)

Consider the following algorithm:

1. $M \leftarrow \varnothing$
2. $S \leftarrow \varnothing$
3. **while** G is not empty **do**
   3.1 Choose an edge $e = \{u, v\} \in E(G)$ and let $M \leftarrow M \cup \{e\}$
   3.2 $S \leftarrow S \cup \{u, v\}$
   3.3 $G \leftarrow G[V \setminus \{u, v\}]$ (Remove isolated nodes)
4. **return** S

This is the combinatorial interpretation of a primal-dual algorithm.

The Algorithm

1. $\mathbf{y} \leftarrow 0$
2. $I \leftarrow \varnothing$
3. **while** there exists $e_i \notin \bigcup_{j \in I} S_j$ **do**
   3.1 Increase the dual variable y_i until there is some ℓ such that $\sum_{j : e_j \in S_\ell} y_j = w_\ell$
   3.2 $I \leftarrow I \cup \{\ell\}$
4. **return** I.

Analysis

The primal-dual algorithm is an f-approximation algorithm for the set cover problem.

$$\begin{aligned}\sum_{j\in I} w_j &= \sum_{j\in I}\sum_{i:e_i\in S_j} y_i \\ &= \sum_{i=1}^{n} y_i \cdot |\{j \in I \mid e_i \in S_j\}| \\ &\leq f \cdot \mathrm{OPT}\end{aligned}$$

Complementary Slackness

The following property is called complementary slackness.

$$\sum_{i=1}^{n} y_i \leq \sum_{i=1}^{n} y_i \sum_{j:e_i \in S_j} x_j = \sum_{j=1}^{m} x_j \sum_{i:e_i \in S_j} y_i \leq \sum_{j=1}^{m} x_j w_j.$$

Let x^* and y^* be the optimal solution of primal and dual LP respectively, then

- $y_i^* > 0 \implies \sum_{j:e_i \in S_j} x_j^* = 1,$
- $x_j^* > 0 \implies \sum_{i:e_i \in S_j} y_i^* = w_j.$

Analysis (revisited)

$$\begin{aligned}\sum_{j\in I} w_j &= \sum_{j\in I}\sum_{i:e_i\in S_j} y_i \\ &= \sum_{i=1}^{n} y_i \cdot \left|\{j\in I \mid e_i\in S_j\}\right| \\ &= \sum_{i=1}^{n} y_i \cdot \sum_{j:e_i\in S_j} x_j \\ &\le f\cdot \mathrm{OPT}\end{aligned}$$

where $x_j \in \{0,1\}$ and $x_j = 1$ if and only if $j \in I$.

Discussion

The primal-dual algorithm ensures

$$x_j > 0 \implies \sum_{i:e_i \in S_j} y_i = w_j$$

In general, we cannot hope

$$y_i > 0 \implies \sum_{j:e_i \in S_j} x_j = 1$$

We want to show it is not too *slack*, i.e.

$$y_i > 0 \implies \sum_{j:e_i \in S_j} x_j \leq \alpha$$

Feedback Vertex Set Problem

Input:	A undirected graph $G = (V, E)$ and nonnegative weights $w_i > 0$ for $i \in V$.
Problem:	Find a set $S \subseteq V$ of minimum weight such that $G[V \setminus S]$ is a forest

LP formulation

$$\begin{aligned} \text{minimize} \quad & \sum_{i \in V} w_i x_i \\ \text{subject to} \quad & \sum_{i \in C} x_i \geq 1, \quad \forall C \in \mathcal{C} \\ & x_i \in \{0, 1\}, \quad \forall i \in V \end{aligned}$$

$$\begin{aligned} \text{minimize} \quad & \sum_{i \in V} w_i x_i \\ \text{subject to} \quad & \sum_{i \in C} x_i \geq 1, \quad \forall C \in \mathcal{C} \\ & x_i \geq 0, \qquad \forall i \in V \end{aligned}$$

Dual LP

$$
\begin{aligned}
\text{maximize} \quad & \sum_{C \in \mathcal{C}} y_C \\
\text{subject to} \quad & \sum_{C \in \mathcal{C} : i \in C} y_C \le w_i, && \forall i \in V, \\
& y_C \ge 0, && \forall C \in \mathcal{C}
\end{aligned}
$$

The Algorithm

1. $\mathbf{y} \leftarrow 0$
2. $S \leftarrow \varnothing$
3. **while** there exists a cycle C in G **do**
   - 3.1 Increase y_C until there is some $\ell \in V$ such that
     $$\sum_{C' \in \mathcal{C}: \ell \in C'} y_{C'} = w_\ell$$
   - 3.2 $S \leftarrow S \cup \{\ell\}$
   - 3.3 Remove ℓ from G
   - 3.4 Repeatedly remove vertices of degree one from G
4. **return** S.

Analysis

$$\sum_{i \in S} w_i = \sum_{i \in S} \sum_{C : i \in C} y_C = \sum_{C \in \mathcal{C}} |S \cap C| y_C.$$

$|S \cap C|$ may be as large as $|V|$!

Analysis (cont'd)

Observation

For any path P of vertices of degree two in graph G, our algorithm will choose at most one vertex from P.

Theorem

In any graph G that has no vertices of degree one, there is a cycle with at most $2\lfloor \log_2 n \rfloor$ vertices of degree three or more, and it can be found in linear time.

Algorithm (revised)

1. $\mathbf{y} \leftarrow 0$
2. $S \leftarrow \varnothing$
3. Repeatedly remove vertices of degree one from G
4. **while** there exists a cycle C in G **do**
   - 4.1 Find cycle C with at most $2\lfloor \log_2 n \rfloor$ vertices of degree three or more
   - 4.2 Increase y_C until there is some $\ell \in V$ such that $$\sum_{C' \in \mathcal{C}: \ell \in C'} y_{C'} = w_\ell$$
   - 4.3 $S \leftarrow S \cup \{\ell\}$
   - 4.4 Remove ℓ from G
   - 4.5 Repeatedly remove vertices of degree one from G
5. **return** S.

Analysis

$$\sum_{i \in S} w_i = \sum_{C \in \mathcal{C}} |S \cap C| y_C \leq (4\lfloor \log_2 n \rfloor) \sum_{c \in \mathcal{C}} y_C \leq (4\lfloor \log_2 n \rfloor)\mathrm{OPT}.$$