Announcements (November 29)

- Homework #4 due today
- Course project demo Dec. 7-14
  - Each project gets a 30-minute slot with me and Yi
  - Watch for an email this weekend scheduling demo slots
- Final exam on Saturday, Dec. 15, 7-10pm
  - Again, open book, open notes
  - Focus on the second half of the course

Keyword search

What are the documents containing both "database" and "search"?
Keywords × documents

<table>
<thead>
<tr>
<th>All keywords</th>
<th>Document 1</th>
<th>Document 2</th>
<th>Document 3</th>
<th>Document 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;cat&quot;</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>&quot;database&quot;</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>&quot;dog&quot;</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>&quot;search&quot;</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

1 means keyword appears in the document; 0 means otherwise

- Inverted lists: store the matrix by rows
- Signature files: store the matrix by columns

Inverted lists

- Store the matrix by rows
- For each keyword, store an inverted list
  - \((\text{keyword}, \text{doc-id-list})\)
  - \(\text{"database"}, \{3, 7, 142, 857, \ldots\}\)
  - \(\text{"search"}, \{3, 9, 192, 512, \ldots\}\)
  - It helps to sort \text{doc-id-list} (why?)
- Vocabulary index on keywords
  - B+-tree or hash-based
- How large is an inverted list index?

Using inverted lists

- Documents containing "database"
  - Use the vocabulary index to find the inverted list for "database"
  - Return documents in the inverted list
- Documents containing "database" AND "search"
- OR? NOT?
What are “all” the keywords?

- All sequences of letters (up to a given length)?
  - … that actually appear in documents!
- All words in English?
- Plus all phrases?
  - Alternative: approximate phrase search by proximity
- Minus all stop words
  - They appear in nearly every document, e.g., a, of, the, it
  - Not useful in search
- Combine words with common stems
  - Example: database, databases
  - They can be treated as the same for the purpose of search

Frequency and proximity

- Frequency
  - \( \{ \text{keyword}, \{ \langle \text{doc-id}, \text{number-of-occurrences} \rangle, \langle \text{doc-id}, \text{number-of-occurrences} \rangle, \ldots \} \} \)
- Proximity (and frequency)
  - \( \{ \text{keyword}, \{ \langle \text{doc-id}, \{ \text{position-of-occurrence}_1, \ldots \} \rangle, \langle \text{doc-id}, \{ \text{position-of-occurrence}_1, \ldots \} \rangle, \ldots \} \} \)
  - When doing AND, check for positions that are near

Signature files

- Store the matrix by columns and compress them
- For each document, store a \( w \)-bit signature
- Each word is hashed into a \( w \)-bit value, with only \( s \) \(< w \) bits turned on
- Signature is computed by taking the bit-wise OR of the hash values of all words on the document

\[ \text{hash("database")} = 0110 \]
\[ \text{hash("dog")} = 1100 \]
\[ \text{hash("cat")} = 0010 \]
\[ \text{Does doc}_3 \text{ contain "database"?} \]
\[ \text{Does doc}_3 \text{ contain "database"?} \]
\[ \text{Does doc}_3 \text{ contain "dog"?} \]
\[ \text{Does doc}_3 \text{ contain "cat" and "dog"?} \]

- Some false positives; no false negatives
Bit-sliced signature files

- **Motivation**
  - To check if a document contains a word, we only need to check the bits that are set in the word’s hash value.
  - So why bother retrieving all $w$ bits of the signature?
- Instead of storing $n$ signature files, store $w$ bit slices.
- Only check the slices that correspond to the set bits in the word’s hash value.
- Start from the sparse slices.

<table>
<thead>
<tr>
<th>Slice</th>
<th>Signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 0 0 0 0 1 0 0</td>
</tr>
<tr>
<td>1</td>
<td>0 0 0 0 1 0 0 0</td>
</tr>
<tr>
<td>2</td>
<td>0 0 0 1 1 0 1 0</td>
</tr>
<tr>
<td>3</td>
<td>0 1 1 0 1 1 0 0</td>
</tr>
<tr>
<td>4</td>
<td>0 1 1 0 0 1 0 0</td>
</tr>
<tr>
<td>5</td>
<td>0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>6</td>
<td>0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>7</td>
<td>0 0 0 0 0 0 0 0</td>
</tr>
</tbody>
</table>

Starting to look like an inverted list again!

Inverted lists versus signatures

- Inverted lists better for most purposes (*TOCS*, 1998)
- Problems of signature files
  - False positives
  - Hard to use because $n$, $w$, and the hash function need tuning to work well.
  - Long documents will likely have mostly 1’s in signatures.
  - Common words will create mostly 1’s for their slices.
  - Difficult to extend with features such as frequency, proximity.
- Saving grace of signature files

Ranking result pages

- A single search may return many pages
  - A user will not look at all result pages.
  - Complete result may be unnecessary.
- Possible ranking criteria
  - Based on content
    - Number of occurrences of the search terms
    - Similarity to the query text
  - Based on link structure
    - Backlink count
    - PageRank
  - And more…
Textual similarity

- Vocabulary: \([w_1, \ldots, w_n]\)
- IDF (Inverse Document Frequency): \([f_1, \ldots, f_n]\)
  - \(f_i = 1 / \text{the number of times } w_i \text{ appears on the Web}\)
- Significance of words on page \(p\): \([p_1 f_1, \ldots, p_n f_n]\)
  - \(p_i \text{ is the number of times } w_i \text{ appears on } p\)
- Textual similarity between two pages \(p\) and \(q\) is defined to be
  \[
  \sum_{i=1}^{n} p_i q_i f_i^2 + \ldots + p_n q_n f_n^2
  \]
- \(q\) could be the query text

Why weight significance by IDF?

- Without IDF weighting, the similarity measure would be dominated by the stop words
- “the” occurs frequently on the Web, so its occurrence on a particular page should be considered less significant
- “engine” occurs infrequently on the Web, so its occurrence on a particular page should be considered more significant

Problems with content-based ranking

- Many pages containing search terms may be of poor quality or irrelevant
  - Example: a page with just a line “search engine”
- Many high-quality or relevant pages do not even contain the search terms
  - Example: Google homepage
- Page containing more occurrences of the search terms are ranked higher; spamming is easy
  - Example: a page with line “search engine” repeated many times
Backlink

- A page with more backlinks is ranked higher
- Intuition: Each backlink is a "vote" for the page's importance

Google’s PageRank

- Main idea: Pages pointed by high-ranking pages are ranked higher
  - Definition is recursive by design
  - Based on global link structure; hard to spam
- Naïve PageRank
  - \( N(p) \): number of outgoing links from page \( p \)
  - \( B(p) \): set of pages that point to \( p \)
  - PageRank\( (p) = \sum_{q \in B(p)} \frac{\text{PageRank}(q)}{N(q)} \)
  - Each page \( p \) gets a boost of its importance from each page that points to \( p \)
  - Each page \( q \) evenly distributes its importance to all pages that \( q \) points to

Calculating naïve PageRank

- Initially, set all PageRank’s to 1; then evaluate
  \[ \text{PageRank}(p) \leftarrow \sum_{q \in B(p)} \left( \text{PageRank}(q) / N(q) \right) \]
  repeatedly until the values converge (i.e. a fixed point is reached)
Random surfer model

- A random surfer starts with a random page.
  - Randomly selects a link on the page to visit next.
  - Never uses the “back” button.

- PageRank($p$) measures the probability that a random surfer visits page $p$.

Problems with the naïve PageRank

- Dead end: a page with no outgoing links.
  - A dead end causes all importance to “leak” eventually out of the Web.

- Spider trap: a group of pages with no links out of the group.
  - A spider trap will eventually accumulate all importance of the Web.

Practical PageRank

- $d$: decay factor.
- $\text{PageRank}(p) =
  d \cdot \sum_{q \in B(p)} \left( \frac{\text{PageRank}(q)}{N(q)} \right) + (1 - d)$

- Intuition in the random surfer model:
  - A surfer occasionally gets bored and jumps to a random page on the Web instead of following a random link on the current page.
Google (1998)

- Inverted lists in practice contain a lot of context information

<table>
<thead>
<tr>
<th>Cap</th>
<th>Hitt</th>
<th>Byte</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

- Relative font size
  - In URL/title/meta tag
  - In anchor text
  - Within the page

- PageRank is not the final ranking
  - Type-weight: depends on the type of occurrence
    - For example, large font weights more than small font
  - Count-weight: depends on the number of occurrences
    - Increases linearly first but then tapers off
  - For multiple search terms, nearby occurrences are matched together and a proximity measure is computed
    - Closer proximity weights more

Trie: a string index

- A tree with edges labeled by characters
- A node represents the string obtained by concatenating all characters along the path from the root

```
  a
 / \  
 b  c
 /  \   
 p  e
```

- Compact trie: replace a path without branches by a single edge labeled by a string

Suffix tree

- Index all suffixes of a large string in a compact trie
- Can support arbitrary substring matching
- Internal nodes have fan-out $\geq 2$ (except the root)
- No two edges out of the same node can share the same first character

To get linear space
- Instead of inlining the string labels, store pointers to them in the original string
- Bad for external memory
Patricia trie, Pat tree, String B-tree

A Patricia trie is just like a compact trie, but
- Instead of labeling each edge by a string, only label by the first character and the string length
- Leaves point to strings
  - Faster search (especially for external memory) because of inlining of the first character
  - But must validate answer at leaves for skipped characters
- A Pat tree indexes all suffixes of a string in a Patricia trie
- A String B-tree uses a Patricia trie to store and compare strings in B-tree nodes

Summary

- General tree-based string indexing tricks
  - Trie, Patricia trie, String B-tree
- Two general ways to index for substring queries
  - Index words: inverted lists, signature files
  - Index all suffixes: suffix tree, Pat tree, suffix array (not covered)
- Web search and information retrieval go beyond substring queries
  - IDF, PageRank, …