EE270
Large scale matrix computation, optimization and learning

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Randomized Linear Algebra and Optimization
Lecture 10: Leverage Scores and Basic Inequality Method

Projected Least Squares Problems

- **Left-sketching**

  Form SA and Sb where $S \in \mathbb{R}^{m \times n}$ is a random projection matrix
- Solve the smaller problem

$$\min_{x \in \mathbb{R}^d} \|SAx - Sb\|_2^2$$

- using any classical method.

  Direct method complexity md^2

Basic Inequality Method

- We minimize $\tilde{x} = \arg\min \|S(Ax - b)\|_2^2$
- x_{LS} minimizes $\|Ax - b\|_2^2$
- How far is $\tilde{x}$ from x_{LS}?
- **Step 1**. Establish two optimality (in)equalities for these variables
- $\|Ax_{LS} - b\|_2^2 \leq \|Ax' - b)\|_2^2$ for any x', i.e., $A^T(Ax_{LS} - b) = 0$
- $\|S(A\tilde{x} - b)\|_2^2 \leq \|S(Ax_{LS} - b)\|_2^2$

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- **Step 2**. Define error $\Delta = \tilde{x} - x_{LS}$ and re-write these inequalities in terms of δ
- $\|SA\Delta\|_2^2 \leq 2{b^{\perp}}^T(S^TS - I)A\Delta$
- **Step 3**. Argue $S^TS \approx I$

Basic Inequality Method

- $\|SA\Delta\|_2^2 \leq 2{b^{\perp}}^T(S^TS - I)A\Delta$

$$\begin{aligned}
\max_{\Delta}\left|\frac{\|SA\Delta\|_2^2}{\|A\Delta\|_2^2} - 1\right| &= \max_{z}\left|\frac{\|SUz\|_2^2}{\|z\|_2^2} - 1\right| \\
&= \max_{z}\left|\frac{z^T}{\|z\|_2}(U^TS^TSU - I)\frac{z}{\|z\|_2}\right| \\
&= \sigma_{\max}^2(U^TS^TSU - I)
\end{aligned}$$

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$$= \max_{z}\left|\frac{z^T}{\|z\|_2}(U^TS^TSU - I)\frac{z}{\|z\|_2}\right|$$
$$= \sigma_{\max}^2(U^TS^TSU - I)$$

- Approximate matrix multiplication (AMM):

$$\sigma_{\max}(U^TS^TSU - I) \leq \|U^TS^TSU - \underbrace{U^TU}_{I}\|_F \leq \epsilon\|U^TU\|_F^2$$

- This is called a Subspace Embedding

  we can rescale ϵ to get $\sigma_{\max}(U^TS^TSU - I) \leq \epsilon$ for appropriate m

Basic Inequality Method

- $\|SA\Delta\|_2^2 \leq 2{b^{\perp}}^T(S^TS - I)A\Delta$
- Now consider the right handside

$$= 2{b^{\perp}}^T(S^TS - I)UU^TA\Delta \leq 2\|{b^{\perp}}^T(S^TS - I)UU^T\|_2\|A\Delta\|$$

- AMM again: $\|b^{\perp}S^TSUU^T - b^{\perp}UU^T\|_F \leq \frac{\epsilon}{\sqrt{m}}\|b^{\perp}\|_F\|UU^T\|_F \leq \frac{\epsilon}{\sqrt{m}}f(x_{LS})\sqrt{d}$

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Basic Inequality Method

- $\|SA\Delta\|_2^2 \leq 2{b^{\perp}}^T(S^TS - I)A\Delta$
- Summarizing two bounds:
- (1) $\max_{\Delta} \left| \frac{\|SA\Delta\|_2^2}{\|A\Delta\|_2^2} - 1 \right| \leq \epsilon'$
- (2) $2{b^{\perp}}^T(S^TS - I)A\Delta \leq \frac{\epsilon}{\sqrt{m}} f(x_{LS})\sqrt{d}\|A\Delta\|_2$

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  (1) implies $-\epsilon'\|A\Delta\|_2^2 \leq \|SA\Delta\|_2^2 - \|A\Delta\|_2^2 \leq \epsilon'\|A\Delta\|_2^2$

  hence $(1 - \epsilon')\|A\Delta\|_2^2 \leq \|SA\Delta\|_2^2$

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- Plugging in: $(1-\epsilon')\|A\Delta\|_2^2 \leq \frac{\epsilon}{\sqrt{m}} f(x_{LS})\sqrt{d}\|A\Delta\|_2$

  $\|A\Delta\|_2 \leq \frac{\epsilon}{1-\epsilon'} f(x_{LS}) \frac{\sqrt{d}}{\sqrt{m}}$

Leverage Scores

- Intuition: Approximate Matrix Multiplication for $U^T U$ i.e, $\|U^T S^T S U - U^T U\|_F = \|U^T S^T S U - I\|_F \leq \epsilon$ implies Least Squares cost approximation

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  $\|U^T S^T S U - U^T U\|_F = \|U^T S^T S U - I\|_F \leq \epsilon$
  implies Least Squares cost approximation
- We can pick a sampling matrix S
- Importance sampling: proportional to the rows norms of U
- Leverage scores: $\ell_i := \|u_i\|_2^2$ for $i = 1, \dots n$
- $\sum_i \ell_i = \sum_i \|u_i\|_2^2 = \|U\|_F^2 = trU^T U = trI_d = d$ when A is full column rank
- Sampling probabilities: $p_i = \frac{1}{d}\|u_i\|_2^2$
  $\sum_i p_i = 1$
- Can be non-uniform or uniform $A = [I; 0]$

Fast Johnson Lindenstrauss Transform

- Let H be the $n \times n$ Hadamard matrix
- Generate an $n \times n$ diagonal matrix of random ± 1 uniform signs
- Uniform $m \times n$ sub-sampling matrix P scaled with $\frac{\sqrt{n}}{\sqrt{m}}$
- Let $S = PHD$.
- Note that $\mathbb{E} S^T S = I$

FJLT Preconditions Leverage Scores

- Fix a set X of n vectors in d-dimension. With high probability $\max_{x \in X} \|HDX\|_\infty \leq \sqrt{\frac{\log(n)}{d}}$

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- Fix a set X of n vectors in d-dimension. With high probability
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  Apply HD to data A
- $PHDA$ is uniformly sampled HDA
  Leverage scores of HDU are near uniform
  uniform sampling works!

Questions?