Optimal Crawling Strategies for Web Search Engines

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joint work with

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May 8, 2002
Introduction

- Web search engines employ multiple crawlers
  - To maintain local copies of web pages
  - To build data structures such as inverted indexes

- But web pages are updated frequently
  - 23% of web pages change daily
  - 40% of commercial web pages change daily
  - Half-life for a web page is 10 days

- So crawlers must revisit web pages frequently to maintain *freshness*
  - Question: How should one do this optimally?
Two part Scheme

- Component 1: Solve the “Crawling frequency” problem
  - Find optimal number of times to crawl each page
  - Find optimal times to crawl each page

- Component 2: Solve the “Crawler Scheduling” problem
  - Create optimal achievable crawler schedule based on idealized crawler times
Contributions

- Crawling frequency problem
  - More appropriate optimization metric
    * Based on level of *embarrassment*, not just on staleness
  - Unified framework (Stationary Marked Point Processes) to handle wide variety of web page update distribution types
    * Poisson, Pareto, Weibull
    * Quasi-deterministic
  - State-of-art algorithms for finding optimal number of crawls
    * General and practical: Real-life constraints
    * Extraordinary computationally efficient: Problems are huge
  - Algorithms for finding ideal crawl times
Contributions

- Scheduling problem
  - Exact transportation problem solution
  - Real-life constraints

- Analysis of update patterns from several IBM-hosted web sites
  - Grand Slam Tennis
    * Australian, French, US Opens; Wimbledon
  - Golf
    * Master’s, Ryder’s Cup
  - Olympic Games
    * Nagano, 1998; Sydney 2000
  - Awards
    * Tonys, Grammys

- Summary: Interupdate time distributions span a wide range of behaviors
Related Work

• Cho & Garcia-Molina (2000)
  – Compare “uniform” and “proportional” allocation rules
  – Solved crawling frequency problem for Poisson updates

• Coffman, Liu, & Weber (2000) consider Poisson updates, and also include access times.
  – Crawls to a page should be as “evenly spaced” as possible (to maximize average freshness)

• Talim, Liu, Nain, & Coffman (1999): optimize number of crawlers. (Indexing capacity v/s starvation of the indexing engine.)
Key Notation

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>Number of web pages to be crawled</td>
</tr>
<tr>
<td>$T$</td>
<td>Web crawler scheduling interval length</td>
</tr>
<tr>
<td>$R$</td>
<td>Number of crawls allowed in interval $[0, T]$</td>
</tr>
<tr>
<td>$C$</td>
<td>Number of crawlers</td>
</tr>
<tr>
<td>$S_k$</td>
<td>Number of crawls by crawler $k$ in time $T$</td>
</tr>
</tbody>
</table>

Table 1: Notation summary
Crawling Frequency Problem: Preliminaries

- Suppose we crawl web page \( i \) \( x_i \) times during scheduling interval \( T \)
  - ...at times \( 0 \leq t_{i,1} < t_{i,2} < \ldots < t_{i,x_i} \leq T \)
  - ...with \( x_i \leq R \).

- Compute probability \( p_i(t_{i,1}, \ldots, t_{i,x_i}, t) \) that search engine will have stale copy of web page \( i \) at time \( t \in [0, T] \):

- Compute \textit{time-average} staleness probability measure

\[
    a_i(t_{i,1}, \ldots, t_{i,x_i}) = \frac{1}{T} \int_0^T p_i(t_{i,1}, \ldots, t_{i,x_i}, t) dt.
\]
• Set *staleness*

\[ A_i(x_i) = a_i(t_{i,1}^*, \ldots, t_{i,x_i}^*). \]  \hspace{1cm} (2)

• Set

  – \( w_i \) to be *embarrassment* weights
  – \( m_i \) to be minimum number of acceptable crawls for web page \( i \)
  – \( M_i \) to be Maximum number of acceptable crawls for web page \( i \)
Crawling Frequency Problem:

Minimize

\[ \sum_{i=1}^{N} w_i A_i(x_i) \]  \quad (3)

subject to the constraints

\[ \sum_{i=1}^{N} x_i = R \]

\[ x_i \in \{m_i, \ldots, M_i\} \]

• Solution to discrete, separable resource allocation problem (RAP):
  
  – \( O(NR^2) \)

• But \( A_i \) is convex
  
  – So much faster algorithms exist
Crawling Frequency Problem: Loose Ends

- Computing the weights \( w_i \) of the *embarassment level* metric for each web page \( i \)

- Computing the functional forms of \( p_i, a_i \) and \( A_i \) for each web page \( i \), based on the update pattern distribution

- Solving the resulting discrete, convex, separable resource allocation problem
Embarrassment Metric

- **Good:** Search engine has fresh copy of web page

- **Bad:** Stale...
  - ...but *lucky*
    - ♠ Web page not returned to client as result of query
    - ♦♦ Returned to client, but not clicked on by client
    - ♦♦♦ Returned to client, clicked on but correct with respect to query
  - ...and *unlucky*
    - Returned to client, clicked on...
      - ♦♠♥ ...and incorrect with respect to query
      - ♦♠♥ ...or gone
      - Up to 14% of search engine links are typically broken

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Computing the Weights $w_i$

GOOD: Page fresh

Page stale

Page not returned

Page returned

Page clicked

BAD BUT LUCKY

Query correct

UGLY: Query incorrect
Let $b_{i,j,k}$ denote the probability that the search engine will return page $i$ in position $j$ of query result page $k$

Let $c_{j,k}$ denote the frequency that a client will click on a returned page in position $j$ of query result page $k$

Let $d_i$ denote the probability that a query to a stale version of page $i$ yields an incorrect response

Then $w_i = d_i \sum_j \sum_k c_{j,k} b_{i,j,k}$
Probability of Clicking As Function of Position/Page
Probability Function for Quasi-Deterministic Web Pages
Computing the Functions $\bar{p}_i$, $\bar{a}_i$ and $A_i$: Quasi-Deterministic Case

- $P_i$ possible update times, $0 \leq s_{i,1} < s_{i,2} < \ldots < s_{i,P_i} \leq T$

- Update $s_{i,j}$ occurs with probability $q_{i,j}$

- $u_{i,j} = s_{i,j+1} - s_{i,j}$

- Can assume $x_i \leq P_i + 1$

- Define binary decision variables

\[ y_{i,j} = \begin{cases} 1 & \text{if a crawl occurs at time } s_{i,j} \\ 0 & \text{otherwise} \end{cases} \quad (4) \]
• Define

\[ J_{1,t} = \max\{j | 0 \leq j \leq x_i, \ s_{i,j} \leq t\}, \quad (5) \]

which is index of latest potential update time before \( t \); and

\[ J_{2,t} = \max\{0, \{j | 0 \leq j \leq x_i, \ y_{i,j} = 1, \ s_{i,j} \leq t\}\}, \quad (6) \]

which is index of latest potential update time before \( t \) that will be crawled

• Then, the freshness probability function is:

\[ \bar{p}(y_{i,0}, \ldots, y_{i,P_i, t}) = \prod_{j=J_{2,t}+1}^{J_{1,t}} (1 - q_{i,j}) \quad (7) \]
• The average staleness is

\[ \bar{a}(y_{i,0}, \ldots, y_{i,P_i}) = \sum_{j=0}^{P} u_{i,j} (1 - \prod_{k=J_{i,j}+1}^{j} (1 - q_{i,j})) \]  

(8)

To compute \( A_i \), minimize

\[ \bar{a}(y_{i,0}, \ldots, y_{i,P_i}) \]  

(9)

Subject to the constraints

\[ y_{i,j} \in \{0, 1\} \]  

(10)

And

\[ \sum_{j=0}^{P} y_{i,j} = x_i \]  

(11)
Quasi-Deterministic Case

- A simple dynamic program solves the problem optimally.

- *Greedy* algorithm does *exceptionally* well; is at least within $e/(e-1)$ of optimal, possibly better. (Series of papers by Fisher, Nemhauser, Wolsey, Cornuejols and Conforti on maximizing submodular functions)
  - Greedy’s $\mathcal{A}_i$ is also convex!
Computing the Functions $p_i$, $a_i$ and $A_i$: Poisson Case

- Probability of update occurring within $t$ units of time: $1 - e^{-\lambda_i t}$

- Suppose we crawl $x_i$ times at times $t_{i,1}, \ldots t_{i,x_i}$

- Define $\hat{t} = \max\{t_{i,j} | 0 \leq j \leq x_i, \ t_{i,j} \leq t\}$

- Then $p_i(t_{i,1}, \ldots , t_{i,x_i}, t) = 1 - e^{-\lambda_i(t-\hat{t})}$

- And $a_i(t_{i,1}, \ldots , t_{i,x_i}) = 1 + \frac{1}{\lambda_i T} \sum_{j=0}^{x_i} (e^{-\lambda_i(t_{j+1}-t_j)} - 1)$

- So let $u_{i,j} = t_{i,j+1} - t_{i,j}$
Poisson Case

To find $A_i$ minimize

$$1 + \frac{1}{\lambda_i T} \sum_{j=0}^{x_i} (e^{-\lambda_i u_{i,j}} - 1)$$  \hspace{1cm} (12)

subject to the constraints

$$0 \leq u_{i,j} \leq T,$$  \hspace{1cm} (13)

and

$$\sum_{j=0}^{x_i} u_{i,j} = T.$$  \hspace{1cm} (14)

- A continuous, convex, separable resource allocation problem: solution is trivial.

- So $u_{i,j}^* = T/(x_i + 1)$
A Unified Framework

Figure 1: Example of a Marked Point Process
A Unified Framework

- From standard renewal-theoretic arguments, the time-average staleness can be computed as:

\[ a_i(t_{i,1}, \ldots, t_{i,x_i}) = \frac{1}{T} \sum_{j=0}^{x_i} \int_{t_{i,j}}^{t_{i,j+1}} \left( 1 - \lambda_i \int_0^\infty G_i(t - t_{i,j} + v) \, dv \right) \, dt. \]

Here \( G_i(\cdot) \) is the complementary c.d.f. of the inter-update time distribution.

NOTE: Summands are *separable, identical*! So optimal crawl times are evenly spaced.
Solving the Discrete, Separable, Convex RAP

- Fox greedy algorithm
  - $O(N + R \log N)$

- Galil and Megiddo algorithm
  - $O(N (\log R)^2)$

- Frederickson and Johnson algorithm
  - $O(\max\{N, N \log (R/N)\})$

- Continuous relaxation / bracket and bisection algorithm also possible
Crawler Scheduling Problem

- $C$ crawlers
  - Crawler $k$ can handle $S_k$ crawls in time $T$

- Time slots $T_{k,l}$

- Cost functions
  - For stochastic web pages $S(t) = |t - t_{i,j}^*|$
  - For quasi-deterministic web pages $S(t) = \begin{cases} 
  \infty & \text{if } t < t_{i,j}^* \\
  t - t_{i,j} & \text{otherwise}
\end{cases}$

- Solvable as transportation problem
Transportation Problem Network

SUPPLY=1

DEMAND=1

CRAWL TASK 1

CRAWL TASK R

SLOT 1

SLOTS

CRAWLER 1

CRAWLER C
Transportation Problem Formulation

Minimize \( \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{M} R_i(T_{jk}) f_{ijk} \) \quad (15)

such that

\[ \sum_{i=1}^{M} f_{ijk} = 1 \ \forall \ 1 \leq j \leq N \ \text{and} \ 1 \leq k \leq M \] (16)

and

\[ \sum_{j=1}^{N} \sum_{k=1}^{M} f_{ijk} = 1 \ \forall \ 1 \leq i \leq M \] (17)
Tail Distributions of Update Processes

- Real web logs

- Can vary across many distribution types
  - Not typically Poisson
  - Often Weibull
  - Sometimes Pareto
  - Quasi-deterministic examples also exist
Average Staleness Metric Examples: Mixed

Average Staleness as Function of Crawl/Web page ratio

- Optimal Scheme
- Proportional Scheme
- Uniform Scheme
Average Staleness Metric Examples: Poisson
Average Staleness Metric Examples:
Pareto

Average Staleness as Function of Crawl/Web page ratio, Pareto Updates

- Typeset by Foil TEXT 31
Average Staleness Metric Examples:
Quasi-Deterministic

Average Staleness as Function of Crawl/Web page ratio, Quasi-Deterministic Updates

- Optimal Scheme
- Proportional Scheme
- Uniform Scheme
Pareto Example

Average Staleness as Function of Pareto Parameter

- Optimal Scheme
- Proportional Scheme
- Uniform Scheme
Scheduling Problem Example

Distribution of Actual/Ideal Task Time Slots

Figure 2: Transportation Problem Solution
Conclusions

• New formulation and solution for important search engine crawler optimization problem
  – Crawling frequency problem
    * Embarassment metric
    * General update distributions
    * Extraordinarily fast RAP solution
  – Crawler scheduling problem
    * Transportation problem formulation

• Study of real web log data
  – Shows many distribution patterns