Lecture 7: Sublinear Time Algorithms

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September 30, 2020

Overview

How do we handle big data? (part II)

Sometimes big data does not come to us (think streaming), but instead we *can query small pieces* of it.

Sometimes big data can also *change over time*, so we need a *robust* answer and/or be able to solve problem quickly multiple times.

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- Many more...

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Connects to *randomized algorithms*, *approximation algorithms*, *parallel algorithms*, *complexity theory*, *statistics*, *learning*

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What we *can* do:

- Can answer **for most** or **averages** or **approximate** type statements *with high probability*
  - are most individuals connected via friendships?
  - are most individuals connected by at most 6 degrees of separation?
  - approximately how many people are left handed?
  - is my program correct on most inputs

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Randomized & *Approximate* algorithms.

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Graphs {
  - Adjacency matrix
  - Adjacency list

$G(V, E)$ $|V| = n$ $|E| = m$

Adjacency matrix

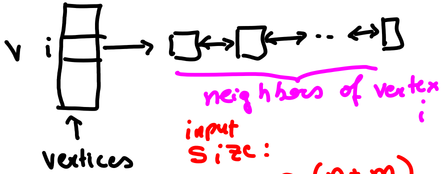
$A \in \mathbb{R}^{n \times n}$

- symmetric*
- $A_{ij} = \begin{cases} 1 & \text{if } \{i, j\} \in E \\ 0 & \text{o.w.} \end{cases}$

(can be weighted)

input size: $N = n^2$

Adjacency list



input size: $N = O(n + m)$

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  - How is input represented?
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    - Location...
    - many others...
- Samples
  - get samples from certain distribution/input at each step

Approximate Diameter of a Point Set

- **Input:** m points and a distance matrix D such that
  - $D_{ij} \leftarrow$ distance from i to j
  - D *symmetric* and satisfies *triangle inequality*

Adjacency matrix representation

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- Let a, b be indices that *maximize* distance D_{ab}. Then D_{ab} is *diameter*
- **Output:** Indices k, ℓ such that

$$D_{k\ell} \geq D_{ab}/2$$

2-multiplicative algorithm

Algorithm & Analysis

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Why does this work?

- Correctness

triangle inequality

symmetry

$$D_{ab} \leq D_{ak} + D_{kb} = D_{ka} + D_{kb}$$
$$\leq D_{k\ell} + D_{k\ell} = 2 \cdot D_{k\ell}$$

↳ property of ℓ.

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- Running time: $O(m) = O(N^{1/2})$

need to find ℓ

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Is this the best we can do?

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- Check that D' satisfies properties of a distance matrix (thus valid)
- **Practice problem:** prove that it would take $\Omega(N)$ time (i.e. number of queries) to decide if diameter is 1 or $2 - \delta$

Connected Components

How to approximate number of connected components of a graph:

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- **Input:** graph $G(V, E)$ in *adjacency list* representation. $\epsilon > 0$.

$$n = |V|,\ m = |E|,\ N = m + n$$

- **Output:** if $C \leftarrow \#$ connected components of G, output with probability $\geq 3/4$ C' such that

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Lemma ($\#$ Connected Components)

Let $G(V, E)$ be a graph. For vertex $v \in V$, let $n_v \leftarrow \#$ vertices in connected component of v. Let C be number of connected components of G. Then:

$$C = \sum_{v \in V} \frac{1}{n_v}$$

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Lemma (Estimating # components)

Let

$$n'_v = \min(n_v, 2/\epsilon)$$

Then

$$\left| \sum_{v \in V} \frac{1}{n_v} - \sum_{v \in V} \frac{1}{n'_v} \right| \leq \frac{\epsilon n}{2}.$$

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How do we do this estimation?

Sample vertex v and run BFS starting at v, short-cutting if see $2/\epsilon$ vertices.

Connected Components - proof of lemma

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- Compute n'_{v_i} using BFS (truncated version)
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- Total running time $O(1/\epsilon^4)$.

Algorithm - Correctness

To prove correctness we need to show that with probability $\geq 3/4$ we have

$$\left| \frac{n}{s} \cdot \sum_{i=1}^{s} \frac{1}{n'_{v_i}} - \sum_{v \in V} \frac{1}{n_v} \right| \leq \epsilon n$$

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Dividing by n/s on both sides:

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By our previous lemma, and triangle inequality, enough to prove that w.h.p.

$$\left| \sum_{i=1}^{s} \frac{1}{n'_{v_i}} - \frac{s}{n} \cdot \sum_{v \in V} \frac{1}{n'_v} \right| \leq \frac{\epsilon s}{2}$$

Lemma and Triangle Inequality

Lemma (Estimating # components)

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$$\left|\sum_{v\in V}\frac{1}{n_v} - \frac{n}{s}\sum_{i=1}^{s}\frac{1}{n'_{v_i}}\right| \le \left|\sum_{v\in V}\frac{1}{n_v} - \sum_{v\in V}\frac{1}{n'_v}\right| +$$

$$\left|\sum_{v\in V}\frac{1}{n'_v} - \frac{n}{s}\sum_{i=1}^{s}\frac{1}{n'_{v_i}}\right| \le \frac{\epsilon n}{2} + \left|\sum_{v\in V}\frac{1}{n'_v} - \frac{n}{s}\sum_{i=1}^{s}\frac{1}{n'_{v_i}}\right| \le \epsilon n$$

$$\Leftrightarrow \left|\sum_{v\in V}\frac{1}{n'_v} - \frac{n}{s}\sum_{i=1}^{s}\frac{1}{n'_{v_i}}\right| \le \frac{\epsilon n}{2} \Leftrightarrow \left|\frac{s}{n}\sum_{v\in V}\frac{1}{n'_v} - \sum_{i=1}^{s}\frac{1}{n'_{v_i}}\right| \le \frac{\epsilon s}{2}$$

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Theorem (Hoeffding's Inequality)

Let X_i be independent random variables, taking values in $[a_i, b_i]$, $X = \sum_{i=1}^{N} X_i$. Then

$$\Pr[|X - \mathbb{E}[X]| \geq \ell] \leq 2 \cdot \exp\left(-\frac{2\ell^2}{\sum_{i=1}^{N}(b_i - a_i)^2} \right)$$

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Setting parameters of Hoeffing's theorem to our setting:

- $a_i = 0$, $b_i = 1$, $N = s$
- $X_i = 1/n'_v$ with probability $1/n$ (pick vertex uniformly at random)

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Hoeffding with the parameters from previous slide and $\ell = \epsilon \cdot s/2$:

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$$\Pr[|X - \mu| \geq \epsilon \cdot s/2] \leq 2 \cdot \exp\left(-\epsilon^2 s/2\right)$$

exactly event we want! (its complement)

Algorithm - Correctness

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Since $s = \Theta(1/\epsilon^2)$, the result follows by choosing $s = 8 \cdot (1/\epsilon^2)$

Acknowledgement

- Lecture based largely on Ronitt's notes.
- See Ronitt's notes at http://people.csail.mit.edu/ronitt/COURSE/F20/Handouts/scribe1.pdf
- See also her notes for approximate MST http://people.csail.mit.edu/ronitt/COURSE/F20/Handouts/scribe2.pdf
- List of open problems in sublinear algorithms https://sublinear.info/index.php?title=Main_Page