Honors Algorithms
G22.3520-001 Fall 2007

Lecture 9
Read: CLRS 16
Example

The Line Breaking Problem

- Given a sequence of words
- Form a paragraph, breaking lines as necessary
- Assumptions:
  - fixed width spacing
  - need at least one space between words
  - words have lengths $l_1, \ldots, l_n$, and lines have length $B$, with each $l_i \leq B$
  - the $l_i$’s and $B$ already include a “trailing space character”
A solution is a sequence \((p_1, p_2, \ldots, p_k)\), meaning that \(p_i\) words go on the \(i\)th line, for \(i = 1, \ldots, k\).

Different ways of measuring the “cost” of a solution

One simple cost metric: \# of lines \((= k)\)

A “greedy” strategy: choose \(p_1\) maximal such that words \(1, \ldots, p_1\) fit on first line, then choose \(p_2\) maximal such that words \(p_1 + 1, \ldots, p_1 + p_2\) fit on second line, and so on . . .

Running time: \(O(n)\)

Claim

This greedy strategy minimizes the number of lines
Proof of claim. Prove by induction on $k$ the statement:

• if the greedy algorithm finds an $k$-line solution, then there is no solution with $< k$ lines

$k = 1$: clear

$k > 1$:

• Suppose greedy algorithm finds an $k$-line solution $(p_1, \ldots, p_k)$
• Consider another solution $(q_1, \ldots, q_{k'})$
• We must have $q_1 \leq p_1$, since $p_1$ was chosen as large as possible by the greedy algorithm
• Modify the solution \((q_1, \ldots, q_{k'})\), moving \(p_1 - q_1\) words from the second line to the first
• This yields a solution of length \(k'' \leq k' - 1\) to the problem instance \((\ell_{p_1+1}, \ldots, \ell_n)\)
• However, \((p_2, \ldots, p_k)\) is a greedy solution to this problem instance
• By induction, \(k - 1 \leq k'' \leq k' - 1\), and so \(k \leq k'\) QED
Different cost functions may not allow a greedy algorithm

- “1 norm” — sum of extra spaces on all but the last line
  - greedy algorithm also works here
- “max norm” — maximum of extra spaces on all but last line
  - greedy algorithm does not work here

<table>
<thead>
<tr>
<th>greedy</th>
<th>better</th>
</tr>
</thead>
<tbody>
<tr>
<td>1   2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>
We can minimize the max-norm cost using dynamic programming

For $i = 1 \ldots n$, define $C(i) =$ minimum max-norm cost to format $\ell_i, \ldots, \ell_n$

For $i = 1 \ldots n$ and $j = i \ldots n$, let $S_{ij} := \sum_{t=i}^{j} \ell_t$

For $i = 1 \ldots n$, we have

$$C(i) = \begin{cases} 
0 \text{ if } S_{in} \leq B \\
\min_{i \leq j < n} \left\{ \max \left( B - S_{ij}, C(j + 1) \right) \right\} \text{ o/w}
\end{cases}$$
Subproblem graph:

Number of nodes = $O(n)$
Number of edges per node = $O(n)$
Running time = $O(n^2)$
Example: Huffman Encoding Problem

Let \( w_1, \ldots, w_n \) be non-negative weights.

Let \( T \) be a binary tree, with each \( w_i \) labeling some leaf of depth \( d_i \).

Define \( \text{Cost}(T) := \sum_i w_i d_i \).

Problem: given \( w_1, \ldots, w_n \), find a minimal cost \( T \).

Without loss of generality, we may assume \( T \) is a \textit{full} binary tree, i.e., each non-leaf has two children.
Example:

\[ \begin{array}{cccc}
1 & 1 & 1 & 10 \\
\end{array} \]

\[ \text{Cost} = 26 \]

\[ \begin{array}{cccc}
1 & 1 \\
\end{array} \]

\[ \text{Cost} = 10 + 2 + 3 + 3 = 18 \]

Application: optimal prefix-free binary encoding

- \( w_i \) represents probability of symbol \( \sigma_i \)
- path in tree represents a bit string encoding
- \( \text{Cost}(T) \) is expected encoding length
- prefix-free property allows for unambiguous parsing of strings
- Example: \( \Pr[A] = \Pr[B] = \Pr[C] = 1/13, \Pr[D] = 10/13 \)

Encoding: \( A \Rightarrow 000, B \Rightarrow 001, C \Rightarrow 01, D \Rightarrow 1 \)
For a tree $T$, define its weight to be the sum of weights of its leaves

Greedy Algorithm:

- Start with a forest of $n$ leaves
- Repeat $n - 1$ times:
  - Take two trees $T_1, T_2$ in the forest of least weight, and join them:

Implement using a heap. Running time: $O(n \log n)$
**Theorem**

This greedy algorithm produces a least-cost tree.

**Lemma 1**

Let \( T \) be a full binary tree with weights \( w(\nu) \) assigned to leaves \( \nu \). Suppose \( \nu_1, \nu_2 \) are leaves of smallest weight. We can construct a new tree \( T' \) from \( T \) such that

1. the leaves of \( T' \) and \( T \) are the same,
2. \( \nu_1 \) and \( \nu_2 \) are siblings in \( T' \), and
3. \( \text{Cost}(T') \leq \text{Cost}(T) \).
Proof of Lemma 1. Assume \( v_1, v_2 \) not siblings in \( T \)
Let \( d_i := \text{depth of } v_i \text{ in } T \) for \( i = 1, 2 \)
Assume \( d_1 \geq d_2 \) and let \( \Delta := d_1 - d_2 \)

Moving \( v_2 \) down *increases* cost by \( \Delta \cdot w(v_2) \)

All leaves in \( T_1 \) have weight \( \geq w(v_2) \) (because \( v_1, v_2 \) have least weight), and so moving \( T_1 \) up *decreases* cost by at least \( \Delta \cdot w(v_2) \)
Lemma 2

Let $T$ be a full binary tree with weights $w(\nu)$ assigned to leaves $\nu$. Suppose $\nu_1, \nu_2$ are leaves that are siblings in $T$ with parent $\nu_3$, and that we create a new tree $\tilde{T}$ by deleting $\nu_1$ and $\nu_2$ and set $w(\nu_3) := w(\nu_1) + w(\nu_2)$:

$$\begin{align*}
\nu_1 & \quad \nu_3 \quad \nu_2 \\
\nu_3 & \quad \nu_1 \quad \nu_2
\end{align*}$$

Then $\text{Cost}(\tilde{T}) = \text{Cost}(T) - w(\nu_1) - w(\nu_2)$.

Proof. Let $d = \text{depth of } \nu_3$ in $T$

$\nu_1$ and $\nu_2$ contribute $(d + 1)(w(\nu_1) + w(\nu_2))$ to $\text{Cost}(T)$

$\nu_3$ contributes $d(w(\nu_1) + w(\nu_2))$ to $\text{Cost}(\tilde{T})$
Proof of Theorem.

Induction on $n$

If $n \leq 2$, clear; assume $n > 2$ and assume theorem holds for all values less than $n$

Let $T$ be the tree produced by the greedy algorithm, and let $X$ be any tree with same weights as $T$

Want to show: $\text{Cost}(T) \leq \text{Cost}(X)$

Consider the first step of the greedy algorithm, which joined two leaves $\nu_1, \nu_2$ of smallest weight

$\nu_1$ and $\nu_2$ are siblings in $T$
Apply Lemma 1 to $X$, obtaining a new tree $X'$ in which $v_1$ and $v_2$ are siblings, and 
$\text{Cost}(X') \leq \text{Cost}(X)$

Apply Lemma 2 to both $T$ and $X'$, removing $v_1$ and $v_2$, obtaining trees $\tilde{T}$ and $\tilde{X}'$ such that

$$\text{Cost}(\tilde{T}) = \text{Cost}(T) - w(v_1) - w(v_2)$$
$$\text{Cost}(\tilde{X}') = \text{Cost}(X') - w(v_1) - w(v_2)$$

$\tilde{T}$ is also a tree that would be produced the greedy algorithm, and so by induction,
$\text{Cost}(\tilde{T}) \leq \text{Cost}(\tilde{X}')$

It follows that

$$\text{Cost}(T) \leq \text{Cost}(X') \leq \text{Cost}(X) \quad \text{QED}$$