CS-GY 9223 D: Lecture 3 Supplemental
The Johnson-Lindenstrauss Lemma

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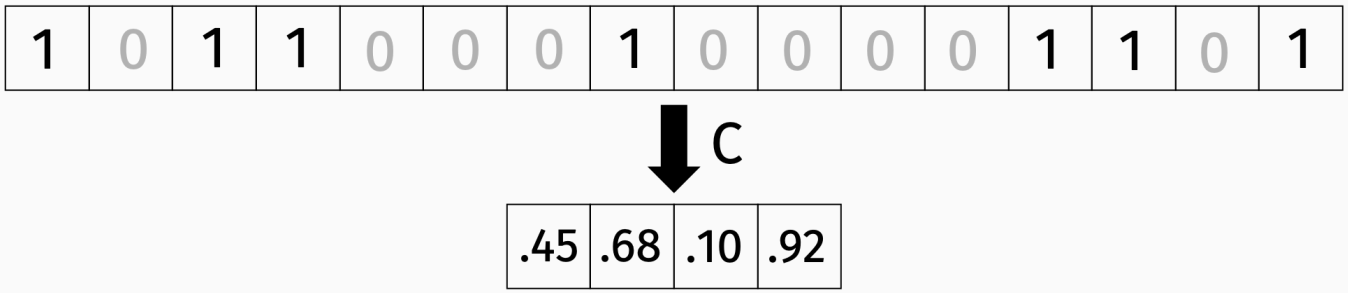
Abstract architecture of a sketching algorithm:

- Given a dataset $D = d_1, \ldots, d_n$ with n pieces of data, we want to output $f(D)$ for some function f.
- **Sketch phase:** For each $i \in 1, \ldots, n$, compute $s_i = C(d_i)$, where C is some compression function and $|s_i| \ll d_i$.
- **Process phase:** Using (lower dimensional) dataset $s_1, \ldots, s_n$, compute an approximation to $f(D)$.

Better space complexity, communication complexity, runtime, all at once.

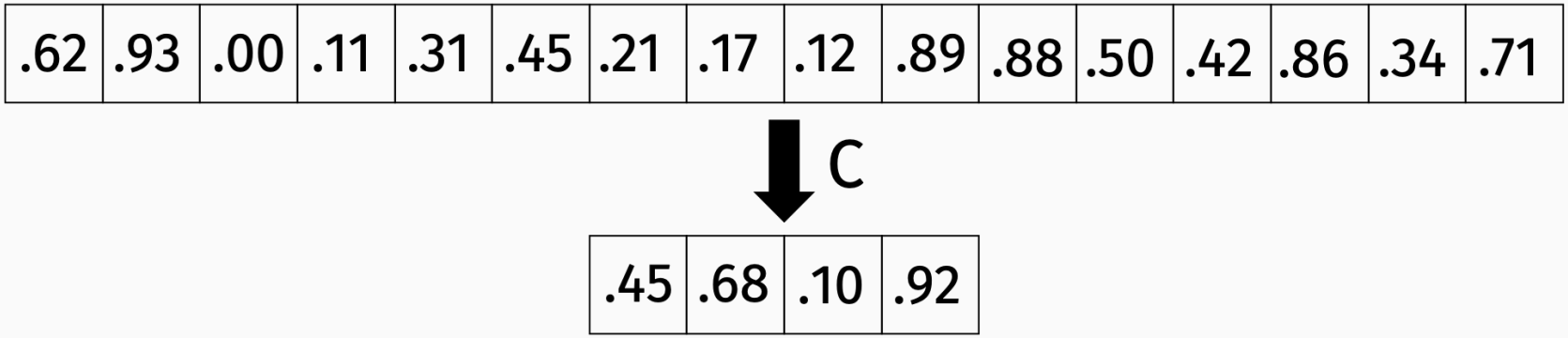
BINARY VECTOR COMPRESSION

We already saw a powerful application of sketching (the MinHash algorithm) to compressing binary vectors.



Let us estimate the Jaccard similarity between any two binary vectors $\mathbf{q}$ and $\mathbf{y}$ using the information in $C(\mathbf{q})$ and $C(\mathbf{y})$ alone.

TODAY: EUCLIDEAN DIMENSIONALITY REDUCTION



Euclidean norm / distance:

- Given $\mathbf{q} \in \mathbb{R}^d$, $\|\mathbf{q}\|_2 = \sqrt{\sum_{i=1}^{d} q(i)^2}$.
- Given $\mathbf{q}, \mathbf{y} \in \mathbb{R}^d$, distance defined as $\|\mathbf{q} - \mathbf{y}\|_2$.

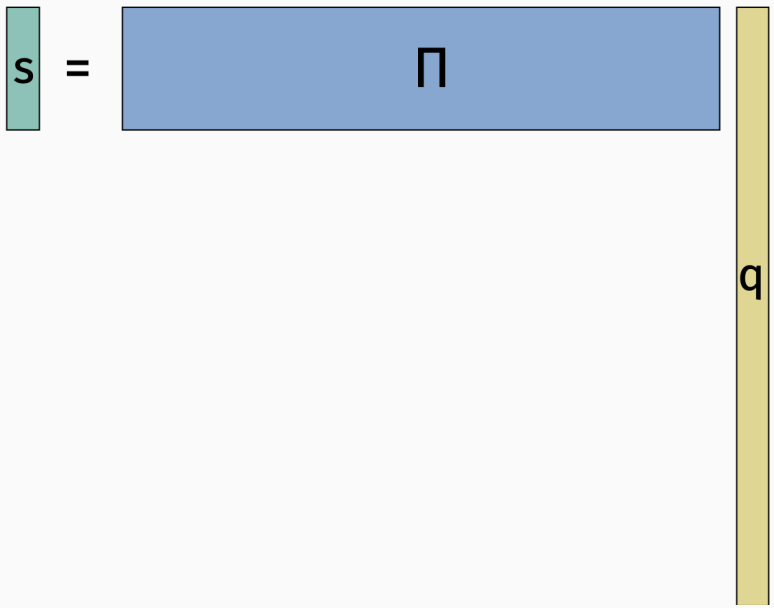
Can we find compact sketches that preserve Euclidean distance, just as we did for Jaccard similarity?

EUCLIDEAN DIMENSIONALITY REDUCTION

Lemma (Johnson-Lindenstrauss, 1984)

For any set of n data points $\mathbf{q}_1, \ldots, \mathbf{q}_n \in \mathbb{R}^d$ there exists a linear map $\Pi : \mathbb{R}^d \to \mathbb{R}^k$ where $k = O\left(\frac{\log n}{\epsilon^2}\right)$ such that for all i, j,

$$(1-\epsilon)\|\mathbf{q}_i - \mathbf{q}_j\|_2 \leq \|\mathbf{\Pi}\mathbf{q}_i - \mathbf{\Pi}\mathbf{q}_j\|_2 \leq (1+\epsilon)\|\mathbf{q}_i - \mathbf{q}_j\|_2.$$



Please remember: This is equivalent to:

Lemma (Johnson-Lindenstrauss, 1984)

For any set of n data points $\mathbf{q}_1, \ldots, \mathbf{q}_n \in \mathbb{R}^d$ there exists a linear map $\mathbf{\Pi} : \mathbb{R}^d \to \mathbb{R}^k$ where $k = O\left(\frac{\log n}{\epsilon^2}\right)$ such that for all i, j,

$$(1-\epsilon)\|\mathbf{q}_i - \mathbf{q}_j\|_2^2 \leq \|\mathbf{\Pi}\mathbf{q}_i - \mathbf{\Pi}\mathbf{q}_j\|_2^2 \leq (1+\epsilon)\|\mathbf{q}_i - \mathbf{q}_j\|_2^2.$$

because for small ϵ, $(1+\epsilon)^2 = 1 + O(\epsilon)$ and $(1-\epsilon)^2 = 1 - O(\epsilon)$.

And this is equivalent to:

Lemma (Johnson-Lindenstrauss, 1984)

For any set of n data points $\mathbf{q}_1, \ldots, \mathbf{q}_n \in \mathbb{R}^d$ there exists a linear map $\Pi : \mathbb{R}^d \to \mathbb{R}^k$ where $k = O\left(\frac{\log n}{\epsilon^2}\right)$ such that for all i, j,

$$(1-\epsilon)\|\mathbf{\Pi}\mathbf{q}_i - \mathbf{\Pi}\mathbf{q}_j\|_2^2 \leq \|\mathbf{q}_i - \mathbf{q}_j\|_2^2 \leq (1+\epsilon)\|\mathbf{\Pi}\mathbf{q}_i - \mathbf{\Pi}\mathbf{q}_j\|_2^2.$$

because for small ϵ, $\frac{1}{1+\epsilon} = 1 - O(\epsilon)$ and $\frac{1}{1-\epsilon} = 1 + O(\epsilon)$.

Remarkably, Π can be chosen completely at random!

One possible construction: Random Gaussian.

$$\Pi_{i,j} = \frac{1}{\sqrt{k}}\mathcal{N}(0,1)$$

The map Π is oblivious to the data set. This stands in contrast to e.g. PCA, amoung other differences.

[Indyk, Motwani 1998] [Arriage, Vempala 1999] [Achlioptas 2001] [Dasgupta, Gupta 2003].

Many other possible choices suffice – you can use random $\{+1, -1\}$ variables, sparse random matrices, pseudorandom Π. Each with different advantages.

RANDOMIZED JL CONSTRUCTIONS

Let $\mathbf{\Pi} \in \mathbb{R}^{k \times d}$ be chosen so that each entry equals $\frac{1}{\sqrt{k}}\mathcal{N}(0,1)$.

... or each entry equals $\frac{1}{\sqrt{k}} \pm 1$ with equal probability.

-2.1384	2.9080	-0.3538	0.0229	0.5201	-0.2938	-1.3320	-1.3617	-0.1952
-0.8396	0.8252	-0.8236	-0.2620	-0.0200	-0.8479	-2.3299	0.4550	-0.2176
1.3546	1.3790	-1.5771	-1.7502	-0.0348	-1.1201	-1.4491	-0.8487	-0.3031
-1.0722	-1.0582	0.5080	-0.2857	-0.7982	2.5260	0.3335	-0.3349	0.0230
0.9610	-0.4686	0.2820	-0.8314	1.0187	1.6555	0.3914	0.5528	0.0513
0.1240	-0.2725	0.0335	-0.9792	-0.1332	0.3075	0.4517	1.0391	0.8261
1.4367	1.0984	-1.3337	-1.1564	-0.7145	-1.2571	-0.1303	-1.1176	1.5270
-1.9609	-0.2779	1.1275	-0.5336	1.3514	-0.8655	0.1837	1.2607	0.4669
-0.1977	0.7015	0.3502	-2.0026	-0.2248	-0.1765	-0.4762	0.6601	-0.2097
-1.2078	-2.0518	-0.2991	0.9642	-0.5890	0.7914	0.8620	-0.0679	0.6252

```
>> Pi = randn(m,d);
>> s = (1/sqrt(m))*Pi*q;
```

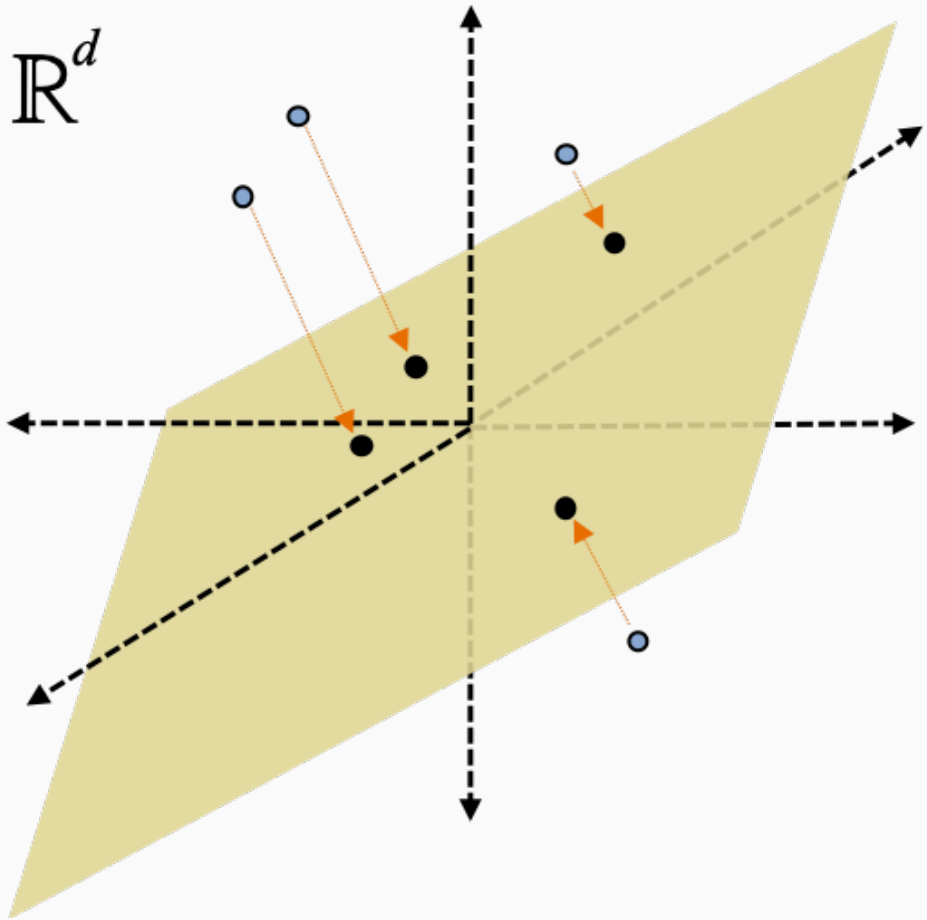
1	1	-1	-1	-1	-1	-1	-1	1	-1	-1	1	-1	-1	1	1	-1
1	1	1	-1	1	-1	-1	-1	1	1	1	1	-1	1	-1	-1	-1
1	1	-1	-1	-1	1	-1	-1	1	1	-1	1	-1	1	-1	1	-1
-1	-1	-1	1	1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1
1	-1	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	-1	1
1	-1	-1	1	-1	1	1	-1	-1	-1	1	-1	-1	-1	1	1	1
1	1	-1	1	1	-1	1	-1	1	-1	1	-1	1	1	1	-1	-1
-1	-1	-1	-1	-1	-1	1	-1	1	1	-1	-1	1	-1	-1	1	1
-1	-1	1	1	1	1	-1	-1	1	-1	1	1	1	-1	1	-1	1
-1	1	-1	1	-1	1	1	-1	-1	1	-1	1	-1	-1	1	-1	1

```
>> Pi = 2*randi(2,m,d)-3;
>> s = (1/sqrt(m))*Pi*q;
```

A random orthogonal matrix also works. I.e. with $\mathbf{\Pi}\mathbf{\Pi}^T = \mathbf{I}_{k \times k}$.

For this reason, the JL operation is often called a “random projection”, even though it technically isn’t a projection when entries are i.i.d.

RANDOM PROJECTION



Intuitively, close points will remain close after projection, and far points will remain far.

Intermediate result:

Lemma (Distributional JL Lemma)

Let $\mathbf{\Pi} \in \mathbb{R}^{k \times d}$ *be chosen so that each entry equals* $\frac{1}{\sqrt{k}}\mathcal{N}(0,1)$, *where* $\mathcal{N}(0,1)$ *denotes a standard Gaussian random variable.*

If we choose $k = O\left(\frac{\log(1/\delta)}{\epsilon^2}\right)$, *then for any vector* $\mathbf{x}$, *with probability* $(1-\delta)$:

$$(1-\epsilon)\|\mathbf{x}\|_2^2 \leq \|\mathbf{\Pi}\mathbf{x}\|_2^2 \leq (1+\epsilon)\|\mathbf{x}\|_2^2$$

Given this lemma, how do we prove the traditional Johnson-Lindenstrauss lemma?

JL FROM DISTRIBUTIONAL JL

We have a set of vectors $\mathbf{q}_1, \ldots, \mathbf{q}_n$. Fix $i, j \in 1, \ldots, n$.

Let $\mathbf{x} = \mathbf{q}_i - \mathbf{q}_j$. By linearity, $\mathbf{\Pi x} = \mathbf{\Pi}(\mathbf{q}_i - \mathbf{q}_j) = \mathbf{\Pi q}_i - \mathbf{\Pi q}_j$.

By the Distributional JL Lemma, with probability $1 - \delta$,

$$(1-\epsilon)\|\mathbf{q}_i - \mathbf{q}_j\|_2 \leq \|\mathbf{\Pi q}_i - \mathbf{\Pi q}_j\|_2 \leq (1+\epsilon)\|\mathbf{q}_i - \mathbf{q}_j\|_2.$$

Finally, set $\delta = \frac{1}{n^2}$. Since there are $< n^2$ total i, j pairs, by a union bound we have that with probability $9/10$, the above will hold for all i, j, as long as we compress to:

$$k = O\left(\frac{\log(1/(1/n^2))}{\epsilon^2}\right) = O\left(\frac{\log n}{\epsilon^2}\right) \text{ dimensions.} \quad \square$$

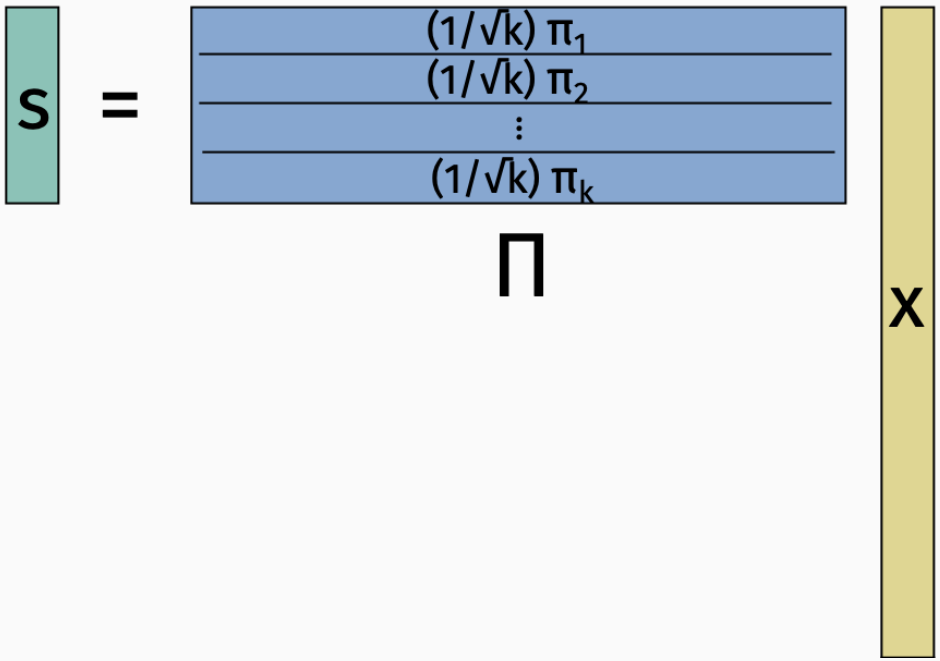
PROOF OF DISTRIBUTIONAL JL

Want to argue that, with probability $(1-\delta)$,

$$(1-\epsilon)\|\mathbf{x}\|_2^2 \leq |\mathbf{\Pi x}\|_2^2 \leq (1+\epsilon)\|\mathbf{x}\|_2^2$$

Claim: $\mathbb{E}\|\mathbf{\Pi x}\|_2^2 = \|\mathbf{x}\|_2^2$.

Some notation:



So each $\boldsymbol{\pi}_i$ contains $\mathcal{N}(0,1)$ entries.

PROOF OF DISTRIBUTIONAL JL

$$\|\mathbf{\Pi}\mathbf{x}\|_2^2 = \sum_i^k \mathsf{s}(i)^2 = \sum_i^k \left(\frac{1}{\sqrt{k}}\langle \boldsymbol{\pi}_i, \mathbf{x}\rangle\right)^2 = \frac{1}{k}\sum_i^k (\langle \boldsymbol{\pi}_i, \mathbf{x}\rangle)^2$$

$$\mathbb{E}\left[\|\mathbf{\Pi}\mathbf{x}\|_2^2\right] = \frac{1}{k}\sum_i^k \mathbb{E}\left[(\langle \boldsymbol{\pi}_i, \mathbf{x}\rangle)^2\right]$$

$$= \mathbb{E}\left[(\langle \boldsymbol{\pi}_i, \mathbf{x}\rangle)^2\right]$$

Goal: Prove $\mathbb{E}\|\mathbf{\Pi}\mathbf{x}\|_2^2 = \|\mathbf{x}\|_2^2$.

$$\langle \boldsymbol{\pi}_i, \mathbf{x} \rangle = Z_1 \cdot \mathbf{x}(1) + Z_2 \cdot \mathbf{x}(2) + \ldots + Z_d \cdot \mathbf{x}(d)$$

where each $Z_1, \ldots, Z_d$ is a standard normal $\mathcal{N}(0, 1)$ random variable.

This implies that $Z_i \cdot \mathbf{x}(i)$ is a normal $\mathcal{N}(0, \mathbf{x}(i)^2)$ random variable.

Goal: Prove $\mathbb{E}\|\boldsymbol{\Pi}\mathbf{x}\|_2^2 = \|\mathbf{x}\|_2^2$. Established: $\mathbb{E}\|\boldsymbol{\Pi}\mathbf{x}\|_2^2 = \mathbb{E}\left[\left(\langle \boldsymbol{\pi}_i, \mathbf{x} \rangle\right)^2\right]$

What type of random variable is $\langle \pi_i, \mathbf{x} \rangle$?

Fact (Stability of Gaussian random variables)

$$\mathcal{N}(\mu_1, \sigma_1^2) + \mathcal{N}(\mu_2, \sigma_2^2) = \mathcal{N}(\mu_1 + \mu_2, \sigma_1^2 + \sigma_2^2)$$

$$\begin{aligned}\langle \pi_i, \mathbf{x} \rangle &= \mathcal{N}(0, \mathbf{x}(1)^2) + \mathcal{N}(0, \mathbf{x}(2)^2) + \ldots + \mathcal{N}(0, \mathbf{x}(d)^2) \\ &= \mathcal{N}(0, \|\mathbf{x}\|_2^2).\end{aligned}$$

So $\mathbb{E}\|\mathbf{\Pi}\mathbf{x}\|_2^2 = \mathbb{E}\left[(\langle \pi_i, \mathbf{x} \rangle)^2\right] = \|\mathbf{x}\|_2^2$, as desired.

PROOF OF DISTRIBUTIONAL JL

Want to argue that, with probability $(1-\delta)$,

$$(1-\epsilon)\|\mathbf{x}\|_2^2 \leq \|\mathbf{\Pi x}\|_2^2 \leq (1+\epsilon)\|\mathbf{x}\|_2^2$$

1. $\mathbb{E}\|\mathbf{\Pi x}\|_2^2 = \|\mathbf{x}\|_2^2$.
2. Need to use a concentration bound.

$$\|\mathbf{\Pi x}\|_2^2 = \frac{1}{k}\sum_{i=1}^{k}(\langle \boldsymbol{\pi}_i, \mathbf{x}\rangle)^2 = \frac{1}{k}\sum_{i=1}^{k}\mathcal{N}(0, \|\mathbf{x}\|_2^2)$$

"Chi-squared random variable with k degrees of freedom."

Concentration of chi-squared random variables

Lemma

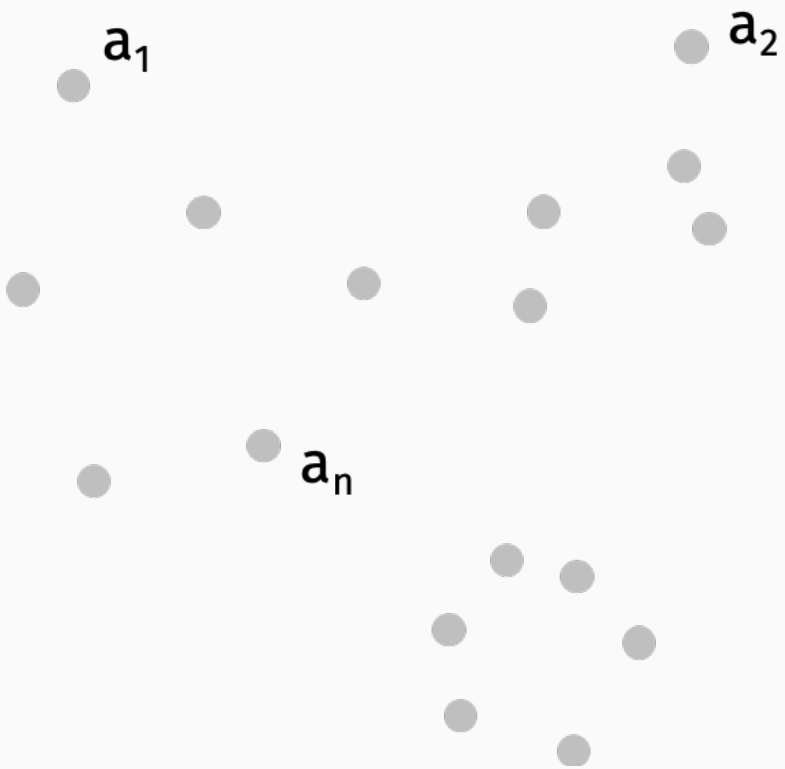
Let Z be a Chi-squared random variable with k degrees of freedom.

$$\Pr[|\mathbb{E}Z - Z| \geq \epsilon \mathbb{E}Z] \leq 2e^{-k\epsilon^2/8}$$

Goal: Prove $\|\mathbf{\Pi x}\|_2^2$ concentrates within $1 \pm \epsilon$ of its expectation, which equals $\|\mathbf{x}\|_2^2$.

k-means clustering: Give data points $\mathbf{a}_1, \ldots, \mathbf{a}_n \in \mathbb{R}^d$, find centers $\boldsymbol{\mu}_1, \ldots, \boldsymbol{\mu}_k \in \mathbb{R}^d$ to minimize:

$$Cost(\boldsymbol{\mu}_1, \ldots, \boldsymbol{\mu}_k) = \sum_{i=1}^{n} \min_{j=1,\ldots,k} \|\boldsymbol{\mu}_j - \mathbf{X}_i\|_2^2$$



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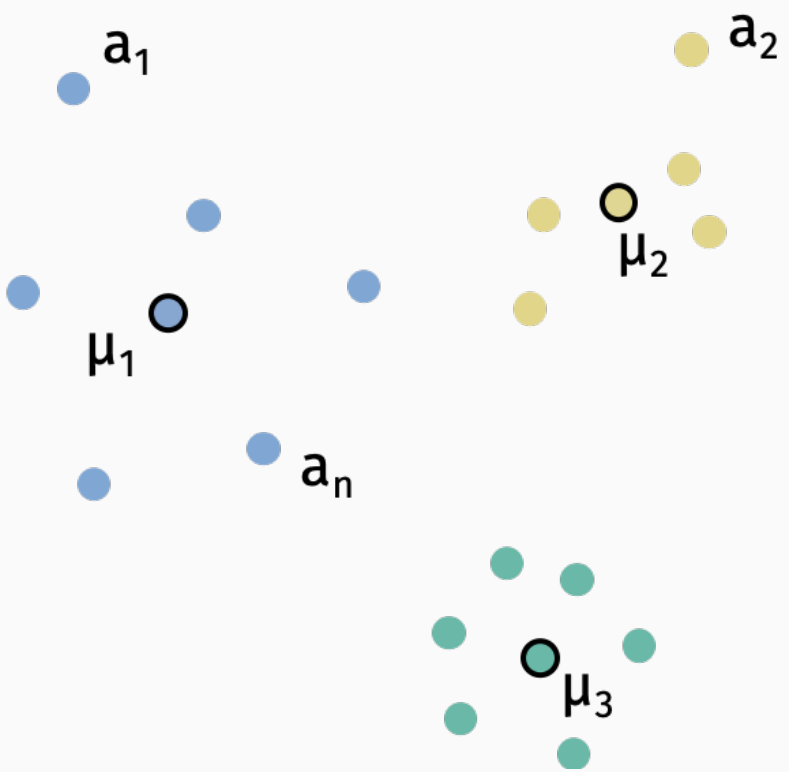

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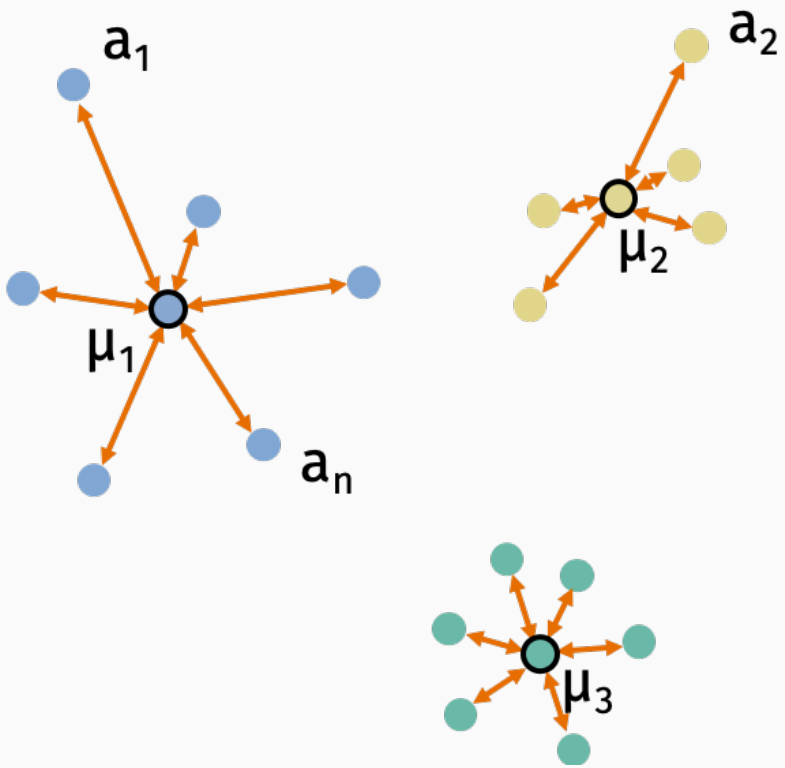
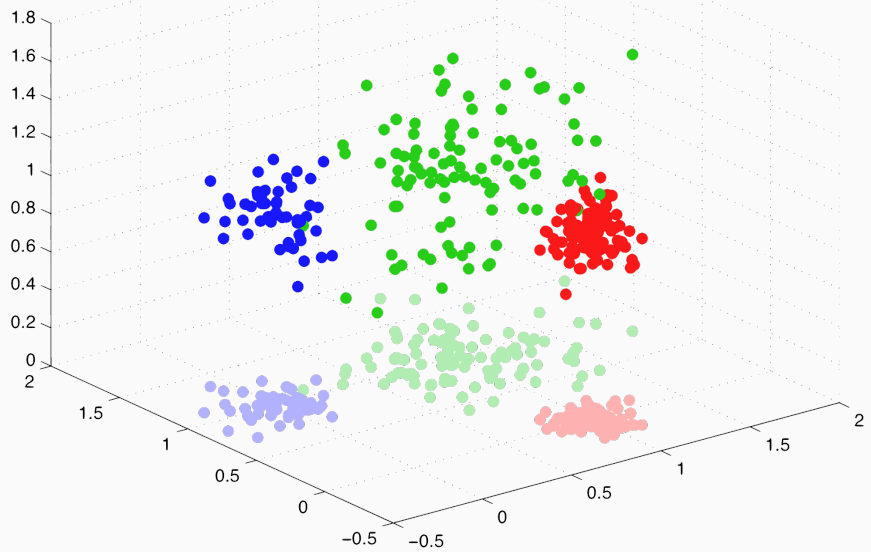


NP hard to solve exactly, but there are many good approximation algorithms. All depend at least linearly on the dimension d.

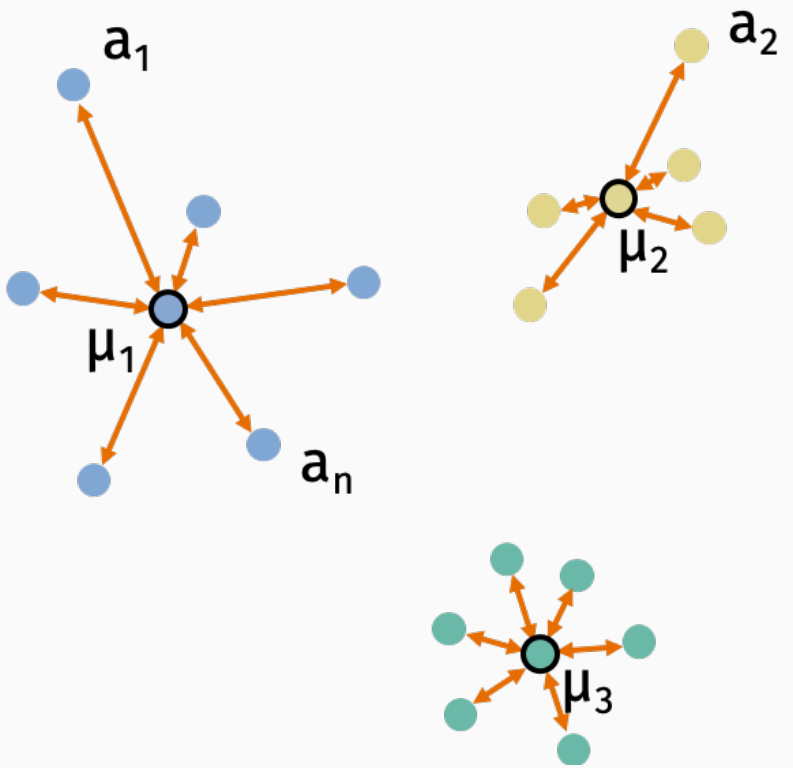
Approximation scheme: Find clusters $\tilde{C}_1, \ldots, \tilde{C}_k$ for the $k = O\left(\frac{\log n}{\epsilon^2}\right)$ dimension data set $\mathbf{\Pi a}_1, \ldots, \mathbf{\Pi a}_n$.



Argue these clusters are near optimal for $\mathbf{a}_1, \ldots, \mathbf{a}_n$.

Equivalent formulation: Find clusters $C_1, \ldots, C_k \subseteq \{1, \ldots, n\}$ to minimize:

$$Cost(C_1, \ldots, C_k) = \sum_{j=1}^{k} \frac{1}{2|C_j|} \sum_{u,v \in C_j} \|\mathbf{a}_u - \mathbf{a}_v\|_2^2.$$



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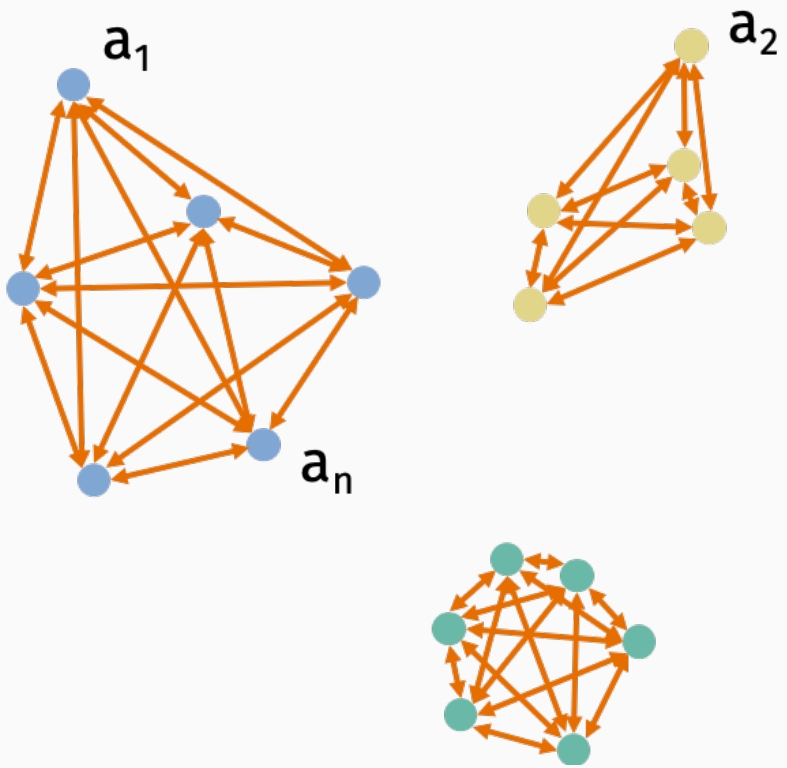

$$Cost(C_1, \ldots, C_k) = \sum_{j=1}^{k} \frac{1}{2|C_j|} \sum_{u,v \in C_j} \|\mathbf{a}_u - \mathbf{a}_v\|_2^2$$

$$\widetilde{Cost}(C_1, \ldots, C_k) = \sum_{j=1}^{k} \frac{1}{2|C_j|} \sum_{u,v \in C_j} \|\Pi\mathbf{a}_u - \Pi\mathbf{a}_v\|_2^2$$

Let $Cost^* = \min Cost(C_1, \ldots, C_k)$ and
$\widetilde{Cost}^* = \min \widetilde{Cost}(C_1, \ldots, C_k)$.

Claim: $(1-\epsilon)Cost^* \leq \widetilde{Cost}^* \leq (1+\epsilon)Cost^*$.

Suppose we use an approximation algorithm to find clusters $B_1, \ldots, B_k$ such that:

$$\widetilde{Cost}(B_1, \ldots, B_k) \leq (1+\alpha)\widetilde{Cost}^*$$

Then:

$$\begin{aligned} Cost(B_1, \ldots, B_k) &\leq \frac{1}{1-\epsilon}\widetilde{Cost}(B_1, \ldots, B_k) \\ &\leq (1+\alpha)(1+O(\epsilon))\widetilde{Cost}^* \\ &\leq (1+\alpha)(1+O(\epsilon))(1+\epsilon)Cost^* \\ &= 1+O(\alpha+\epsilon)Cost^* \end{aligned}$$

CONNECTION TO LAST LECTURE

If high dimensional geometry is so different from low-dimensional geometry, why is dimensionality reduction possible? Doesn't Johnson-Lindenstrauss tell us that high-dimensional geometry can be approximated in low dimensions?

Hard case: $\mathbf{x}_1, \ldots, \mathbf{x}_n \in \mathbb{R}^d$ are all mutually orthogonal unit vectors:

$$\|\mathbf{x}_i - \mathbf{x}_j\|_2^2 = 2 \qquad \text{for all } i, j.$$

From our result earlier, in $O(\log n/\epsilon^2)$ dimensions, there exists $2^{O(\epsilon^2 \cdot \log n/\epsilon^2)} \geq n$ unit vectors that are close to mutually orthogonal.

$O(\log n/\epsilon^2)$ = just enough dimensions.