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Advertising on the Web

CS246: Mining Massive Datasets
Jure Leskovec, Stanford University
http://cs246.stanford.edu
Infinite data: Online Algorithms

High dim. data
- Locality sensitive hashing
- Clustering
- Dimensionality reduction

Graph data
- PageRank, SimRank
- Community Detection
- Spam Detection

Infinite data
- Filtering data streams
- Web advertising
- Queries on streams

Machine learning
- SVM
- Decision Trees
- Parallel SGD

Apps
- Recommender systems
- Association Rules
- Duplicate document detection
Online Algorithms

- Classic model of algorithms
  - You get to see the entire input, then compute some function of it
  - In this context, “offline algorithm”

- Online Algorithms
  - You get to see the input one piece at a time, and need to make irrevocable decisions along the way
  - Similar to the data stream model
Query-to-advertiser graph:

[Andersen, Lang: Communities from seed sets, 2006]
Graph Matching for Advertising

Advertiser X wants to show an ad for topic/query Y

This is an online problem: We have to make decisions as queries/topics show up. We do not know what topics will show up in the future.
Online Bipartite Matching
Example: Bipartite Matching

Nodes: Boys and Girls; Links: Preferences

Goal: Match boys to girls so that the most preferences are satisfied
Example: Bipartite Matching

\[ M = \{(1,a),(2,b),(3,d)\} \text{ is a matching} \]

Cardinality of matching = \( |M| = 3 \)
Example: Bipartite Matching

$M = \{(1,c),(2,b),(3,d),(4,a)\}$ is a **perfect matching**

**Perfect matching** … all vertices of the graph are matched

**Maximum matching** … a matching that contains the largest possible number of matches
Problem: Find a maximum matching for a given bipartite graph
- A perfect one if it exists


But what if we do not know the entire graph upfront?
Initially, we are given the set **boys**

In each **round**, **one girl’s choices are revealed**

- That is, the girl’s **edges** are revealed

At that time, we have to decide to either:

- Pair the **girl** with a **boy**
- Do not pair the **girl** with any **boy**

**Example of application:**
Assigning tasks to servers
Online Graph Matching: Example

\[(1,a)\]
\[(2,b)\]
\[(3,d)\]
Greedy Algorithm

- **Greedy algorithm for the online graph matching problem:**
  - Pair the new girl with **any** eligible boy
    - If there is none, do not pair the girl

- **How good is the algorithm?**
For input $I$, suppose greedy produces matching $M_{greedy}$ while an optimal matching is $M_{opt}$.

Competitive ratio = $\min_{\text{all possible inputs } I} \left( \frac{|M_{greedy}|}{|M_{opt}|} \right)$

(what is greedy’s worst performance over all possible inputs $I$)
Consider a case: $M_{\text{greedy}} \neq M_{\text{opt}}$

Consider the set $G$ of girls matched in $M_{\text{opt}}$ but not in $M_{\text{greedy}}$

(1) By definition of $G$:
$$|M_{\text{opt}}| \leq |M_{\text{greedy}}| + |G|$$

(2) Define set $B$ of boys linked to girls in $G$

- Notice boys in $B$ are already matched in $M_{\text{greedy}}$. Why?
  - If there would exist such non-matched (by $M_{\text{greedy}}$) boy adjacent to a non-matched girl then greedy would have matched them

So: $$|M_{\text{greedy}}| \geq |B|$$
Analyzing the Greedy Algorithm

- **Summary so far:**
  - Girls $G$ matched in $M_{opt}$ but not in $M_{greedy}$
  - Boys $B$ adjacent to girls in $G$
  - (1) $|M_{opt}| \leq |M_{greedy}| + |G|$
  - (2) $|M_{greedy}| \geq |B|$

- Optimal matches all girls in $G$ to (some) boys in $B$
  - (3) $|G| \leq |B|$

- Combining (2) and (3):
  - $|G| \leq |B| \leq |M_{greedy}|$
So we have:

- (1) \(|M_{\text{opt}}| \leq |M_{\text{greedy}}| + |G|\)
- (4) \(|G| \leq |B| \leq |M_{\text{greedy}}|\)

Combining (1) and (4):

- Worst case is when \(|G| = |B| = |M_{\text{greedy}}|\)
- \(|M_{\text{opt}}| \leq |M_{\text{greedy}}| + |M_{\text{greedy}}|\)
- Then \(|M_{\text{greedy}}|/|M_{\text{opt}}| \geq 1/2\)
Worst-case Scenario

1 2 3 4

(1, a)
(2, b)
Web Advertising
History of Web Advertising

- **Banner ads (1995-2001)**
  - Initial form of web advertising
  - Popular websites charged $X for every 1,000 “impressions” of the ad
    - Called “**CPM**” rate (Cost per thousand impressions)
  - Modeled similar to TV, magazine ads
  - From **untargeted** to **demographically targeted**
  - **Low click-through rates**
    - Low ROI for advertisers
Performance-based Advertising

- Introduced by Overture around 2000
  - Advertisers *bid on search keywords*
  - When someone searches for that keyword, the highest bidder’s ad is shown
  - Advertiser is charged only if the ad is clicked on

- Similar model adopted by Google with some changes around 2002
  - Called *Adwords*
Ads vs. Search Results

GEICO Car Insurance. Get an auto insurance quote and save today...
GEICO auto insurance, online car insurance quote, motorcycle insurance quote, online insurance sales and service from a leading insurance company.
www.geico.com/ - 21k - Sep 22, 2005 - Cached - Similar pages
Auto Insurance - Buy Auto Insurance
Contact Us - Make a Payment
More results from www.geico.com »

Geico, Google Settle Trademark Dispute
The case was resolved out of court, so advertisers are still left without legal guidance on use of trademarks within ads or as keywords.

Google and GEICO settle AdWords dispute | The Register
Google and car insurance firm GEICO have settled a trade mark dispute over ... Car insurance firm GEICO sued both Google and Yahoo! subsidiary Overture in ...www.theregister.co.uk/2005/09/09/google_geico_settlement/ - 21k - Cached - Similar pages

GEICO v. Google
... involving a lawsuit filed by Government Employees Insurance Company (GEICO). GEICO has filed suit against two major Internet search engine operators, ...
www.consumeraffairs.com/news04/geico_google.html - 19k - Cached - Similar pages
Performance-based advertising works!
- Multi-billion-dollar industry

Interesting problem:
Which ads to show for a given query?
- (Today’s lecture)

If I am an advertiser, which search terms should I bid on and how much should I bid?
- (Not focus of today’s lecture)
A stream of queries arrives at the search engine: \( q_1, q_2, \ldots \)

Several advertisers bid on each query

When query \( q_i \) arrives, search engine must pick a subset of advertisers to show their ads

**Goal:** Maximize search engine’s revenues

- **Simple solution:** Instead of raw bids, use the “expected revenue per click” (i.e., \( \text{Bid} \times \text{CTR} \))

- **Clearly we need an online algorithm!**
# The Adwords Innovation

<table>
<thead>
<tr>
<th>Advertiser</th>
<th>Bid</th>
<th>CTR</th>
<th>Bid * CTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$1.00</td>
<td>1%</td>
<td>1 cent</td>
</tr>
<tr>
<td>B</td>
<td>$0.75</td>
<td>2%</td>
<td>1.5 cents</td>
</tr>
<tr>
<td>C</td>
<td>$0.50</td>
<td>2.5%</td>
<td>1.25 cents</td>
</tr>
</tbody>
</table>

Click through rate

Expected revenue
## The Adwords Innovation

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Instead of sorting advertisers by bid, sort by expected revenue.
Limitations of Simple Algorithm

Instead of sorting advertisers by bid, sort by expected revenue

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Challenges:

- CTR of an ad is unknown
- Advertisers have limited budgets and bid on multiple queries
Two complications:

- Budget
- CTR of an ad is unknown

1) Budget: Each advertiser has a limited budget

- Search engine guarantees that the advertiser will not be charged more than their daily budget
2) CTR (Click-Through Rate): Each ad-query pair has a different likelihood of being clicked

- **Advertiser 1** bids $2 on query A, click probability = 0.1
- **Advertiser 2** bids $1 on query B, click probability = 0.5

**CTR** is predicted or measured historically

- Averaged over a time period

Some complications we will **not** cover:

- 1) CTR is position dependent:
  - Ad #1 is clicked more than Ad #2
Some complications we will cover (next lecture):

2) Exploration vs. exploitation

Exploit: Should we keep showing an ad for which we have good estimates of click-through rate?

or

Explore: Shall we show a brand new ad to get a better sense of its click-through rate?
Online Algorithms
The BALANCE Algorithm
Given:

1. A set of bids by advertisers for search queries
2. A click-through rate for each advertiser-query pair
3. A budget for each advertiser (say for 1 month)
4. A limit on the number of ads to be displayed with each search query

Respond to each search query with a set of advertisers such that:

1. The size of the set is no larger than the limit on the number of ads per query
2. Each advertiser has bid on the search query
3. Each advertiser has enough budget left to pay for the ad if it is clicked upon
Our setting: Simplified environment

- There is 1 ad shown for each query
- All advertisers have the same budget $B$
- All ads are equally likely to be clicked
- Bid value of each ad is the same ($=\$1$)

Simplest algorithm is greedy:

- For a query pick any advertiser who has bid 1 for that query
- Competitive ratio of greedy is $1/2$
Two advertisers A and B

- A bids on query $x$, B bids on $x$ and $y$
- Both have budgets of $4$

Query stream: $x \ x \ x \ x \ y \ y \ y \ y$

- Worst case greedy choice: B B B B _ _ _ _
- Optimal: A A A A B B B B
- Competitive ratio $= \frac{1}{2}$

This is the worst case!

Note: Greedy algorithm is deterministic – it always resolves draws in the same way
**BALANCE Algorithm [MSVV]**

- **BALANCE** Algorithm by Mehta, Saberi, Vazirani, and Vazirani
  - For each query, pick the advertiser with the largest unspent budget
    - Break ties arbitrarily (**but in a deterministic way**)
Two advertisers A and B

- A bids on query $x$, B bids on $x$ and $y$
- Both have budgets of $4$

Query stream: $x \ x \ x \ x \ y \ y \ y \ y$

BALANCE choice: A B A B B _ _

- Optimal: A A A A B B B B

In general: For BALANCE on 2 advertisers

Competitive ratio $= \frac{3}{4}$
Consider simple case (w.l.o.g.):
- 2 advertisers, $A_1$ and $A_2$, each with budget $B \geq 1$
- Optimal solution exhausts both advertisers’ budgets

**BALANCE must exhaust at least one budget:**
- If not, we can allocate more queries
  - Whenever BALANCE makes a mistake (both advertisers bid on the query), advertiser’s unspent budget only decreases
  - Since optimal exhausts both budgets, one will for sure get exhausted
- Assume BALANCE exhausts $A_2$’s budget, but allocates $x$ queries fewer than the optimal
  - So revenue of $BALANCE = 2B - x$ (where OPT is $2B$)
- Let’s work out what $x$ is!
Analyzing Balance

Opt revenue = 2B
Balance revenue = 2B - x = B + y

Queries allocated to $A_1$ in optimal solution
Queries allocated to $A_2$ in optimal solution

We claim $y \geq x$ (next slide).
Balance revenue is minimum for $x=y=B/2$.
Minimum Balance revenue = $3B/2$.
Competitive Ratio = $3/4$.
Analyzing BALANCE: What’s x?

Optimal revenue = 2B
Assume Balance gives revenue = 2B - x = B + y
Assume we exhausted A₂’s budget

Notice: Unassigned queries should be assigned to A₂ (since if we could assign to A₁ we would since we still have the budget)

Goal: Show we have y ≥ B/2

Case 1) BALANCE assigns at ≥B/2 blue queries to A₁.
Then trivially, y ≥ B/2
Optimal revenue = 2B
Assume Balance gives revenue = 2B-x = B+y
Assume we exhausted A₂’s budget

Unassigned queries should be assigned to A₂
(if we could assign to A₁ we would since we still have the budget)

**Goal:** Show we have \( y \geq B/2 \)

Balance revenue is minimum for \( x = y = B/2 \)
Minimum Balance revenue = \( 3B/2 \)
**Competitive Ratio:** BAL/OPT = 3/4

**Case 2)** BALANCE assigns \( \geq B/2 \) blue queries to A₂.
Consider the last blue query assigned to A₂.
At that time, A₂’s unspent budget must have been at least as big as A₁’s.
That means at least as many queries have been assigned to A₁ as to A₂.
At this point, we have already assigned at least B/2 queries to A₂.
So, \( x \leq B/2 \) and \( x + y = B \) then \( y > B/2 \)
In the general case, worst competitive ratio of BALANCE is \( 1 - \frac{1}{e} \approx 0.63 \)
- \( e = 2.7182 \)
- Interestingly, no online algorithm has a better competitive ratio!

Let’s see the worst case example that gives this ratio
Worst case for BALANCE

- **N advertisers:** $A_1, A_2, \ldots, A_N$
  - Each with budget $B > N$

- **Queries:**
  - $N \cdot B$ queries appear in $N$ rounds of $B$ queries each

- **Bidding:**
  - Round 1 queries: bidders $A_1, A_2, \ldots, A_N$
  - Round 2 queries: bidders $A_2, A_3, \ldots, A_N$
  - Round $i$ queries: bidders $A_i, \ldots, A_N$

- **Optimum allocation:**
  - Allocate all round $i$ queries to $A_i$
  - Optimum revenue $N \cdot B$
BALANCE assigns each of the queries in round 1 to $N$ advertisers. After $k$ rounds, sum of allocations to each of advertisers $A_1, \ldots, A_N$ is

$$S_k = S_{k+1} = \cdots = S_N = \sum_{i=1}^{k} \frac{B}{N-(i-1)}$$

If we find the smallest $k$ such that $S_k \geq B$, then after $k$ rounds we cannot allocate any queries to any advertiser.
**BALANCE: Analysis**

\[
\begin{align*}
B/1 & \quad B/2 & \quad B/3 & \ldots & \quad B/(N-(k-1)) & \ldots & \quad B/(N-1) & \quad B/N \\
1/1 & \quad 1/2 & \quad 1/3 & \ldots & \quad 1/(N-(k-1)) & \ldots & \quad 1/(N-1) & \quad 1/N \\
\end{align*}
\]

- \(S_1\)
- \(S_2\)
- \(S_k = B\)
- \(S_k = 1\)
**Fact:** $H_n = \sum_{i=1}^{n} 1/i \approx \ln(n)$ for large $n$

- Result due to Euler

\[
\begin{align*}
\frac{1}{1} & \quad \frac{1}{2} & \quad \frac{1}{3} & \quad \ldots & \quad \frac{1}{(N-(k-1))} & \quad \ldots & \quad \frac{1}{(N-1)} & \quad \frac{1}{N} \\
\ln(N) & \quad \ln(N-1) & \quad S_k = 1
\end{align*}
\]

- $S_k = 1$ implies: $H_{N-k} = \ln(N) - 1 = \ln\left(\frac{N}{e}\right)$
- We also know: $H_{N-k} = \ln(N - k)$
- So: $N - k = \frac{N}{e}$
- Then: $k = N\left(1 - \frac{1}{e}\right)$

$N$ terms sum to $\ln(N)$.
Last $k$ terms sum to 1.
First $N-k$ terms sum to $\ln(N-k)$ but also to $\ln(N-1)$
BALANCE: Analysis

- So after the first $k=N(1-1/e)$ rounds, we cannot allocate a query to any advertiser

- Revenue = $B \cdot N \cdot (1-1/e)$

- Competitive ratio = $1-1/e$

- Note: So far we assumed:
  - All advertisers have the same budget $B$
  - All advertisers bid 1 for the ad
  - (but each advertiser can bid on any subset of ads)
Arbitrary bids and arbitrary budgets!

Consider we have 1 query $q$, advertiser $i$

- Bid = $x_i$
- Budget = $b_i$

In a general setting BALANCE can be terrible

- Consider two advertisers $A_1$ and $A_2$
  - $A_1$: $x_1 = 1$, $b_1 = 110$
  - $A_2$: $x_2 = 10$, $b_2 = 100$

- Consider we see 10 instances of $q$
- BALANCE always selects $A_1$ and earns 10
- Optimal earns 100
Generalized BALANCE

- **Arbitrary bids**: consider query $q$, bidder $i$
  - Bid = $x_i$
  - Budget = $b_i$
  - Amount spent so far = $m_i$
  - Fraction of budget left over $f_i = 1 - m_i/b_i$
  - Define $\psi_i(q) = x_i(1 - e^{-f_i})$

- Allocate query $q$ to bidder $i$ with largest value of $\psi_i(q)$

- Same competitive ratio $(1 - 1/e) = 0.63$