CSE 392/CS 395T/M 397C: Matrix and Tensor Algorithms for Data

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Spring 2025

Lecture 12: Subspace iteration (power) method

Outline

1. Iterative methods
2. Subspace iteration methods
   - Power method
   - Block power method

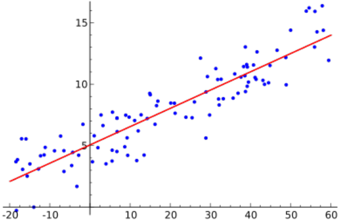
Covered so far:

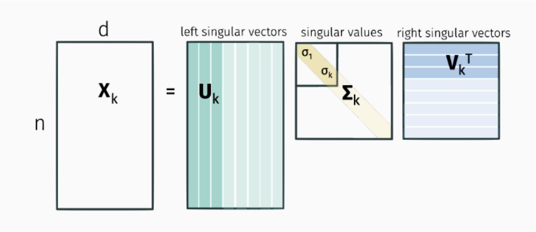
- Linear least squares regression and Low rank approximation.
- *Linear Regression*: Given a data matrix $\boldsymbol{A} \in \mathbb{R}^{n \times d}$ and a column vector $\boldsymbol{b} \in \mathbb{R}^n$, *least-squares* regression solves:

$$\boldsymbol{x}^* = \arg\min_{\boldsymbol{x} \in \mathbb{R}^d} \|\boldsymbol{A}\boldsymbol{x} - \boldsymbol{b}\|^2. \tag{1}$$

- *Low rank approximation*: Given a data matrix $\boldsymbol{A} \in \mathbb{R}^{n \times d}$ and integer k, find a rank-k approximation of $\boldsymbol{A}$, such that.

$$\boldsymbol{A}_k = \arg\min_{\boldsymbol{W}:\mathrm{rank}(\boldsymbol{W})=k} \|\boldsymbol{A} - \boldsymbol{W}\|_F. \tag{2}$$





Covered so far: Sketching

SKETCH AND SOLVE

Generic scheme using sketching:

```
generate sketching matrix S ∈ ℝ^{m×n},
compute SA and Sb
return x̃ := argmin_{x∈ℝ^d} ||S(Ax − b)||
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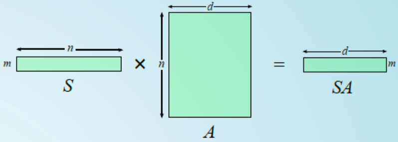

- Oblivious sketching - subspace embedding property.
- $\|\boldsymbol{A}\tilde{\boldsymbol{x}} - \boldsymbol{b}\| \leq (1+\epsilon)\|\boldsymbol{A}\boldsymbol{x}^* - \boldsymbol{b}\|$.
- Similarly for low rank approximation: Suppose $\tilde{\boldsymbol{A}}_k$ is rank k approximation obtained using sketching $\boldsymbol{A}\boldsymbol{S}$, then
$$\|\boldsymbol{A} - \tilde{\boldsymbol{A}}_k\|_F \leq (1+\epsilon)\|\boldsymbol{A} - \boldsymbol{A}_k\|_F.$$
- *Skylark project*: open source library for distributed randomized numerical linear algebra, funded through XDATA program by **DARPA** and **Air Force Research Laboratory**.

Iterative methods

- *Sketching methods* : Single pass over data. Advantageous when data is too large to fit in memory. Streaming settings.
- *Sketch size:* For rank-k approximation, for dense input matrices - Gaussian - $O\left(\frac{k}{\epsilon}\right)$ or SRFT/SRHT - $O\left(\frac{k\log(k/\epsilon)}{\epsilon}\right)$.

  Sparse matrices - Countsketch - $O\left(\frac{k^2}{\epsilon}\right)$.

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- *Iterative methods* - Multiple passes over data. Improved numerical results. Predate sketching methods.
- In *numerous fields* (system solvers, optimization, control systems, PDE solvers, scientific computing, NLP, etc.) and *many industry* (oil refineries, auto modeling, electronics, Google and Twitter (X?) and many more.)
- Partial SVD - compute top k singular vectors/values.
  1. Subspace iteration or block power method.
  2. Krylov subspace method.

Recall : PageRank

- PageRank value of a page is given as:

$$PR(p_i) = \frac{1-d}{N} + d \sum_{p_j \in M(p_i)} \frac{PR(p_j)}{L(p_j)},$$

  $p_1, p_2, ..., p_N$ are the pages, $M(p_i)$ = set of pages that link to p_i, $L(p_j)$ = number of outbound links on page p_j, N = total number of pages, and d = damping factor.
- The values are the entries of the dominant right eigenvector of the modified adjacency matrix rescaled so that each column adds up to one.

$$\mathbf{r} = \begin{bmatrix} PR(p_1) \\ PR(p_2) \\ \vdots \\ PR(p_N) \end{bmatrix}$$

- $\mathbf{r}$ is the solution of the equation

$$\mathbf{r} = \begin{bmatrix} (1-d)/N \\ (1-d)/N \\ \vdots \\ (1-d)/N \end{bmatrix} + d \begin{bmatrix} \ell(p_1,p_1) & \ell(p_1,p_2) & \cdots & \ell(p_1,p_N) \\ \ell(p_2,p_1) & \ddots & & \vdots \\ \vdots & & \ell(p_i,p_j) & \\ \ell(p_N,p_1) & \cdots & & \ell(p_N,p_N) \end{bmatrix} \mathbf{r}$$

  the adjacency function $\ell(p_i,p_j)$ is the ratio between number of links outbound from page j to page i to the total number of outbound links of page j.

- $$\sum_{i=1}^{N} \ell(p_i,p_j) = 1,$$

  The matrix is a stochastic matrix. Closely related to the problem of finding the stationary points of Markov processes. It is also a variant of the eigenvector centrality measure used commonly in network analysis.

Subspace iteration methods

Questions

- Given a symmetric matrix $\boldsymbol{A}$ with eigen-decomposition $\boldsymbol{A} = \boldsymbol{U}\Lambda\boldsymbol{U}^\top$, then
  1. What are the eigenvalues/eigenvectors of $\boldsymbol{A}^q$ for a given integer power q?
  2. If $\boldsymbol{A}$ is nonsingular what are the eigenvalues/eigenvectors of $\boldsymbol{A}^{-1}$?
  3. What are the eigenvalues/eigenvectors of $p(\boldsymbol{A})$ for a polynomial $p(\cdot)$?
- If the matrix $\boldsymbol{A}$ has a certain spectral gap $|\lambda_1 - \lambda_2|$, what can we say about the spectral gap of $\boldsymbol{A}^2$? Does it increase, decrease or remain the same in general?
- Similarly, for a general matrix $\boldsymbol{A} \in \mathbb{R}^{n \times d}$, with SVD $\boldsymbol{A} = \boldsymbol{U}\Sigma\boldsymbol{V}^\top$, what are the singular/eigen-values of $\boldsymbol{A}^\top\boldsymbol{A}$?

Power Method

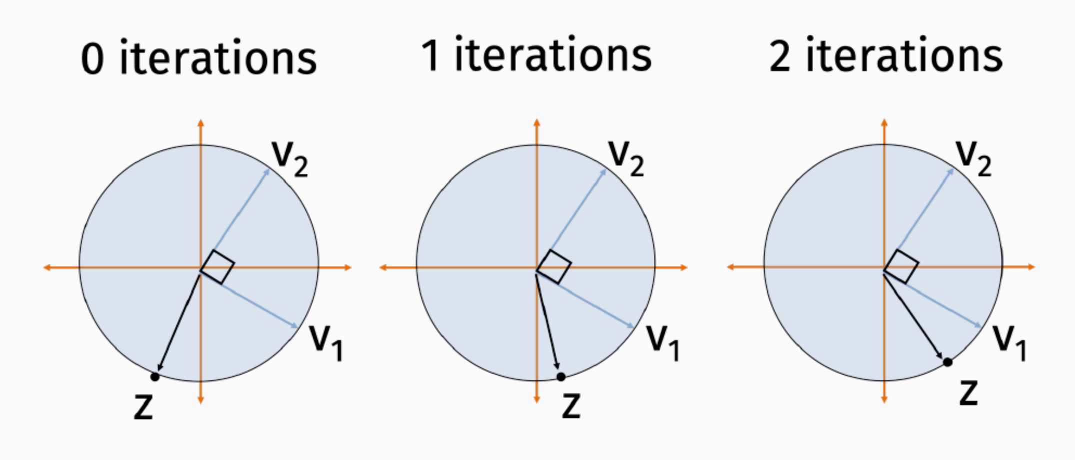
- Let us start with $k = 1$ (finding the top singular vector/value).
- Given a matrix $\boldsymbol{A} \in \mathbb{R}^{n \times d}$, with SVD $\boldsymbol{A} = \boldsymbol{U}\Sigma\boldsymbol{V}^\top$, find a vector $\boldsymbol{z} \approx \boldsymbol{v}_1$.

Power Method

- Choose a random vector $\boldsymbol{z}_0$, E.g., $\boldsymbol{z}_0 \sim \mathcal{N}(0, 1)$.
- $\boldsymbol{z}_0 = \boldsymbol{z}_0 / \|\boldsymbol{z}_0\|_2$
- For $l = 1, \ldots, q$
  - $\boldsymbol{z}_l = \boldsymbol{A}^\top(\boldsymbol{A}\boldsymbol{z}_{l-1})$
  - $\boldsymbol{z}_l = \boldsymbol{z}_l / \|\boldsymbol{z}_l\|_2$
- Return $\boldsymbol{z}_q$

Runtime = ?

Power method intuition



Convergence

Theorem (Power Method Convergence)

Let $\gamma = \frac{\sigma_1 - \sigma_2}{\sigma_1}$ be parameter capturing the gap between the first and second largest singular values. If Power Method is initialized with a random Gaussian vector with $\boldsymbol{A} \in \mathbb{R}^{n \times d}$ then, with high probability, after $q = O\left(\frac{\log d/\epsilon}{\gamma}\right)$ steps, we have:

$$\|\boldsymbol{v}_1 - \boldsymbol{z}_q\|_2 \leq \epsilon.$$

Total runtime: $O(\mathrm{nnz}(\boldsymbol{A})q) = O\left(\mathrm{nnz}(\boldsymbol{A}) \cdot \frac{\log d/\epsilon}{\gamma}\right)$.

Above also implies, $\|\boldsymbol{A}\boldsymbol{z}_q\boldsymbol{z}_q^\top\|_F^2 \geq (1-\epsilon)^2\|\boldsymbol{A}\boldsymbol{v}_1\boldsymbol{v}_1^\top\|_F^2$.

Proof

- Let us write $\boldsymbol{z}_0 = \sum_{i=1}^{d} \mu_i \boldsymbol{v}_i$ in terms of the right singular vector basis.
- If $\boldsymbol{\mu} = [\mu_1, \ldots, \mu_d]$, we have $\boldsymbol{\mu} = \boldsymbol{V}^\top \boldsymbol{g} / \|\boldsymbol{g}\|_2$ for random Gaussian $\boldsymbol{g}$.
- Since $\boldsymbol{V}$ is orthogonal , we have $\|\boldsymbol{\mu}\|^2 = 1$.
- With high probability,

$$1/\text{poly}(d) \leq |\mu_i| \leq 1 \quad i = 1, \ldots, d.$$

Note that $\boldsymbol{\mu}$ is Gaussian. We can show that $\text{poly}(d) \approx d^3$ with high probability.

- After q steps, we have $\boldsymbol{z}_q = c(\boldsymbol{A}^\top \boldsymbol{A})^q \boldsymbol{z}_0$ for some scaling c.
- If we write $\boldsymbol{z}_q = \sum_{i=1}^{d} \rho_i \boldsymbol{v}_i$, we have

$$\rho_i = c\sigma_i^{2q} \mu_i.$$

Since $\boldsymbol{A}^\top \boldsymbol{A} = \boldsymbol{V} \Sigma^2 \boldsymbol{V}^\top$.

- After q steps, we have $\boldsymbol{z}_q = c(\boldsymbol{A}^\top \boldsymbol{A})^q \boldsymbol{z}_0$ for some scaling c.
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  Since $\boldsymbol{A}^\top \boldsymbol{A} = \boldsymbol{V}\Sigma^2\boldsymbol{V}^\top$.
- If the gap parameter is $\gamma = \frac{\sigma_1 - \sigma_2}{\sigma_1}$, we can show that, for all $j \geq 2$:

$$\frac{\sigma_j}{\sigma_1} \leq (1-\gamma).$$

- For all $j \geq 2$,

$$\frac{|\rho_j|}{|\rho_1|} \leq (1-\gamma)^{2q}\frac{|\mu_i|}{|\mu_1|} \leq (1-\gamma)^{2q}\text{poly}(d).$$

- For any $0 < x \leq 1$, we can show that $(1-x)^{\frac{q}{x}} \leq e^{-q}$.
(Hint: use Taylor series for $\log(1-x)$).
- If we set $q = \frac{\log(\text{poly}(d)\sqrt{d/\epsilon})}{\gamma} = O\left(\frac{\log d/\epsilon}{\gamma}\right)$, then we get $\frac{|\rho_j|}{|\rho_1|} \leq \sqrt{\epsilon/d}$.
- Since $\boldsymbol{z}_q$ is a unit vector, we have $\sum_i \rho_i^2 = 1$, and $|\rho_1| \leq 1$, hence

$$\rho_1^2 \geq 1 - d(\sqrt{\epsilon/d})^2 \implies |\rho_1| \geq 1 - \epsilon.$$

Therefore,

$$\|\boldsymbol{v}_1 - \boldsymbol{z}_q\|_2 = 2 - 2\langle \boldsymbol{v}_1, \boldsymbol{z}_q \rangle \leq 2\epsilon.$$

Analysis without gap

Theorem (Gapless Power Method Convergence)

If Power Method is initialized with a random Gaussian vector then, with high probability, after $q = O\left(\frac{\log d/\epsilon}{\epsilon}\right)$ steps, we obtain a $\boldsymbol{z}_q$ satisfying:

$$\|\boldsymbol{A} - \boldsymbol{A}\boldsymbol{z}_q\boldsymbol{z}_q^\top\|_F^2 \leq (1+\epsilon)\|\boldsymbol{A} - \boldsymbol{A}\boldsymbol{v}_1\boldsymbol{v}_1^\top\|_F^2.$$

Gap γ might be too small. Then, we do not care to find $\boldsymbol{v}_1$. Say, $\sigma_1 = \sigma_2$, then $\boldsymbol{v}_2$ is as *good* as $\boldsymbol{v}_1$.

Proof:
We know that $\|\boldsymbol{A} - \boldsymbol{A}\boldsymbol{z}_q\boldsymbol{z}_q^T\|_F^2 = \|\boldsymbol{A}\|_F^2 - \|\boldsymbol{A}\boldsymbol{z}_q\boldsymbol{z}_q^T\|_F^2$.
So, to prove the above, we need to show $\|\boldsymbol{A}\boldsymbol{z}_q\|_2^2 \geq (1-\epsilon)^2\sigma_1^2$.

We have,

$$\|\boldsymbol{A}\boldsymbol{z}_q\|_2^2 = \boldsymbol{z}_q^T\boldsymbol{A}^T\boldsymbol{A}\boldsymbol{z}_q = \sum_{i=1}^{d} \rho_i^2\sigma_i^2,$$

where $\rho_i = \boldsymbol{v}_i^T\boldsymbol{z}_q$.

Proof:
We know that $\|\boldsymbol{A} - \boldsymbol{A}\boldsymbol{z}_q\boldsymbol{z}_q^T\|_F^2 = \|\boldsymbol{A}\|_F^2 - \|\boldsymbol{A}\boldsymbol{z}_q\boldsymbol{z}_q^T\|_F^2$.
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We have,

$$\|\boldsymbol{A}\boldsymbol{z}_q\|_2^2 = \boldsymbol{z}_q^T\boldsymbol{A}^T\boldsymbol{A}\boldsymbol{z}_q = \sum_{i=1}^{d} \rho_i^2\sigma_i^2,$$

where $\rho_i = \boldsymbol{v}_i^T\boldsymbol{z}_q$.
For $q = O\left(\frac{\log d/\epsilon}{\epsilon}\right)$, from our previous analysis we have $\rho_1 \geq (1-\epsilon)$. Hence,

$$\|\boldsymbol{A}\boldsymbol{z}_q\|_2^2 = \sum_{i=1}^{d} \rho_i^2\sigma_i^2 \geq \rho_1^2\sigma_1^2 \geq (1-\epsilon)^2\sigma_1^2.$$

Subspace iteration

- For larger $k \geq 1$ (finding the top-k singular vectors/values).
- Block Power Method aka Simultaneous Iteration aka Subspace Iteration aka Orthogonal Iteration.

Block Power Method

- Choose $\boldsymbol{S} \in \mathbb{R}^{d \times k}$ a random Gaussian matrix .
- $\boldsymbol{Z}_0 = \mathrm{orth}(\boldsymbol{S})$
- For $l = 1, \ldots, q$
  - $\boldsymbol{Z}_l = \boldsymbol{A}^\top(\boldsymbol{A}\boldsymbol{Z}_{l-1})$
  - $\boldsymbol{Z}_l = \mathrm{orth}(\boldsymbol{Z}_l)$.
- Return $\boldsymbol{Z}_q$

Total runtime: $O(\mathrm{nnz}(\boldsymbol{A})kq)$.

Subspace iteration

- Equivalent to sketching with input $(\boldsymbol{A}^\top \boldsymbol{A})^q$.
- With $q = O\left(\frac{\log d/\epsilon}{\epsilon}\right)$, we obtain a nearly optimal low-rank approximation:

$$\|\boldsymbol{A} - \boldsymbol{A}\boldsymbol{Z}\boldsymbol{Z}^\top\|_F^2 \le (1+\epsilon)\|\boldsymbol{A} - \boldsymbol{A}\boldsymbol{V}_k\boldsymbol{V}_k^\top\|_F^2.$$

- For $q = O\left(\frac{\log(nd)}{\epsilon}\right)$, we have

$$\|\boldsymbol{A} - \boldsymbol{A}\boldsymbol{Z}\boldsymbol{Z}^\top\|_2 \le (1+\epsilon)\|\boldsymbol{A} - \boldsymbol{A}_k\|_2.$$

Subspace iteration

Further Reading:

- *Sketching as a Tool for Numerical Linear Algebra* by David Woodruff.
- *Subspace iteration randomization and singular value problems* by Ming Gu.
- *Finding structure with randomness: Probabilistic algorithms for constructing approximate matrix decompositions* by N Halko, P. Martinsson and J. Tropp.

Matlab Demo