



University of Colorado **Boulder**

Randomization methods for big-data (other than SGD)

Stephen Becker, CU Applied Math dept

CU Computer Science Department Colloquium, Oct 26 2023

Joint work with several author, mostly my former PhD students:

(and colleagues at CU & the Colorado School of Mines)



Farhad Pourkamali-Anaraki
(Asst. Prof at UC Denver)



David Kozak
(private sector)



Osman Asif Malik
(Alvarez postdoc at Berkeley Labs)

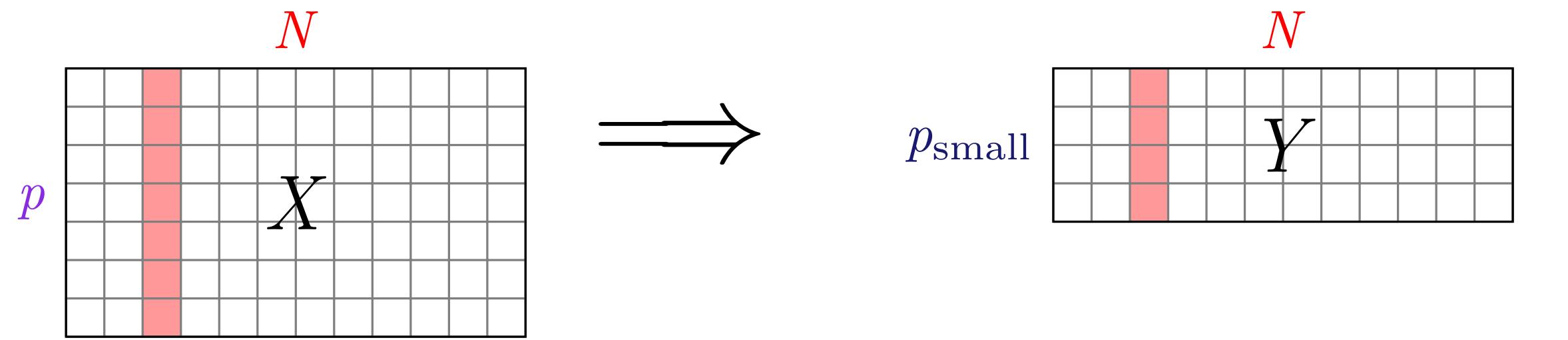
OUTLINE

1. Randomized “sketches”
 - a. Warmup: PCA
 - b. Classical sketches
 - c. Structured sketches
2. Applications
 - a. Warmup: linear algebra
 - b. K-means clustering
 - c. Tensor factorizations
 - d. Gradient-free optimization

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Reducing the dimensionality of data

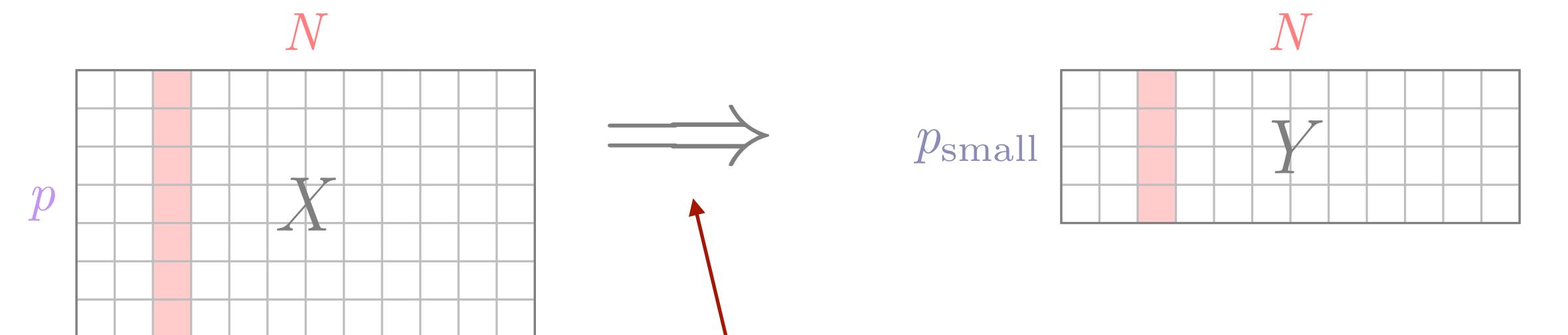


$x_i \in \mathbb{R}^p, \quad i = 1, \dots, N$ is converted to $y_i \in \mathbb{R}^{p_{\text{small}}}, \quad i = 1, \dots, N$

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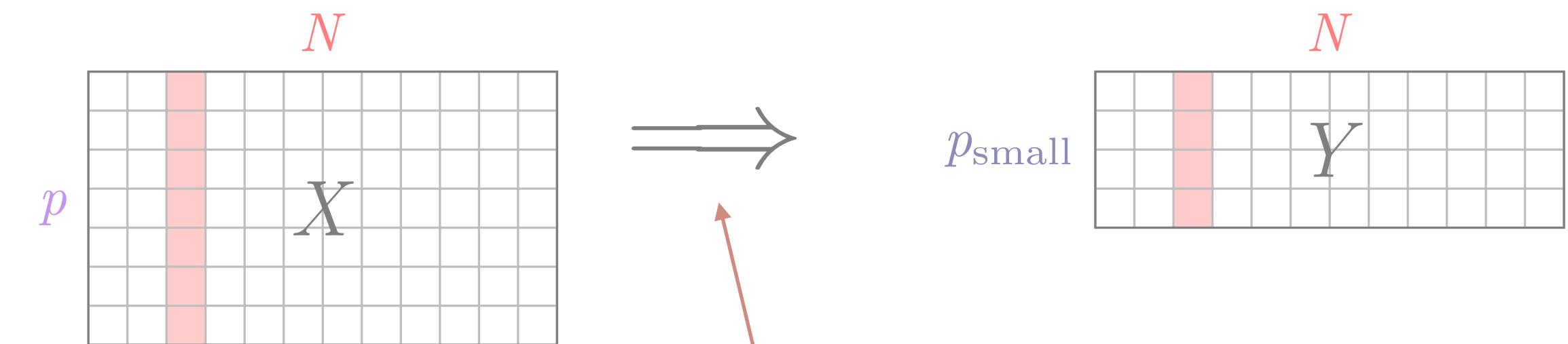
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this reduction is often **linear**, in which case can write as

$$p_{\text{small}} \begin{matrix} N \\ Y \end{matrix} = p_{\text{small}} \begin{matrix} p \\ \Phi \end{matrix} \begin{matrix} N \\ X \end{matrix}$$

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Why?

- ▶ Faster computation
 - ▶ Especially if the complexity of subsequent processing is $\mathcal{O}(p^2 N)$
 - ▶ If $p_{\text{small}} = 0.05p$ then speedup is $400\times$
- ▶ Denoising (remove irrelevant components)
- ▶ Fewer degrees-of-freedom reduces chance of overfitting models
- ▶ Visual interpretation (e.g., $p_{\text{small}} = \{2, 3\}$) ← This is “multidimensional scaling”. Specialized techniques (tSNE, UMAP) are best

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Method 1: PCA (non-linear)

Principal Component Analysis (aka Hotelling or Karhunen-Loeve transform)

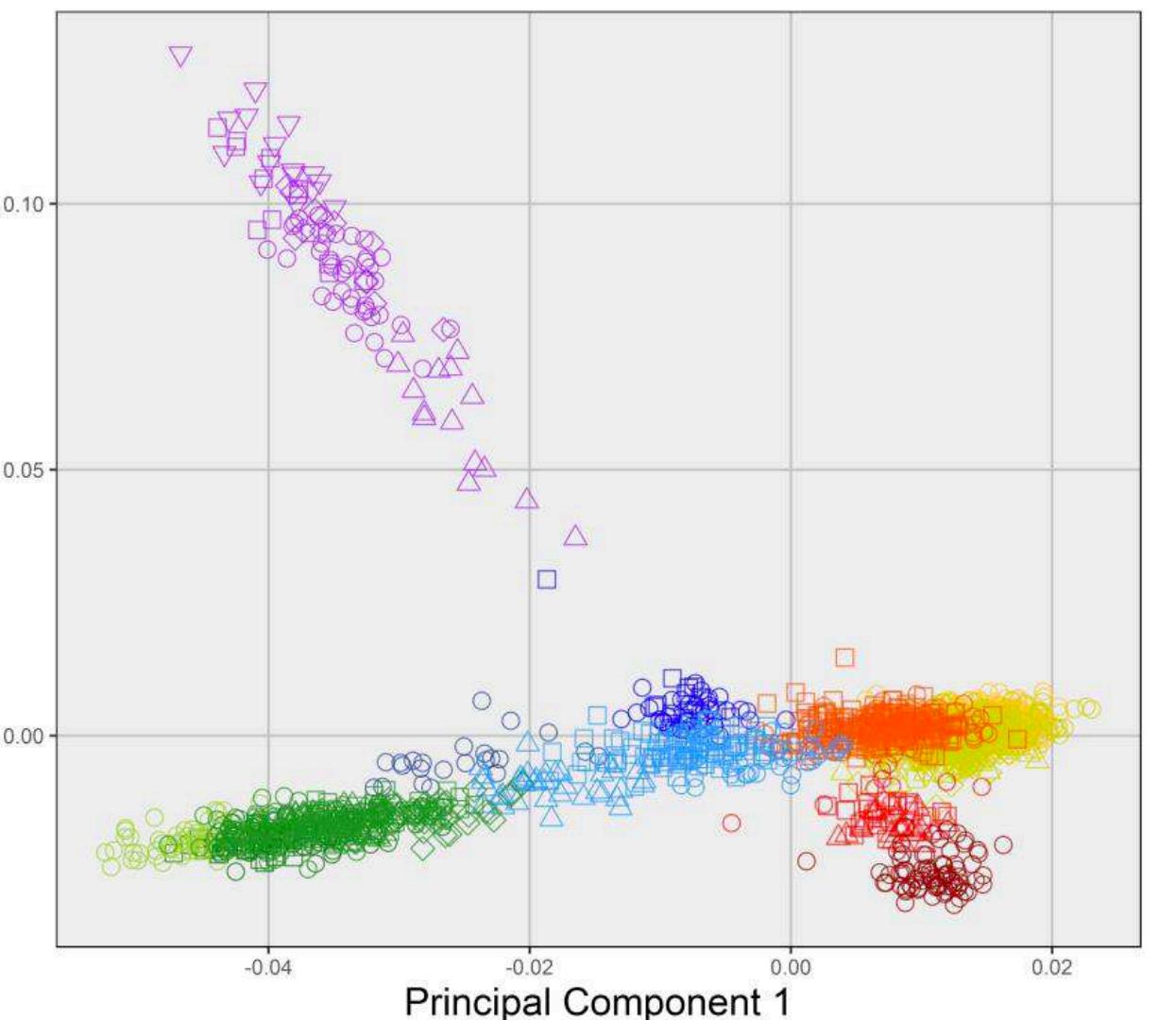
Take SVD

$$X = [\mathbf{U}_1 \mathbf{U}_2] \begin{bmatrix} \Sigma_1 & 0 \\ 0 & \Sigma_2 \end{bmatrix} \begin{bmatrix} \mathbf{V}_1^T \\ \mathbf{V}_2^T \end{bmatrix}$$

where $\|\Sigma_2\| \approx$ small. Then PCA takes the form of

$$Y \leftarrow \Phi_{\text{PCA}} \cdot X$$

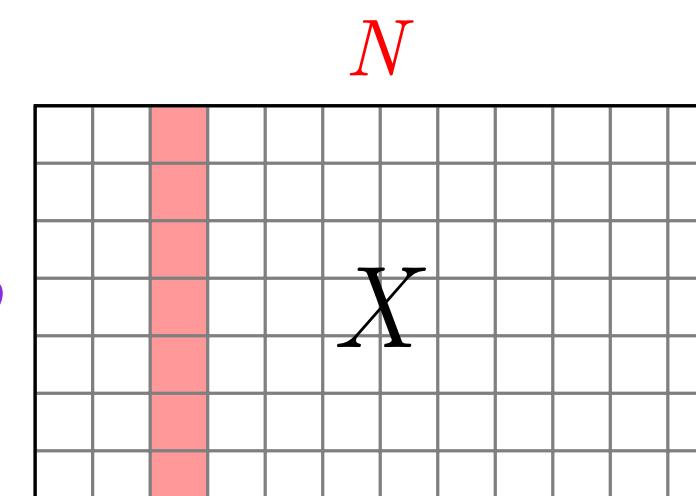
where $\Phi_{\text{PCA}} = \mathbf{U}_1^T$.



England I	S Wales II
N England I	S Wales III
Devon I	N Wales I
N England II	Connacht
Marches I	Dublin
Cornwall I	C Ireland
N England III	Leinster
N England IV	Ulster
N Scotland I	N Munster
N Scotland II	S Munster
N Ireland I	Orkney I
N Ireland II	Orkney II
N Ireland III	Orkney III
W Scotland I	Orkney IV
S Wales I	Orkney V

Note:

- ▶ Costly but linear in N : $(\mathcal{O}(p^2 N))$ direct, or about $\mathcal{O}(p_{\text{small}} p N)$ Krylov)
- ▶ Non-linear, since Φ_{PCA} is determined by X
- ▶ Need to process all of X before we can apply $y_i \leftarrow \Phi_{\text{PCA}} \cdot x_i$



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Method 2: sub-sample dimensions (i.e., rows)

R randomly samples rows

$$\Phi_{\text{rows}} = p_{\text{small}} \begin{matrix} & p \\ & \boxed{R} \\ p & \end{matrix}$$

$$p_{\text{small}} \begin{matrix} N \\ Y \end{matrix} = p_{\text{small}} \begin{matrix} p \\ \Phi \end{matrix} \begin{matrix} N \\ X \end{matrix}$$

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$$\Phi_{\text{rows}} = p_{\text{small}} \begin{matrix} & p \\ & | \\ \textcolor{blue}{\Phi}_{\text{rows}} = & \begin{matrix} & & & \\ & \textcolor{red}{R} & & \\ & & & \\ & & & \end{matrix} \\ & | \\ & p \end{matrix}$$

$$p_{\text{small}} \begin{matrix} & N \\ & | \\ Y & \end{matrix} = p_{\text{small}} \begin{matrix} & p \\ & | \\ \Phi & \end{matrix} \begin{matrix} & N \\ & | \\ X & \end{matrix}$$

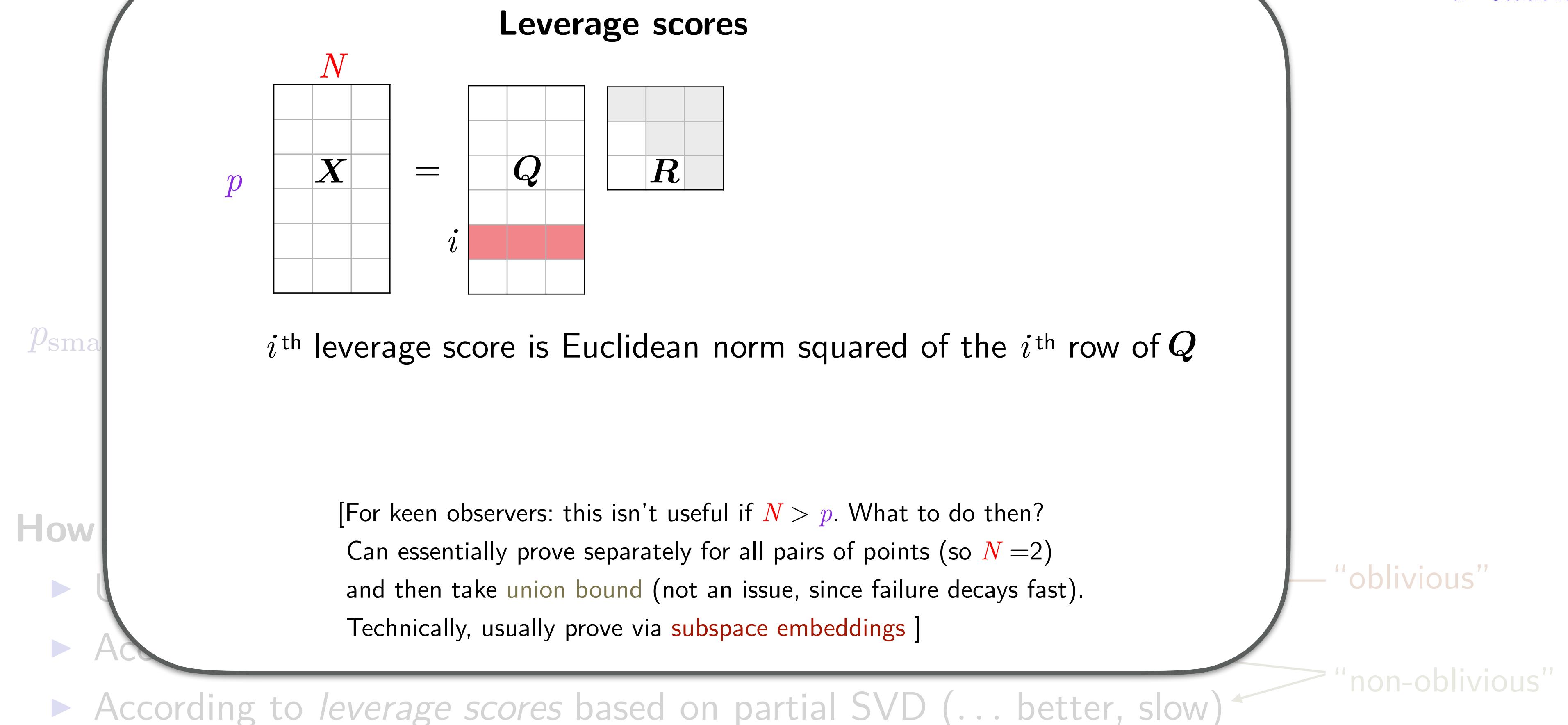
How to choose R ?

- ▶ Uniformly at random (... poor performance) “oblivious”
- ▶ According to row-norm (... better, not great, and slower) “non-oblivious”
- ▶ According to *leverage scores* based on partial SVD (... better, slow)

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Method 3: random matrix

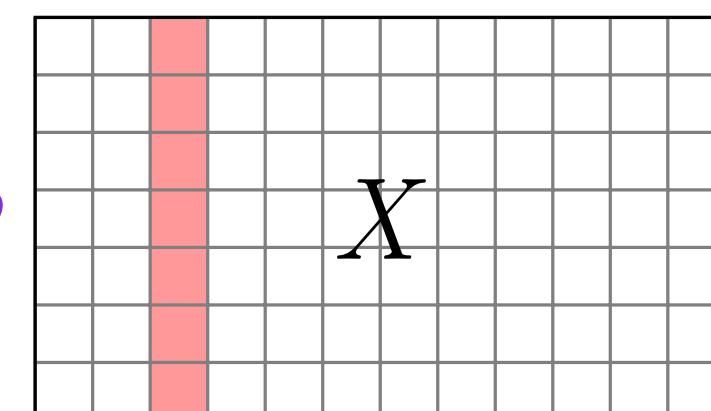
Theorem (Johnson-Lindenstrauss, 1984 (and Indyk-Motwani, 1998))

Choose $\Phi = \Phi_{randn}$ with $p_{small} \propto \varepsilon^{-2} \log N$ iid rows each $\mathcal{N}(0, p/p_{small})$, then for all $x_i, x_j \in \{x_1, \dots, x_N\} \subset \mathbb{R}^p$,

$$1 - \varepsilon \leq \frac{\|\Phi x_i - \Phi x_j\|_2}{\|x_i - x_j\|_2} \leq 1 + \varepsilon$$

with constant probability.

N



Method 3: random matrix

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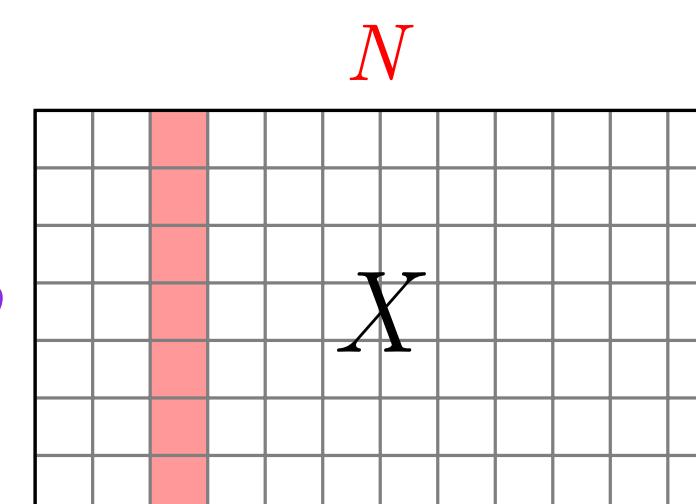
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with constant probability.

- ▶ Φ is linear and data-independent (unlike PCA)
- ▶ but Φ is not orthogonal (unlike PCA)
- ▶ Independent of original dimension p
- ▶ Independent of conditioning of X (unlike PCA)
- ▶ Probabilistic (unlike PCA)

Usually not practical since too costly since computing ΦX is $\mathcal{O}(pp_{small}N)$



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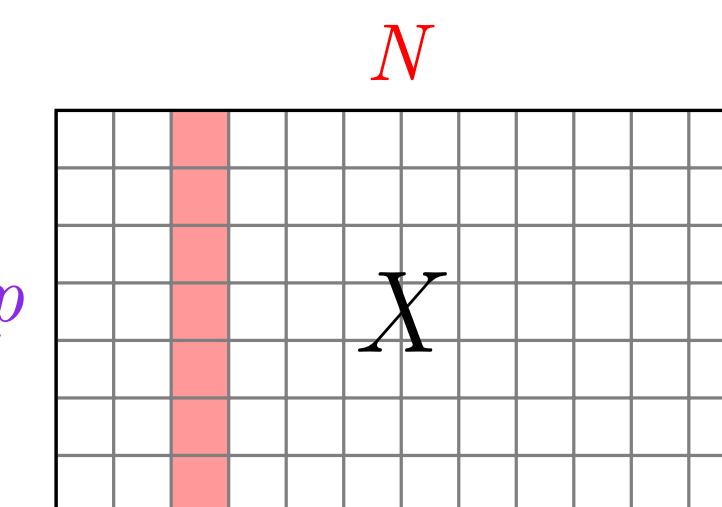
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Many **extensions**, for example:

- sub-Gaussian entries, and/or dependent rows (e.g., columns uniform on sphere)
- dependent columns, e.g., Haar measure on orthogonal matrices
- sparse matrix (worse performance though)

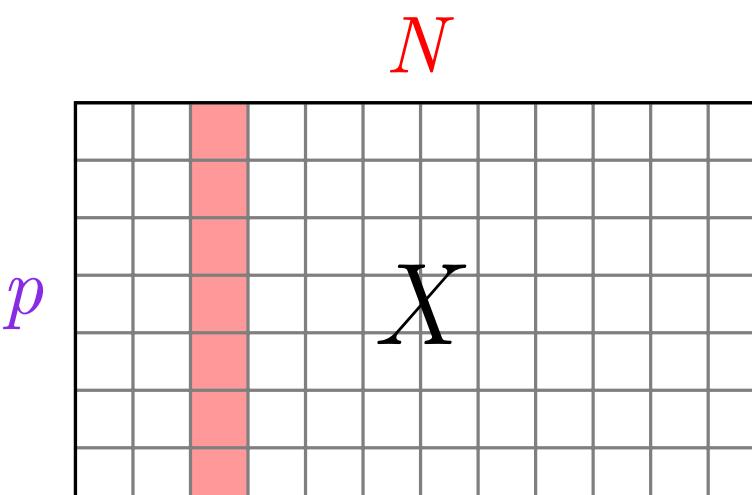


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Method 4: Fast Johnson-Lindenstrauss Transforms

R samples rows; \mathcal{F} Fourier-like; D diag. w/ random ± 1 entries (“Rademacher”) (uniformly)

$$\Phi_{\text{FFT}} = p_{\text{small}} \begin{matrix} p & p & p \\ \boxed{R} & \boxed{\mathcal{F}} & \boxed{D} \end{matrix}$$



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$$\Phi_{\text{FFT}} = p_{\text{small}} \begin{array}{c} p \\ R \\ \hline \end{array} \quad \begin{array}{c} p \\ \mathcal{F} \\ \hline \end{array} \quad \begin{array}{c} p \\ D \\ \hline \end{array}$$

Cost:

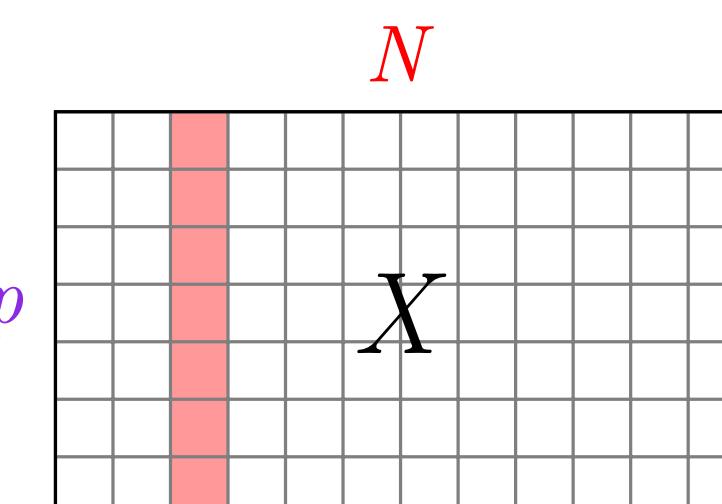
- ▶ $\mathcal{F}(x)$ costs $p \log p$ (vs p^2 naively)
- ▶ hence $\mathcal{O}(pN \log p)$ to compute ΦX , so good if $\log p < N$

Guarantees: almost as good as classical Johnson-Lindenstrauss
First guarantees in the **Fast Johnson-Lindenstrauss** paper

Ailon and Chazelle, “Approximate nearest neighbors and the fast Johnson-Lindenstrauss transform”, STOC 2006

Think of \mathcal{F} as FFT or DCT or Hadamard transform

also known under many names, e.g., Random Orthogonal System, FJLT



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How to get guarantees?

Cost:

- ▶ $\mathcal{F}(x)$ costs $p \log p$
- ▶ hence $\mathcal{O}(pN \log p)$

Basic idea is that after applying the first two steps, resulting matrix has (almost) uniform leverage scores...
... so uniform subsampling is (almost) leverage score sampling.

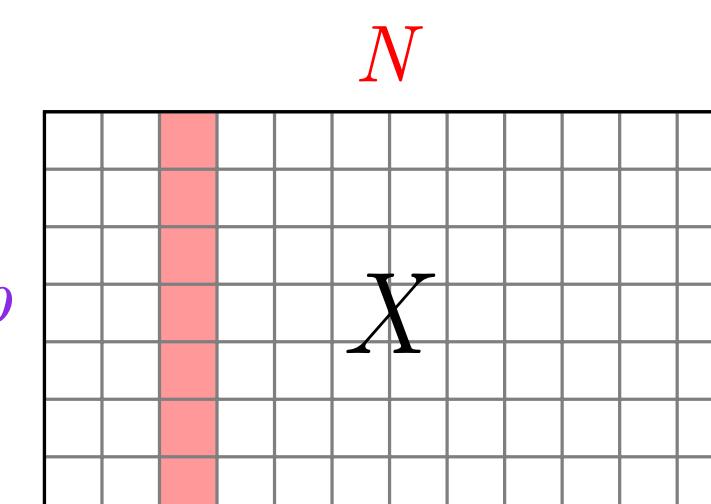
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Method 5: subsample entries of a matrix

Keep $x'_i \in \mathbb{R}^{\textcolor{violet}{p}}$ but with only p_{small} nonzeros

Idea goes back to landmark Achlioptas/McSherry paper (2001)

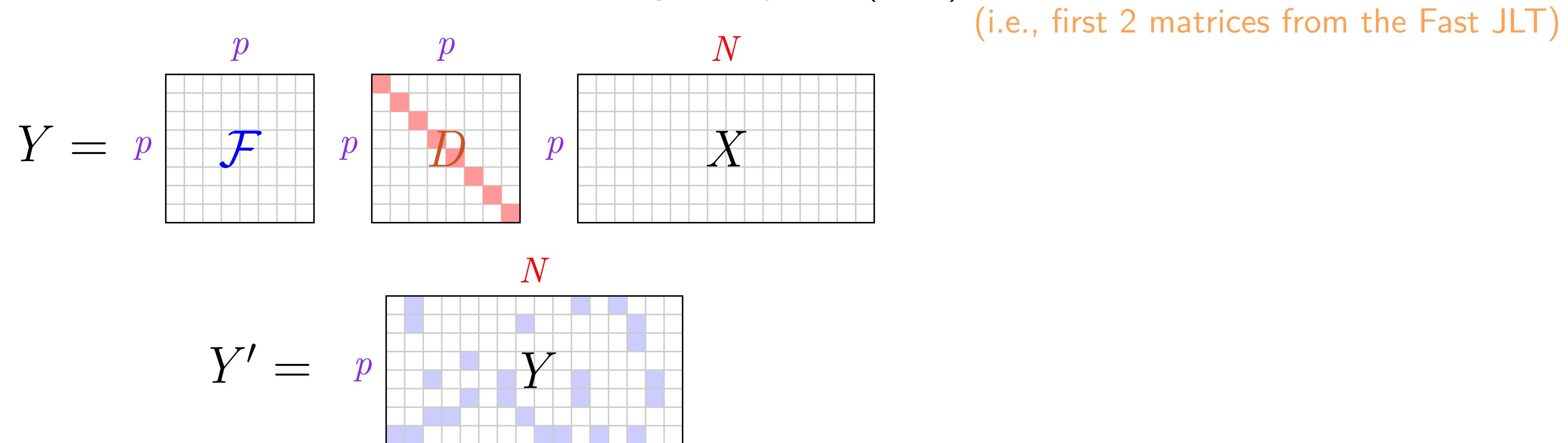
$$X' = \textcolor{violet}{p} \begin{matrix} & N \\ & | \\ X & \end{matrix}$$

This is the **odd-one-out** so far, because it's not the same linear operator applied to every column

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Method 6: “precondition,” then subsample entries of a matrix

Our new twist: first **precondition** with Random Orthogonal System (ROS)



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Why precondition?

Easy to see that better than uniform sampling of X is **non-uniform** sampling, with probability proportional to magnitude of entry

cf. Achlioptas, Z. Karnin, and E. Liberty 2013

Disadvantage of weighted sampling is the extra pass through data

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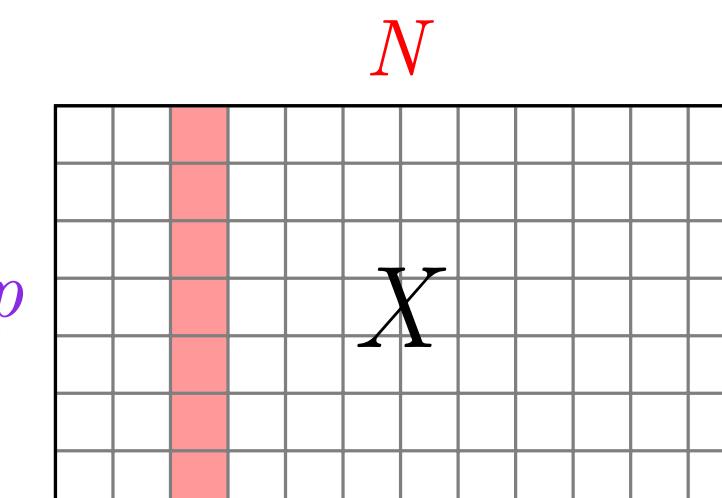
Disadvantage of weighted sampling is the extra pass through data

In our analysis, we have terms like (want this small)

$$\|X\|_{\text{max-entry}} = \max_{\substack{i=1, \dots, N \\ j=1, \dots, p}} |X_{ij}|$$

Assuming $\|x_i\|_2 = 1$,

- ▶ it is possible for $\|X\|_{\text{max-entry}} = 1$ (BAD)
- ▶ best case is $\|X\|_{\text{max-entry}} = 1/\sqrt{p}$



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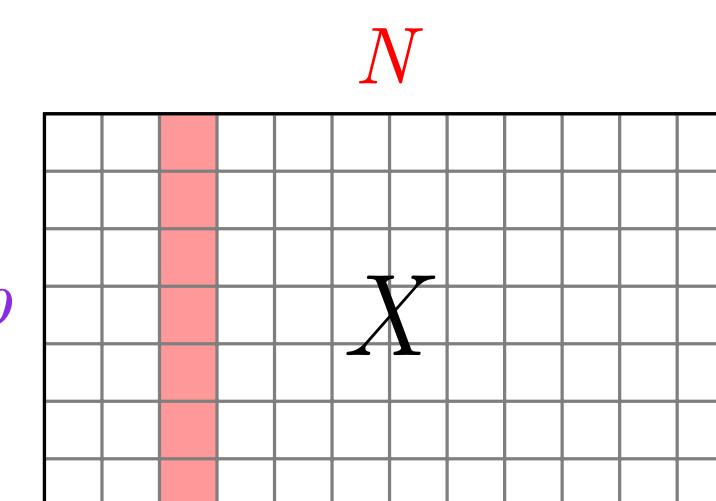
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Benefit of preconditioning

After applying ROS, exponentially small chance that

$$\|Y\|_{\text{max-entry}} > \sqrt{\log(Np)}/\sqrt{p}$$

N.B. Since $\mathcal{F}D$ is unitary, bounds in spectral/Frobenius norm are unchanged



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Theory: estimating the mean

Given a true mean $\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i$, and our estimate of it \hat{x} from sampled data,



Theorem (Pourkamali-Anaraki & B., *IEEE Trans. Info Theory* 2017)

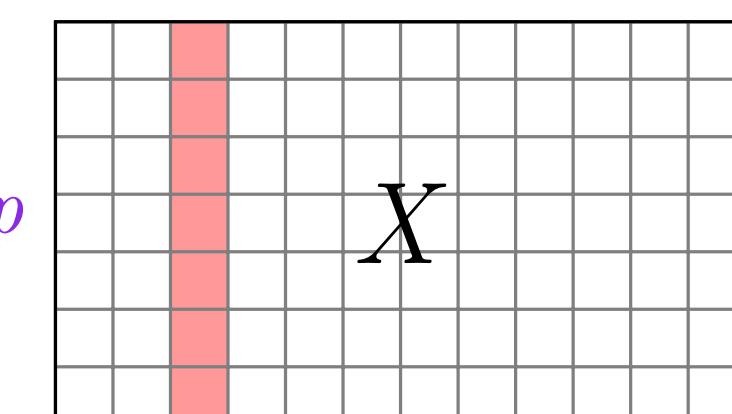
$\mathbb{E} \hat{x} = \bar{x}$ and $\|\hat{x} - \bar{x}\|_\infty \leq t$ with probability greater than

$$1 - 2p \exp\left(\frac{-N\gamma t^2/2}{\|X\|_{max-row}^2 + t/3\|X\|_{max-entry}}\right)$$

where $\gamma = p_{small}/p$

(simplifying to $p_{small} \ll p \ll N$)

N



X

p

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where $\gamma = p_{small}/p$

(simplifying to $p_{small} \ll p \ll N$)

If X has normalized columns, then $\|X\|_{\max\text{-entry}} = 1$ and $\|X\|_{\max\text{-row}} = \sqrt{N}$ are possible, which is bad.

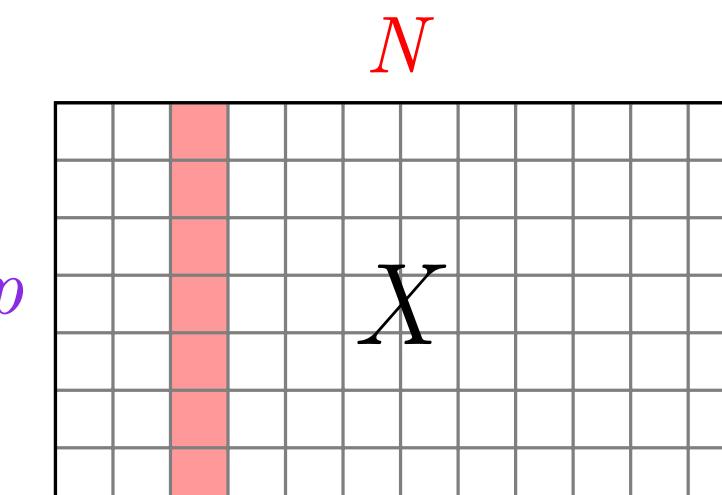
Lemma

If X is preconditioned, then

(for $Np = 10^{10}$, $\sqrt{\log(2Np) + 1000} = 32$)

$$\mathbb{P} \left\{ \|X\|_{\max\text{-entry}} \geq \frac{\sqrt{2}}{\sqrt{p}} \cdot \sqrt{\log(2Np) + 1000} \right\} \leq .001$$

$$\mathbb{P} \left\{ \|X\|_{\max\text{-row}} \geq \frac{\sqrt{2N}}{\sqrt{p}} \cdot \sqrt{\log(2Np) + 1000} \right\} \leq .001$$



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Theory: estimating the mean

Given a true mean μ

Theorem:

$$\mathbb{E} \hat{x} =$$

where

If X has finite variance, it is possible to estimate μ .

Lemmas:

If X is bounded, it is possible to estimate μ .

$1 \rightarrow N$

Probability theory aside

Let $y_i = \pm 1$ be iid Bernoulli, $\hat{x} = \frac{1}{N} \sum_{i=1}^N y_i$

- ▶ $\mathbb{E}(\hat{x}) = 0$
- ▶ $\text{Var}(\hat{x}) = 1/N$

Chebyshev, Markov inequalities

$$\mathbb{P}(|\hat{x}| \geq t) \leq \frac{1}{Nt^2}$$

Example: $N = 10^4$ and $t = 0.1$, $\mathbb{P}(|\hat{x}| \geq t) \leq 0.01$

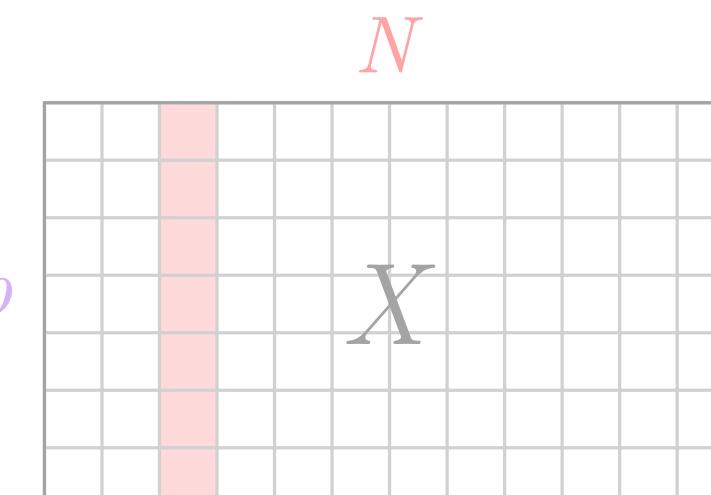
Concentration ineq.

Bernstein, Hoeffding, Chernoff

$$\mathbb{P}(|\hat{x}| \geq t) \leq 2 \exp \left(\frac{-Nt^2/2}{1 + t/3} \right)$$

Example: $N = 10^4$ and $t = 0.1$, $\mathbb{P}(|\hat{x}| \geq t) \leq 2 \cdot 10^{-21}$

intuition: central limit theorem says random sums of iid rv should look Gaussian, and for a Gaussian, we have exponential concentration



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Method 7: CountSketch

p

	± 1				± 1	
± 1						
					± 1	
			Φ		± 1	
		± 1	± 1			
						± 1
p_{small}						

Introduced in [Charikar et al. \(2004\)](#), more analysis in, e.g., [Clarkson and Woodruff \(2017\)](#)

Based on **hash functions**

(as a side-effect, doesn't need full iid random variables for analysis to work)

See “[appendix](#)” of these slides for more details

Every column has exactly 1 nonzero entry, location chosen uniformly at random (and value is a Rademacher r.v.)

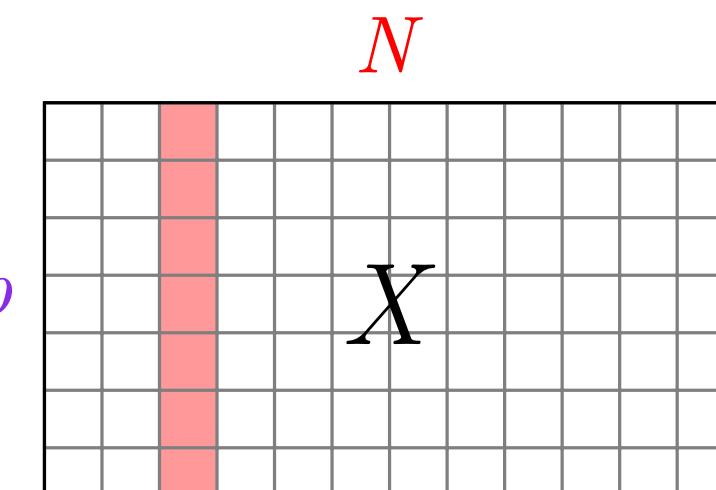
Has some guarantees, though not as good as a Gaussian (and not a JLT)

... but it's very **fast** to apply

cost: $\text{nnz}(X)$, so no more than pN (vs $p_{\text{small}}pN$ with a Gaussian)



new linear algebra application in: [Malik, B.](#) "Fast randomized matrix and tensor interpolative decomposition using CountSketch", *Adv. Comp. Math* (2020)



Method 8: TensorSketch

Introduced in Pagh (2013), more analysis
in, e.g., Diao, Zong, Sun, Woodruff (2018)

TensorSketch is just CountSketch when the input can be written as a tensor product
(for a special choice of the hash and sign functions)

$$\Phi_{\mathcal{T}} : \mathbb{R}^{\textcolor{violet}{p}} \rightarrow \mathbb{R}^{p_{\text{small}}}$$
$$\mathbf{v} = \mathbf{v}^{(1)} \otimes \mathbf{v}^{(2)} \quad \text{where size is } \textcolor{violet}{p} = \textcolor{violet}{p}^{(1)} \cdot \textcolor{violet}{p}^{(2)}$$

Not (yet!) related to tensors

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$$\Phi_{\mathcal{T}} : \mathbb{R}^{\textcolor{violet}{p}} \rightarrow \mathbb{R}^{p_{\text{small}}}$$

$$\mathbf{v} = \mathbf{v}^{(1)} \otimes \mathbf{v}^{(2)} \quad \text{where size is } \textcolor{violet}{p} = \textcolor{violet}{p}^{(1)} \cdot \textcolor{violet}{p}^{(2)}$$

Kronecker/tensor product of vectors

$$\mathbf{a} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}, \quad \mathbf{b} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} \quad \mathbf{a} \otimes \mathbf{b} = \begin{bmatrix} a_1 \mathbf{b} \\ a_2 \mathbf{b} \\ a_3 \mathbf{b} \end{bmatrix} = \begin{bmatrix} a_1 b_1 \\ a_1 b_2 \\ a_1 b_3 \\ a_2 b_1 \\ a_2 b_2 \\ a_2 b_3 \\ a_3 b_1 \\ a_3 b_2 \\ a_3 b_3 \end{bmatrix}$$

Method 8: TensorSketch

Introduced in Pagh (2013), more analysis
in, e.g., Diao, Zong, Sun, Woodruff (2018)

TensorSketch is just CountSketch when the input can be written as a tensor product
(for a special choice of the hash and sign functions)

$$\Phi_{\mathcal{T}} : \mathbb{R}^{\textcolor{violet}{p}} \rightarrow \mathbb{R}^{p_{\text{small}}}$$

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Kronecker/tensor product of vectors

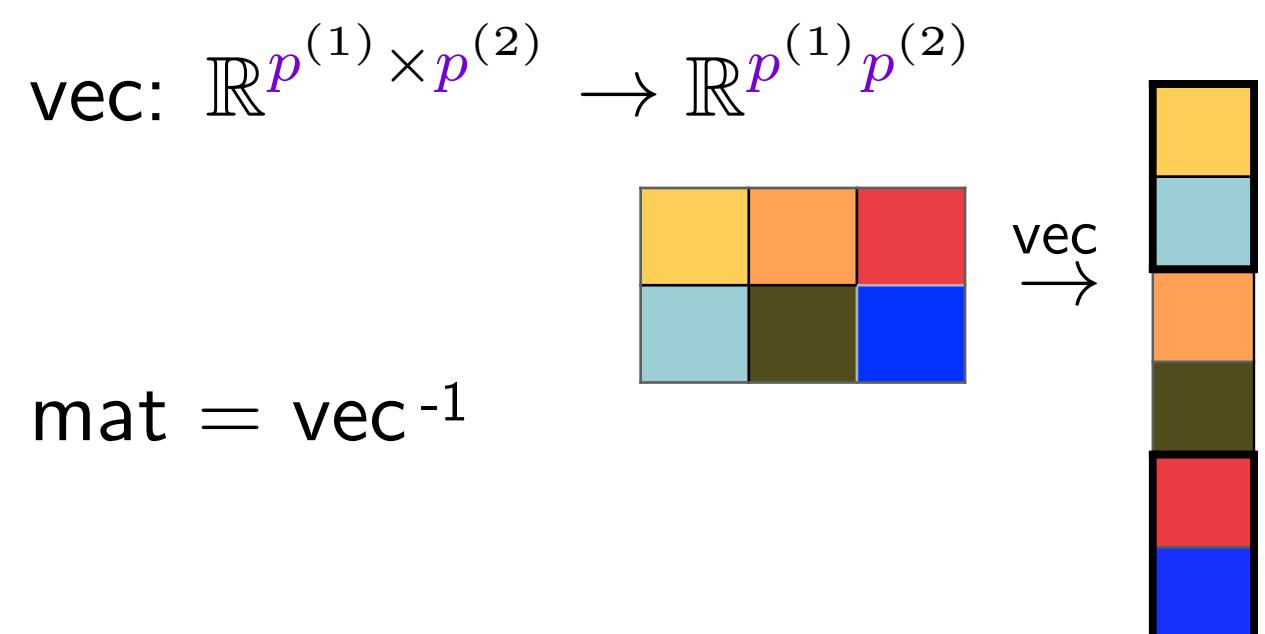
$$\mathbf{a} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}, \quad \mathbf{b} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}$$

$$\mathbf{a} \otimes \mathbf{b} = \begin{bmatrix} \mathbf{a}_1 \mathbf{b} \\ \mathbf{a}_2 \mathbf{b} \\ \mathbf{a}_3 \mathbf{b} \end{bmatrix} = \begin{bmatrix} a_1 b_1 \\ a_1 b_2 \\ a_1 b_3 \\ a_2 b_1 \\ a_2 b_2 \\ a_2 b_3 \\ a_3 b_1 \\ a_3 b_2 \\ a_3 b_3 \end{bmatrix}$$

another equivalent definition:

$$\mathbf{a} \otimes \mathbf{b} = \text{vec}_{\text{col}} (\mathbf{b} \mathbf{a}^T)$$

$$\mathbf{b} \mathbf{a}^T = \begin{bmatrix} b_1 a_1 & b_1 a_2 & b_1 a_3 \\ b_2 a_1 & b_2 a_2 & b_2 a_3 \\ b_3 a_1 & b_3 a_2 & b_3 a_3 \end{bmatrix} = \begin{bmatrix} a_1 b_1 & a_2 b_1 & a_3 b_1 \\ a_1 b_2 & a_2 b_2 & a_3 b_2 \\ a_1 b_3 & a_2 b_3 & a_3 b_3 \end{bmatrix}$$



more generally,

$$(\mathbf{A} \otimes \mathbf{B}) \text{vec}_{\text{col}} (\mathbf{X}) = \text{vec}_{\text{col}} (\mathbf{B} \mathbf{X} \mathbf{A}^T)$$

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TensorSketch: applying to matrices

From vector case $\mathbf{v} = \mathbf{v}^{(1)} \otimes \mathbf{v}^{(2)}$ to matrix case $\mathbf{A} = \mathbf{A}^{(1)} \otimes \mathbf{A}^{(2)} \otimes \dots \otimes \mathbf{A}^{(N)}$

Recall the **Kronecker** product:

$$\begin{aligned}\mathbf{A} \otimes \mathbf{B} &= \begin{bmatrix} a_{11}\mathbf{B} & a_{12}\mathbf{B} & \cdots & a_{1J}\mathbf{B} \\ a_{21}\mathbf{B} & a_{22}\mathbf{B} & \cdots & a_{2J}\mathbf{B} \\ \vdots & \vdots & \ddots & \vdots \\ a_{I1}\mathbf{B} & a_{I2}\mathbf{B} & \cdots & a_{IJ}\mathbf{B} \end{bmatrix} \in \mathbb{R}^{IK \times JL} \\ &= [\mathbf{a}_1 \otimes \mathbf{b}_1 \quad \mathbf{a}_1 \otimes \mathbf{b}_2 \quad \mathbf{a}_1 \otimes \mathbf{b}_3 \quad \cdots \quad \mathbf{a}_J \otimes \mathbf{b}_{L-1} \quad \mathbf{a}_J \otimes \mathbf{b}_L]\end{aligned}$$

Khatri-Rao product

$$\mathbf{A} \odot \mathbf{B} = [\mathbf{a}_1 \otimes \mathbf{b}_1 \quad \mathbf{a}_2 \otimes \mathbf{b}_2 \quad \cdots \quad \mathbf{a}_K \otimes \mathbf{b}_K] \in \mathbb{R}^{IJ \times K}$$

Observe

pointwise multiplication (aka Hadamard product)

$$\mathbf{a} \circ \mathbf{b} = (\mathbf{a}^\top \odot \mathbf{b}^\top)^\top$$

and with some work, $\Phi_{\mathcal{T}}(\mathbf{A}) = \text{FFT}^{-1} \left(\left(\bigodot_{n=1}^N \left(\text{FFT} \left(\mathbf{S}^{(n)} \mathbf{A}^{(n)} \right) \right)^\top \right)^\top \right)$

small countSketch

FFTs are doing circular convolution, i.e., multiplying polynomials modulo a fixed modulus. See appendix

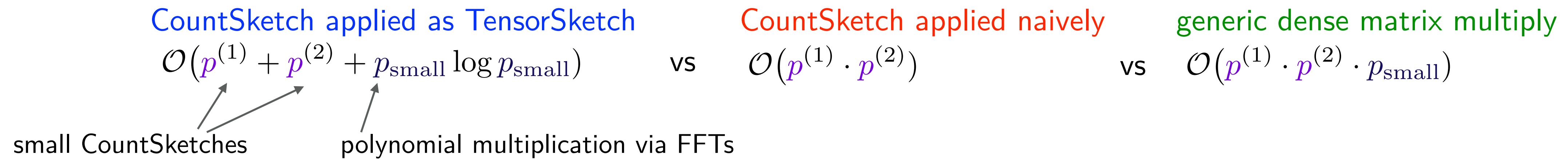
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TensorSketch: complexity analysis

$$\Phi_{\mathcal{T}} : \mathbb{R}^{\textcolor{violet}{p}} \rightarrow \mathbb{R}^{p_{\text{small}}}$$

$$p = \textcolor{violet}{p}^{(1)} \cdot \textcolor{violet}{p}^{(2)}$$

Complexity (per mat-vec):



Savings grow as we have more tensor products

If $p = \textcolor{violet}{p}^{(1)} \cdot \textcolor{violet}{p}^{(2)} \cdot \textcolor{violet}{p}^{(q)}$

$$\mathcal{O}(\textcolor{violet}{p}^{(1)} + \textcolor{violet}{p}^{(2)} + \dots \textcolor{violet}{p}^{(q)} + p_{\text{small}} \log p_{\text{small}}) \quad \text{vs} \quad \mathcal{O}(\textcolor{violet}{p}^{(1)} \textcolor{violet}{p}^{(2)} \dots \textcolor{violet}{p}^{(q)})$$

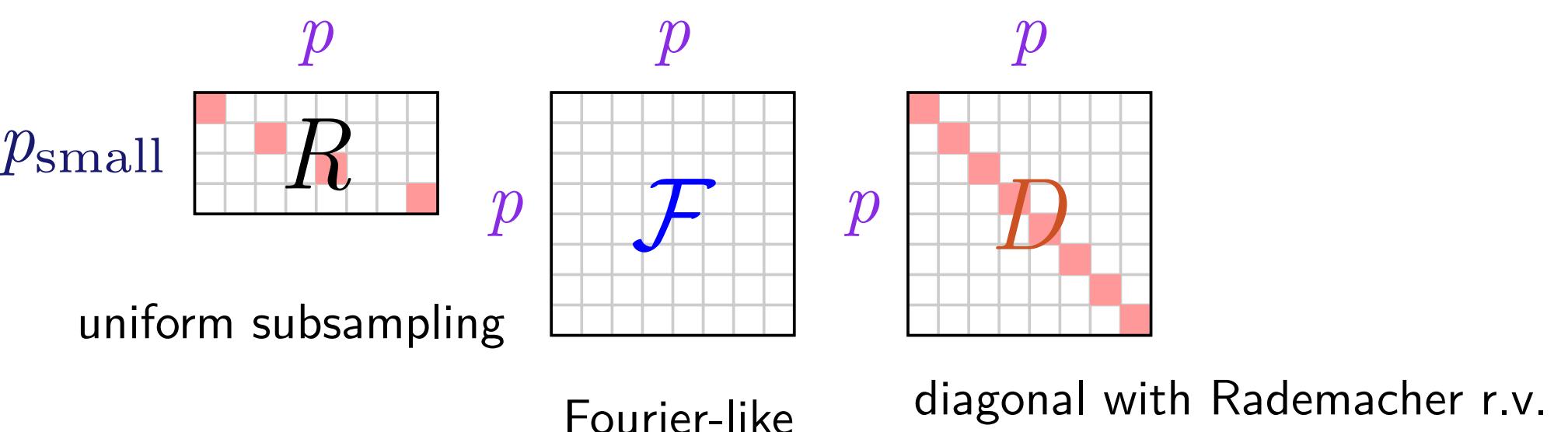
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Method 9: Kronecker Fast Johnson-Lindenstrauss sketch

As for TensorSketch, suppose each column of data looks like $\mathbf{v} = \mathbf{v}^{(1)} \otimes \mathbf{v}^{(2)}$

sizes: $p = p^{(1)} \cdot p^{(2)}$

Recall the Fast Johnson-Lindenstrauss (FJLT): $\Phi = R\mathcal{F}\mathbf{D}$



The **Kronecker** FJLT has a similar structure:

$$\Phi_{\text{KFJLT}} = R \left(\mathcal{F}^{(1)} \mathbf{D}^{(1)} \otimes \mathcal{F}^{(2)} \mathbf{D}^{(2)} \right)$$

which is efficient to apply since

$$R \left(\mathcal{F}^{(1)} \mathbf{D}^{(1)} \otimes \mathcal{F}^{(2)} \mathbf{D}^{(2)} \right) \cdot \left(\mathbf{v}^{(1)} \otimes \mathbf{v}^{(2)} \right) = R \left(\left(\mathcal{F}^{(1)} \mathbf{D}^{(1)} \mathbf{v}^{(1)} \right) \otimes \left(\mathcal{F}^{(2)} \mathbf{D}^{(2)} \mathbf{v}^{(2)} \right) \right)$$



- Battaglino, Ballard, Kolda, “A practical randomized CP tensor decomposition”, *SIAM J. Matrix Anal. Appl.* (2018)
- Jin, Kolda, Ward. “Faster Johnson–Lindenstrauss transforms via Kronecker products,” *Information and Inference: A Journal of the IMA* (2021)
- Malik, B. “Guarantees for the Kronecker fast Johnson–Lindenstrauss transform using a coherence and sampling argument,” *Lin. Alg. & its Applications* (2020)

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Method 9: Kronecker Fast Johnson-Lindenstrauss sketch

$$\Phi_{\text{KFJLT}} = R \left(\mathcal{F}^{(1)} \mathcal{D}^{(1)} \otimes \mathcal{F}^{(2)} \mathcal{D}^{(2)} \otimes \dots \otimes \mathcal{F}^{(q)} \mathcal{D}^{(q)} \right) \quad p = p^{(1)} p^{(2)} \dots p^{(q)}$$

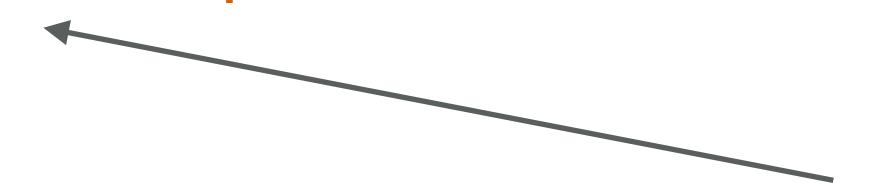
Theorem (Thm 4.2 in Malik, B. 2020)

If all datapoints have a Kronecker structure, $p_{\text{small}} > \frac{16}{2} \frac{4^q}{\varepsilon^2} \log \left(\frac{4N^2(q+1)}{\delta} \right) \log \left(\frac{4p^{(1)} N^2(q+1)}{\delta} \right) \dots \log \left(\frac{4p^{(q)} N^2(q+1)}{\delta} \right)$
and $\Phi = \Phi_{\text{KFJLT}}$

then with probability at least $1 - \delta$

$$\forall x_i, x_j \in \{x_1, \dots, x_N\} \subset \mathbb{R}^p \quad 1 - \varepsilon \leq \frac{\|\Phi x_i - \Phi x_j\|_2^2}{\|x_i - x_j\|_2^2} \leq 1 + \varepsilon$$

proof idea: FJLT keeps leverage scores almost uniform. With Kronecker product structure, this is (almost) true also, due to properties of **leverage scores of Kronecker products**



in fact, can extend. See: [Malik, Xu, Cheng, B., Doostan, Narayan.](#)

"Fast Algorithms for Monotone Lower Subsets of Kronecker Least Squares Problems",
<https://arxiv.org/abs/2209.05662>



o [Malik, B.](#) "Guarantees for the Kronecker fast Johnson–Lindenstrauss transform using a coherence and sampling argument," *Lin. Alg. & its Applications* (2020)

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Method 9: Kronecker Fast Johnson-Lindenstrauss sketch

$$\Phi_{\text{KFJLT}} = R \left(\mathcal{F}^{(1)} D^{(1)} \otimes \mathcal{F}^{(2)} D^{(2)} \otimes \dots \otimes \mathcal{F}^{(q)} D^{(q)} \right) \quad p = p^{(1)} p^{(2)} \dots p^{(q)}$$

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Theorem (Johnson-Lindenstrauss, 1984 (and Indyk-Motwani, 1998))

Choose $\Phi = \Phi_{\text{randn}}$ with $p_{\text{small}} \propto \varepsilon^{-2} \log N$ iid rows each $\mathcal{N}(0, p/p_{\text{small}})$, then for all $x_i, x_j \in \{x_1, \dots, x_N\} \subset \mathbb{R}^p$,

for reference:

$$1 - \varepsilon \leq \frac{\|\Phi x_i - \Phi x_j\|_2}{\|x_i - x_j\|_2} \leq 1 + \varepsilon$$

with constant probability.

no dependence on p

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One application of sketching: least-squares

Least-squares

Solve $x_{\text{LS}} = \operatorname{argmin} \|Ax - b\|$, A is $p \times N$ with $p \gg N$

Approach 1: randomization to quickly find preconditioner

BLENDENPIK, LSRN

- ▶ If $A = QR$ is a QR-decomposition, then AR^{-1} is well-conditioned
- ▶ Idea: do QR-decomp on reduced-dimension matrix ΦA
- ▶ On large, very ill-conditioned matrices (and tall), about $4\times$ faster than LAPACK

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Approach 2: directly solve sketched problem

Sarlos, Woodruff, Mahoney, etc.

- ▶ Directly solve $\min_x \|\Phi(Ax - b)\|$
- ▶ Theoretical bounds on objective error if Φ has $p_{\text{small}} = N \text{polylog}(N)$ rows
 - ▶ i.e., p_{small} is independent of p

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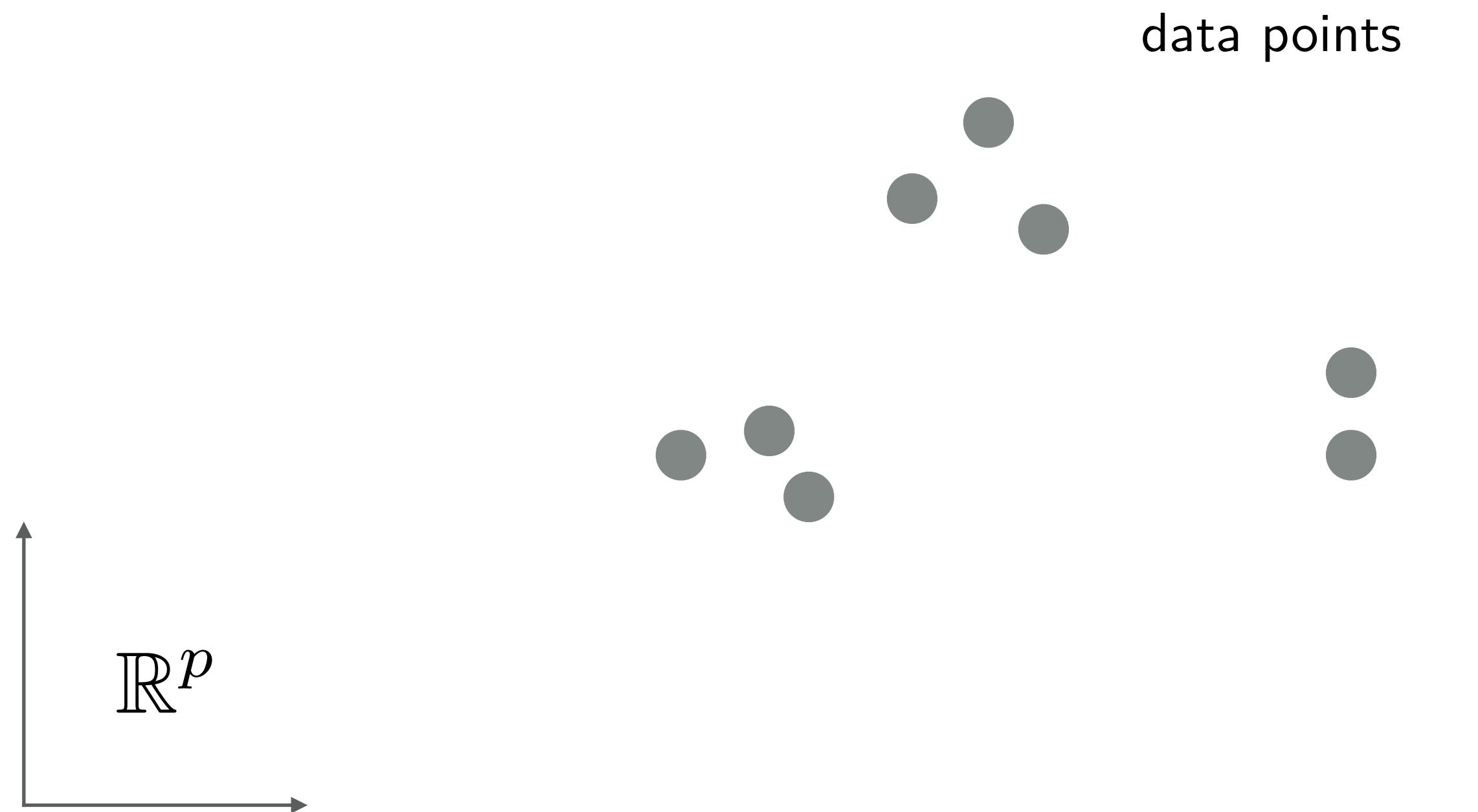
Other applications: SVDs, matrix multiplies, Nyström/CUR/Interpolative Decompositions, QR without pivoting

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Machine Learning 101: K-means clustering

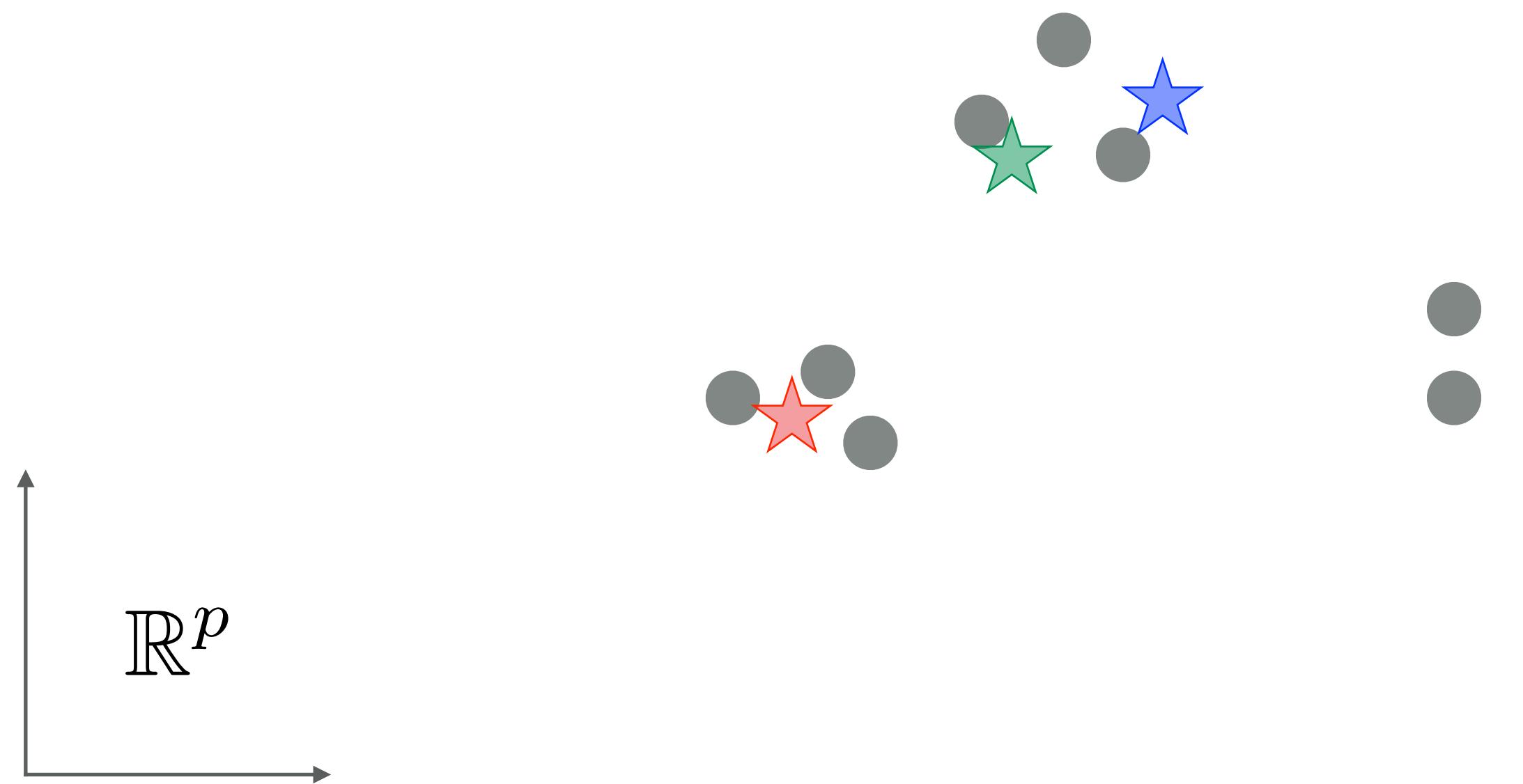
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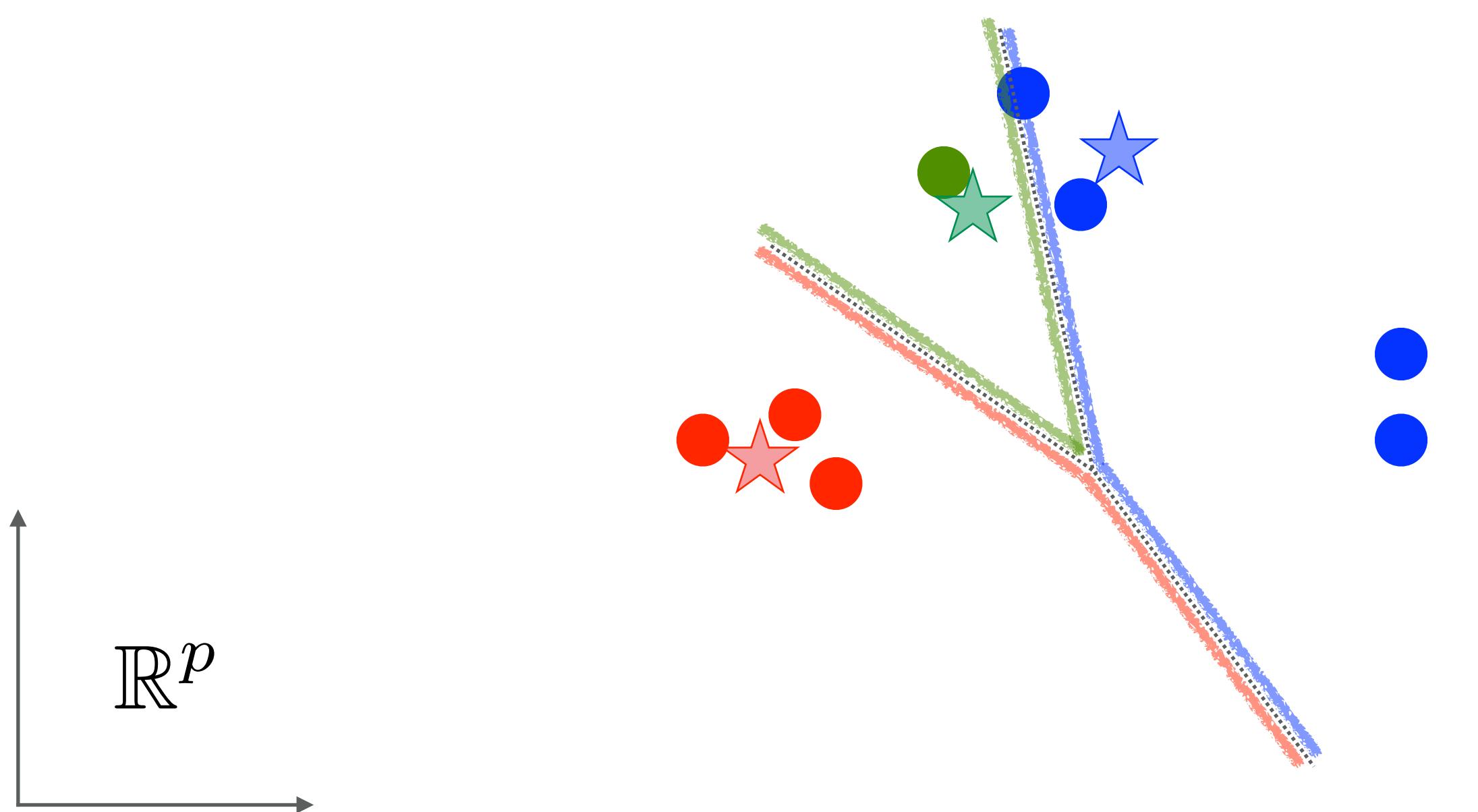
Step: initialize with guesses for cluster **centers**



Machine Learning 101: K-means clustering

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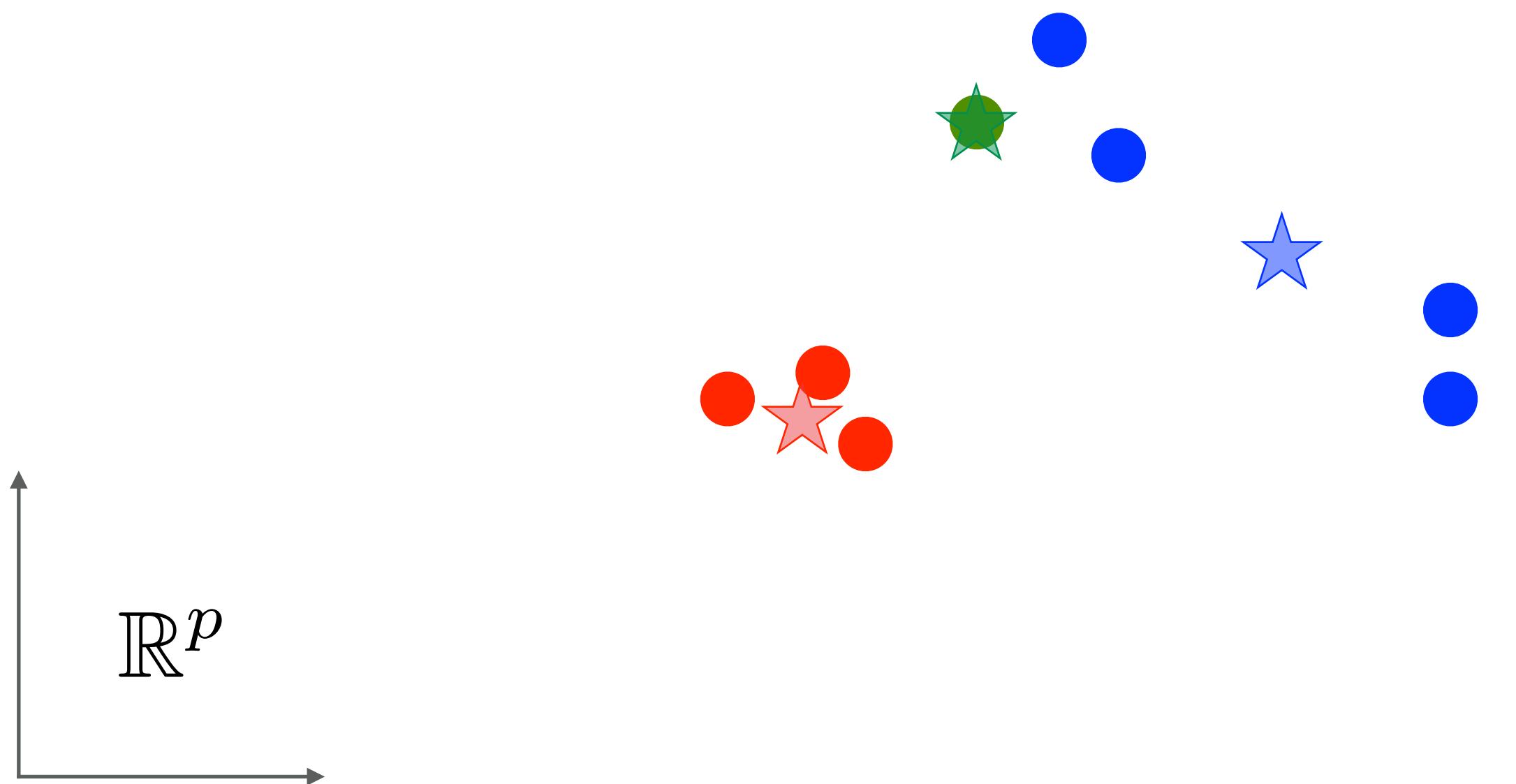
Step: update **assignments**



Machine Learning 101: K-means clustering

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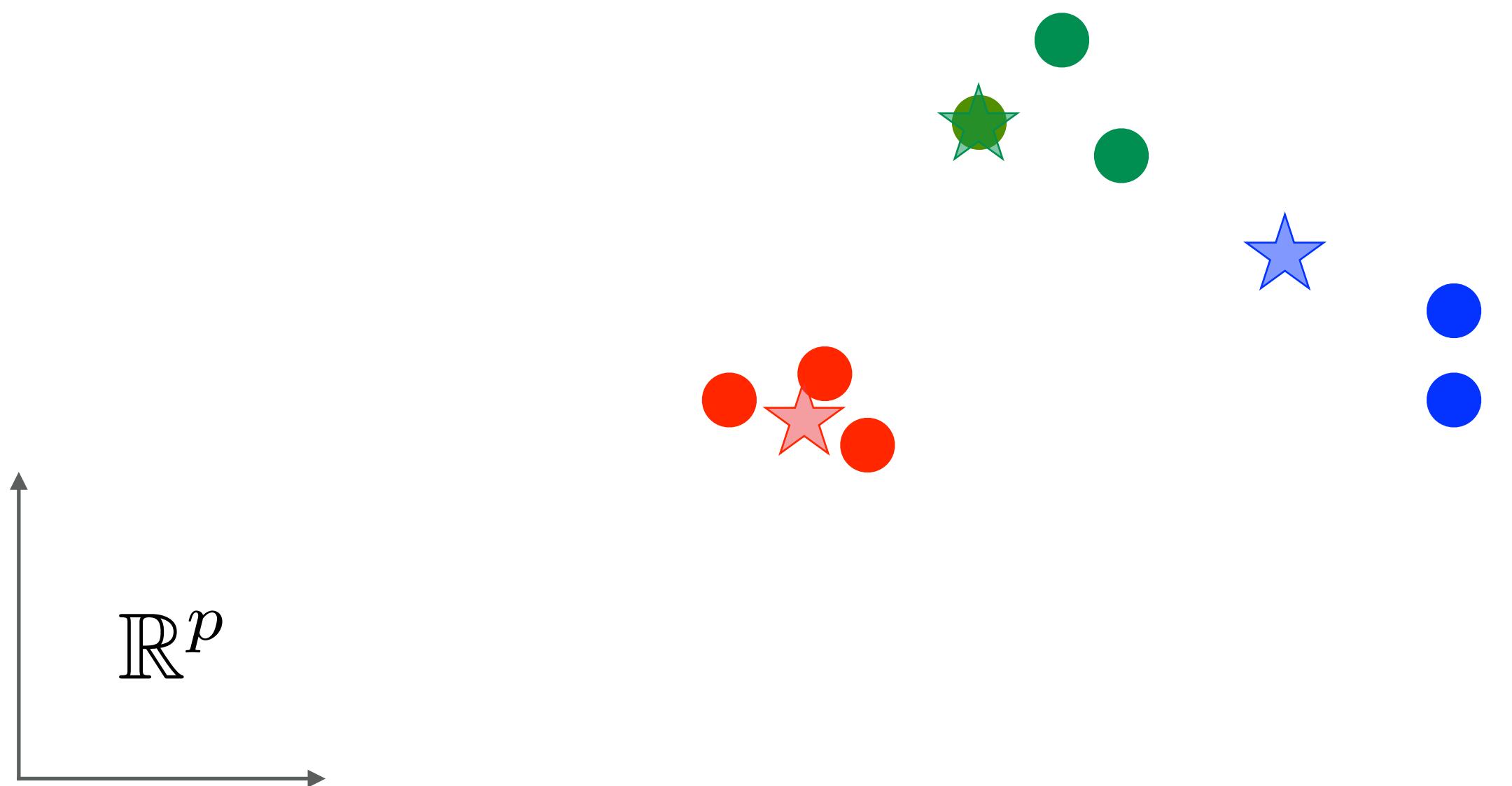
Step: recompute **cluster means**



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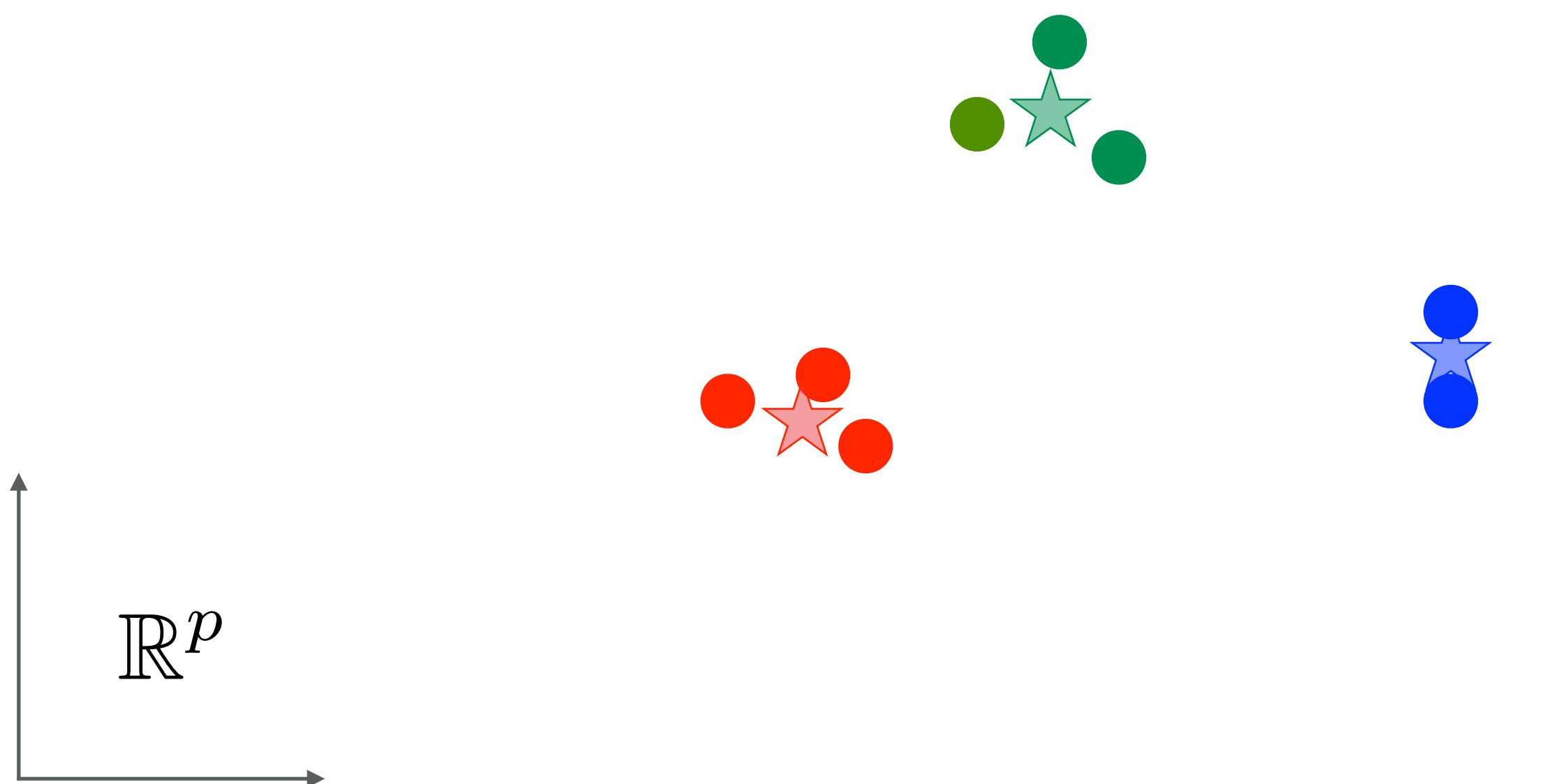
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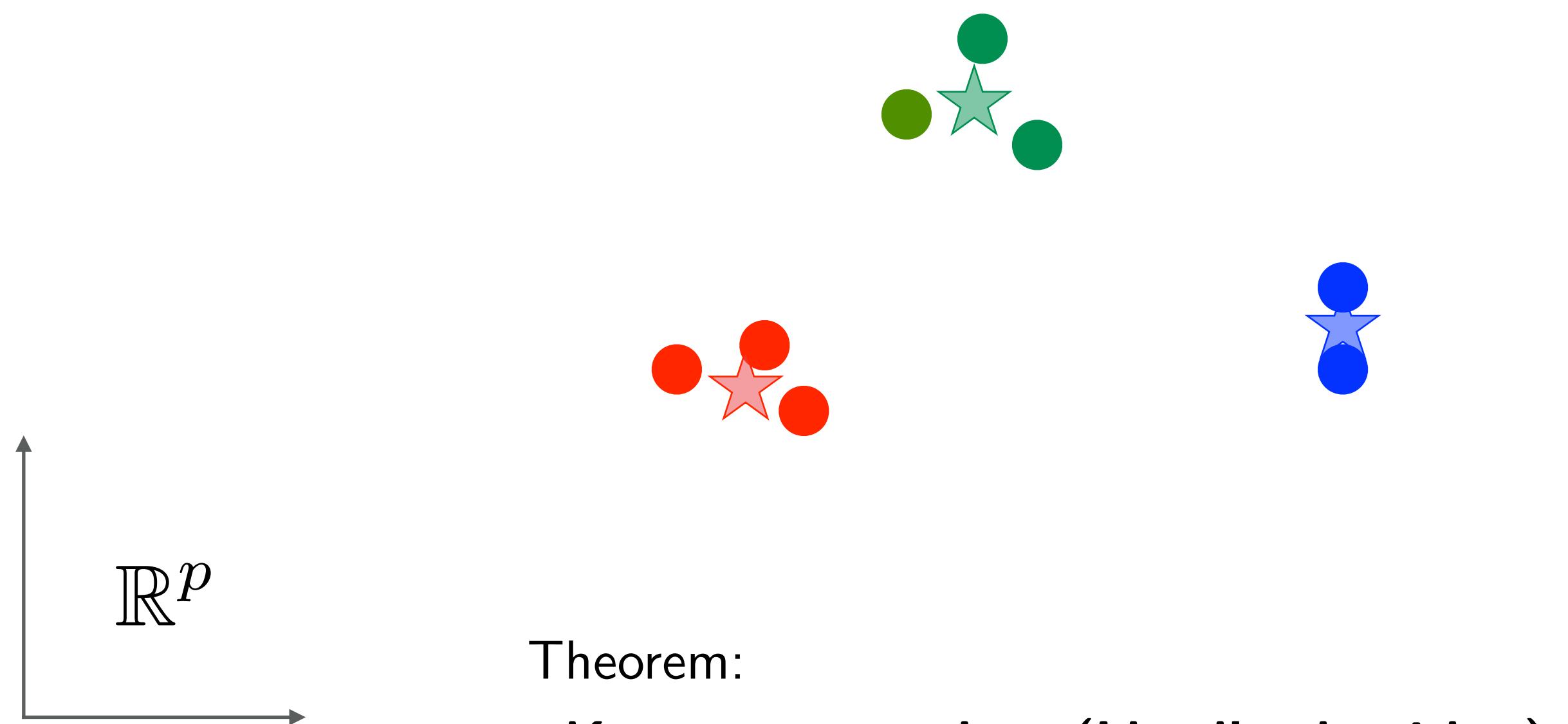
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Machine Learning 101: K-means clustering

Step: recompute **cluster means**



Theorem:

K-means procedure (Lloyd's algorithm) converges

Proof:

*There are only a finite number of assignments, and
we can never cycle since each iteration is an improvement*

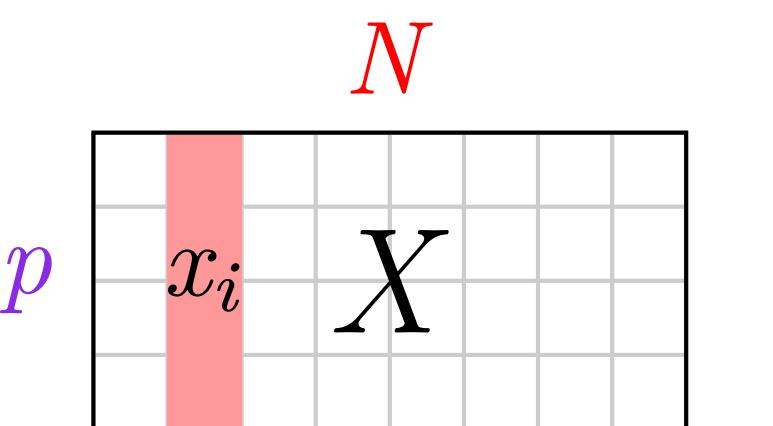
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K-means clustering: complexity

Hard K-means / Lloyd's algorithm:

$$\{x_i\}_{i=1,\dots,N} \subset \mathbb{R}^p$$

1. Update cluster centers $\mu_k \in \mathbb{R}^p$ for $k = 1, \dots, K$
2. Update assignments $c_i \in \{1, \dots, K\}$ for $i = 1, \dots, N$



Let $X = (x_i)_{i=1,\dots,N}$

To update assignment of x_i :

- ▶ Compute $\|x_i - \mu_k\|$ (cost: p flops).
- ▶ For all k , and all i , this means $\mathcal{O}(KNp)$ cost.

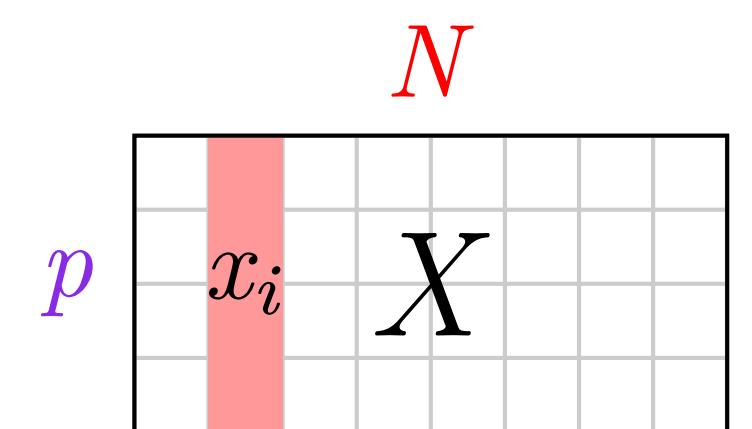
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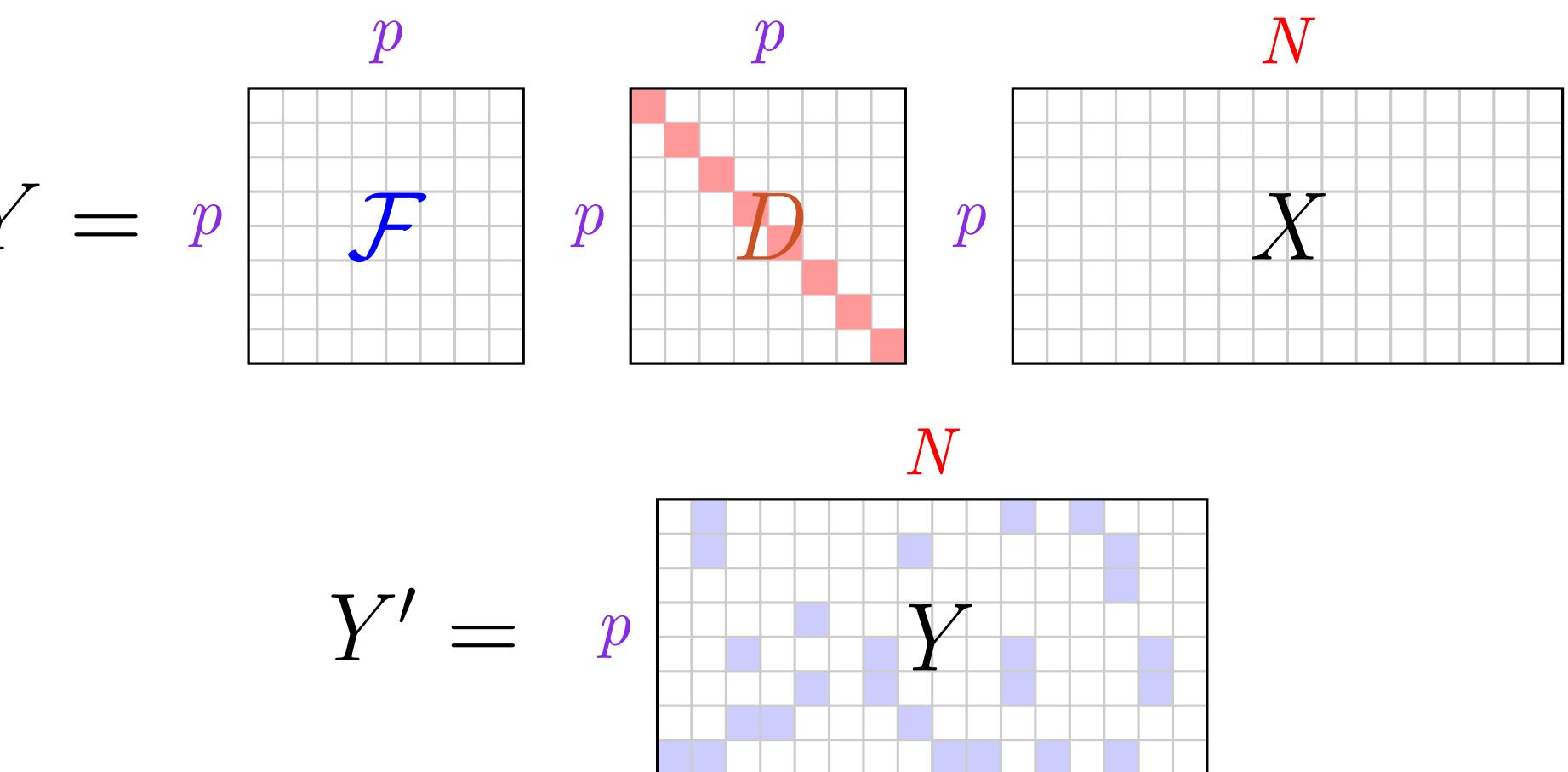


$$\text{Let } X = (x_i)_{i=1,\dots,N}$$

To update assignment of x_i :

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- ▶ For all k , and all i , this means $\mathcal{O}(KNp)$ cost.

Our idea: apply “preconditioned” entry-wise subsampling



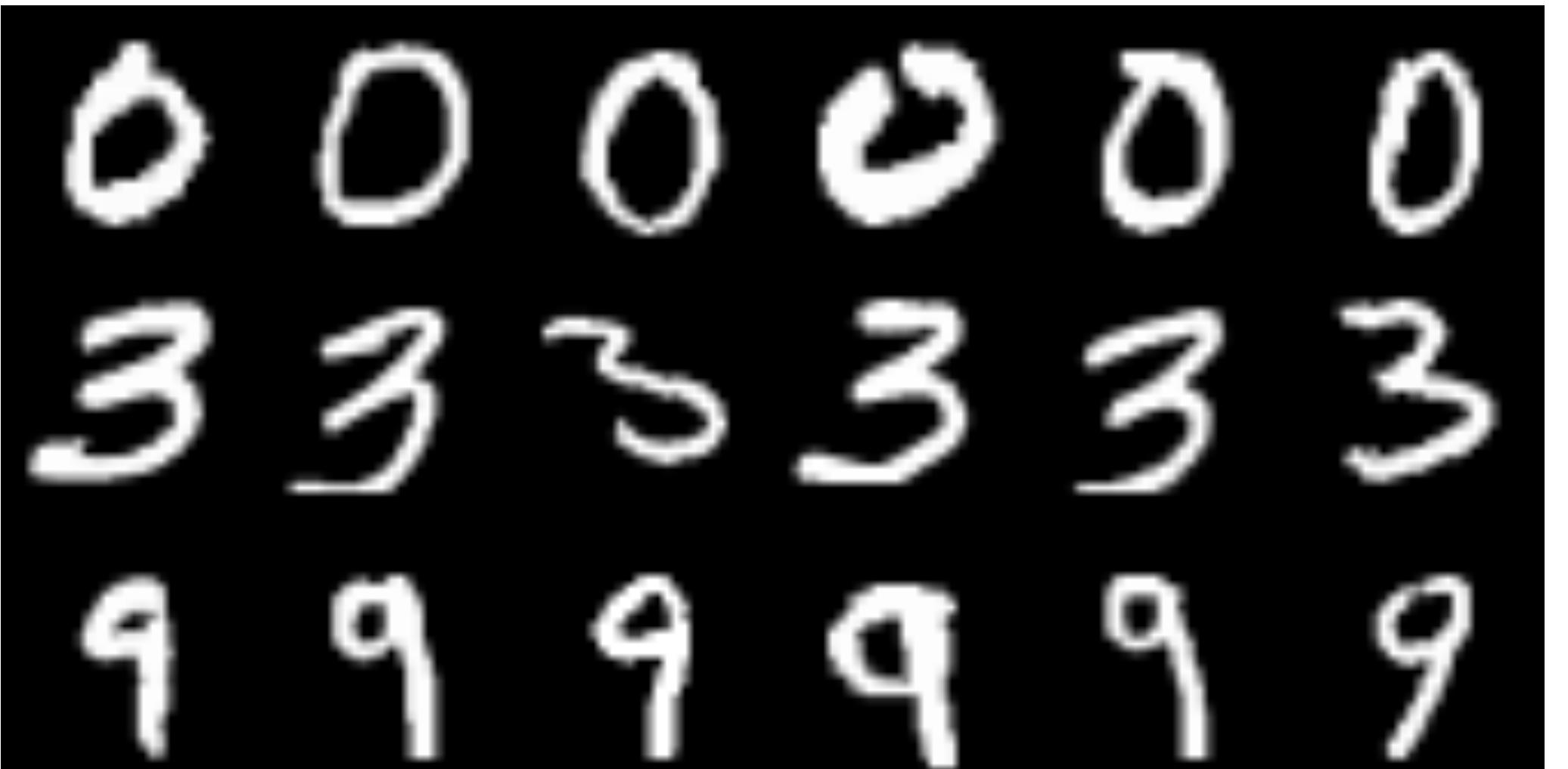
Our sampling is suitable for **streaming** data

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MNIST handwritten digits

Goal: recover cluster centers, using K-means clustering algorithm

Data: $N = 21,002$ examples of 28×28 pixel images ($p = 784$)



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Experiments: MNIST handwritten digits



(a) true cluster centers



(b) K-means, many passes

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Experiments: MNIST handwritten digits



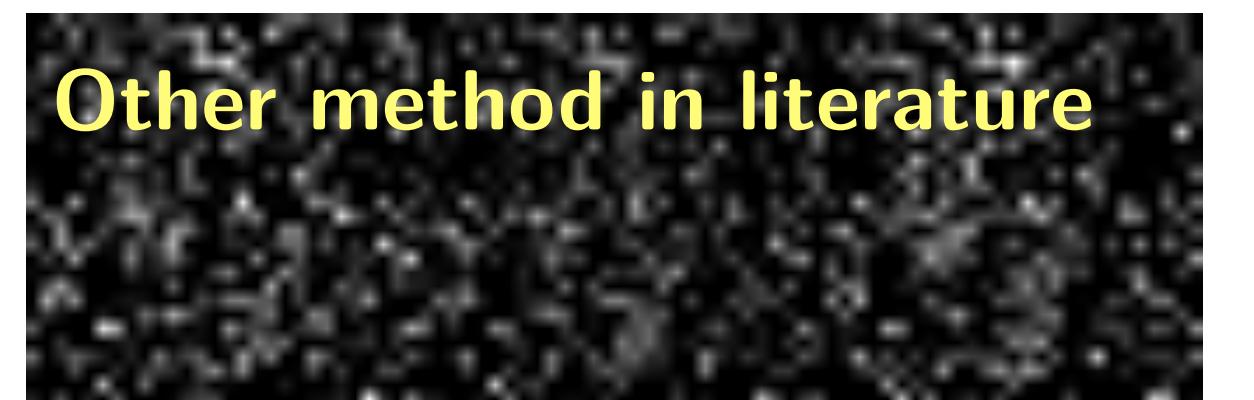
(a) true cluster centers



(b) K-means, many passes



(c) sparsified K-means, 1 pass,
no preconditioning



(g) feature extraction, 1 pass



(h) feature selection, 3 passes

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Experiments: MNIST handwritten digits



(a) true cluster centers



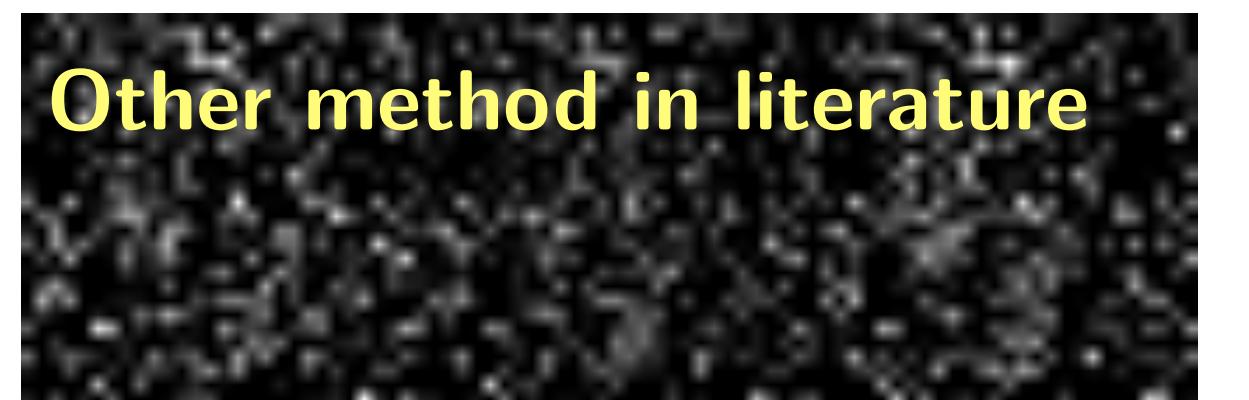
(b) K-means, many passes



(c) sparsified K-means, 1 pass,
no preconditioning



(d) sparsified K-means, 1 pass,
preconditioned



(g) feature extraction, 1 pass

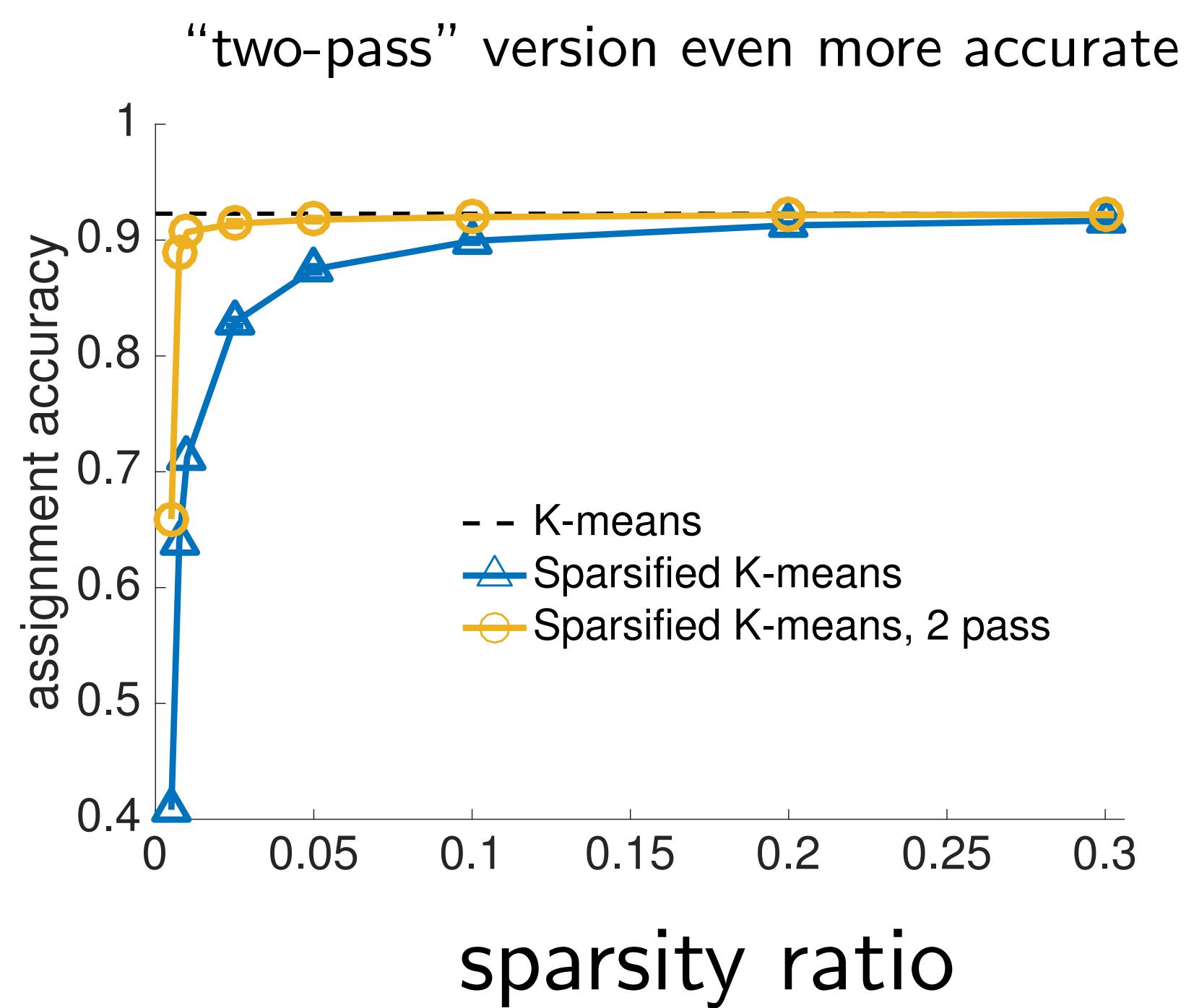
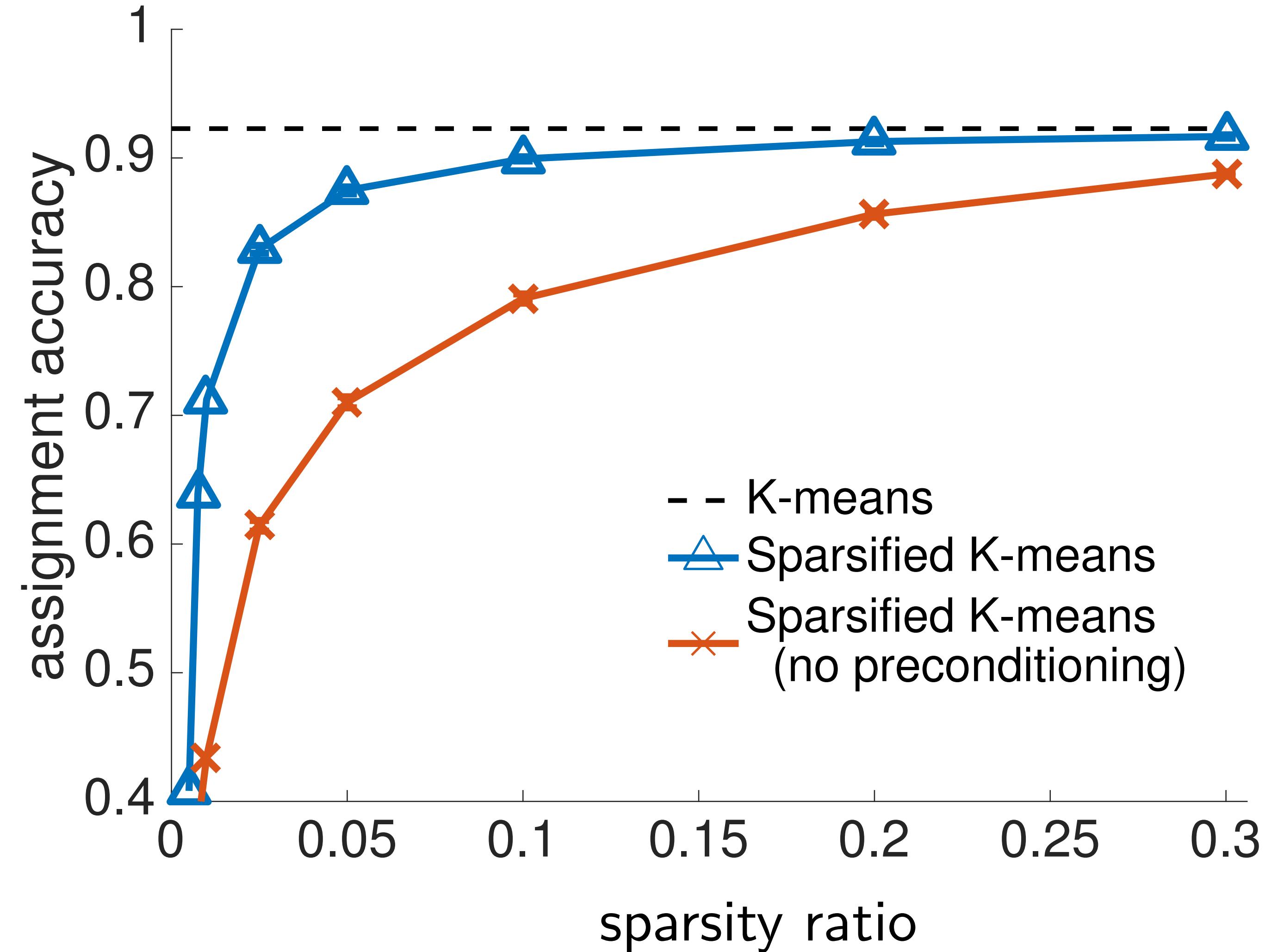


(h) feature selection, 3 passes

Accuracy on MNIST

Now look at **classification accuracy** (averaged over 50 trials)

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Speed on “Infinite MNIST”

“Infinite MNIST”, $p = 784$, but now $N = 9,631,605$ instead of 21,002

56 GB data, split into 58 chunks to keep RAM usage around 1 GB

Algorithm	Time to find assignments		Time to update all centers		Combined time	
	Absolute	Speedup	Absolute	Speedup	Absolute	Speedup
K-means	130.0s	1×	150.8s	1×	280.8s	1×
Sparsified	1.3s	100×	5.7s	26.4×	7.0s	40.1×

at 20x undersampling; accuracy is 89% (vs 92% for K-means)

OUTLINE

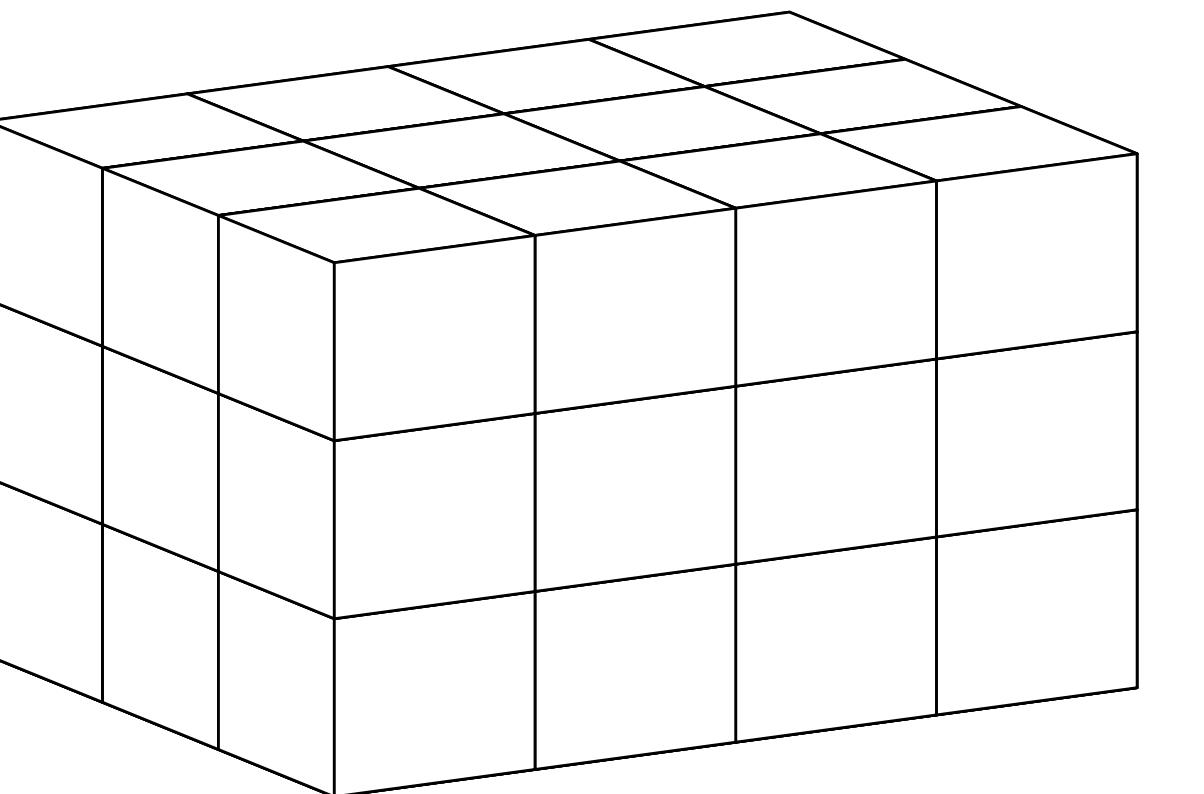
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Tensor Background: what is a tensor?



Change in notation temporarily



- ▶ A *tensor* $\mathcal{X} \in \mathbb{R}^{I_1 \times I_2 \times \dots \times I_N}$ is an array of dimension N , also called an N -way *tensor* or *order N tensor*.
- ▶ A matrix $\mathbf{X} \in \mathbb{R}^{I_1 \times I_2}$ is a 2-way tensor.
- ▶ A vector $\mathbf{x} \in \mathbb{R}^{I_1}$ is a 1-way tensor.
- ▶ A scalar $x \in \mathbb{R}$ is a 0-way tensor.

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Examples of tensors

For example, [Kolda & Sun, '08] consider these datasets:

- ▶ **The Enron dataset** has size $1K \times 1K \times 1.1K \times 200$ and consists of elements of the form (user,user,keyword,day). Element (i, j, k, l) is 1 if user i sent an email to user j with keyword k on day l , 0 otherwise.
- ▶ **The DBLP dataset** has size $5K \times 1K \times 1K$ and consists of elements of the form (author,conference,keyword). Element (i, j, k) is 1 if author i published a paper at conference j containing the keyword k in the title, 0 otherwise.

These are examples of **sparse** tensors

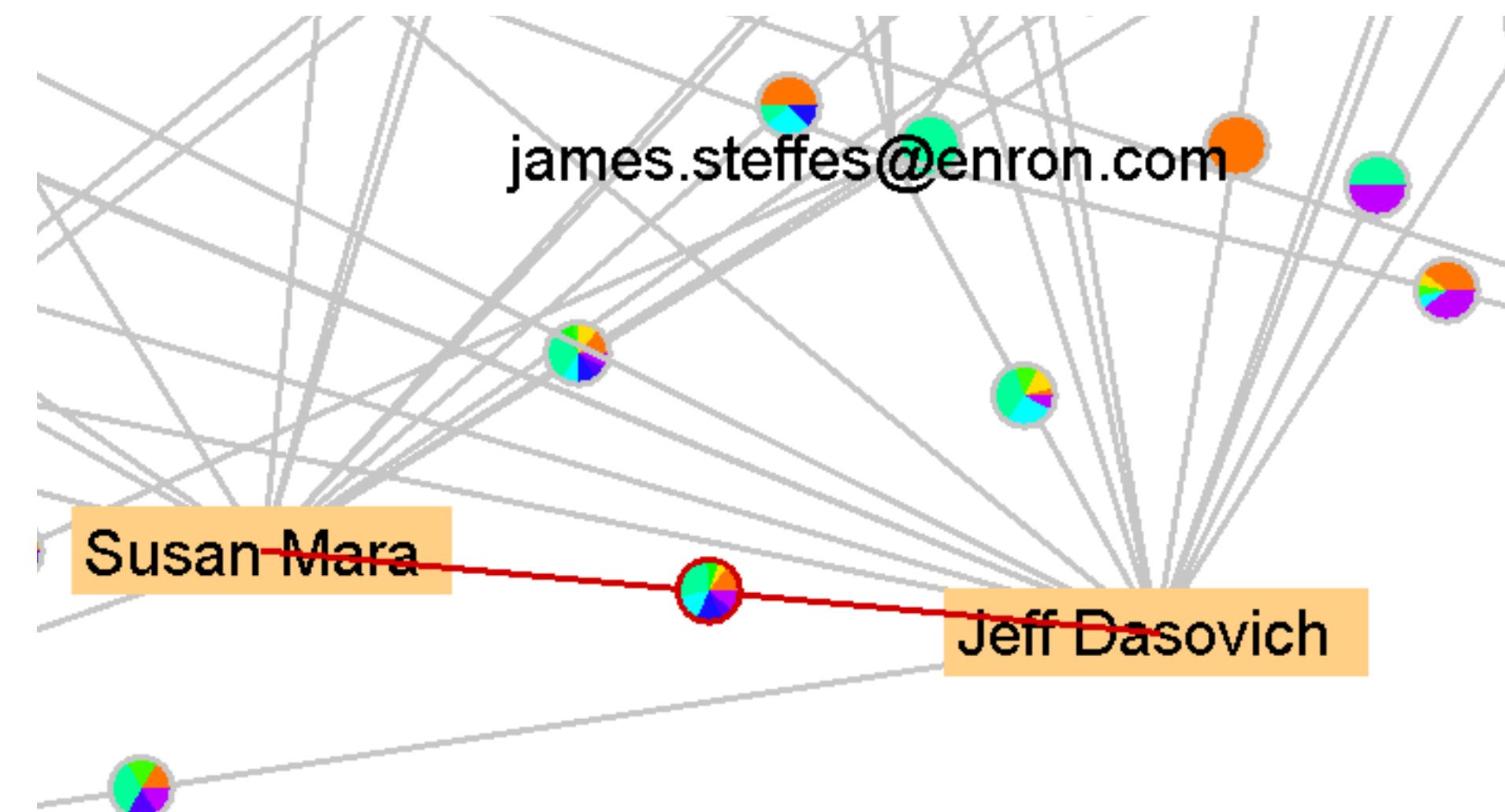


Image: <https://homes.cs.washington.edu/~jheer/projects/enron/>

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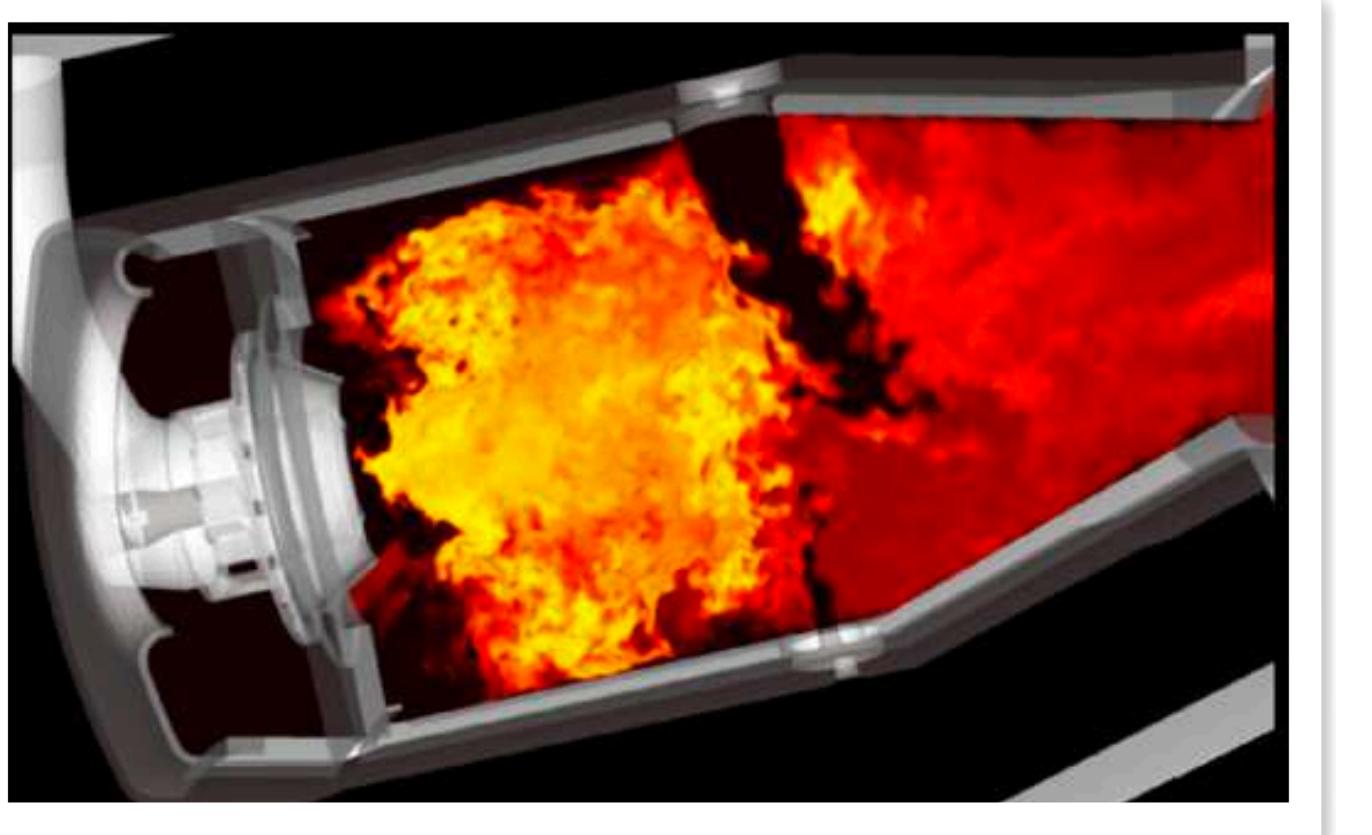
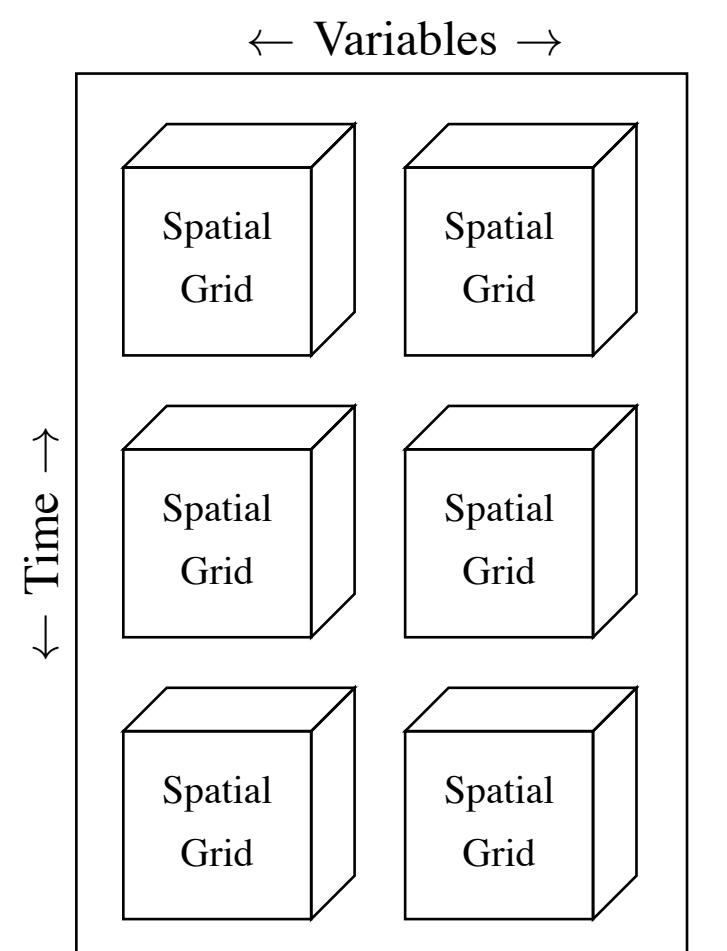


Image: Center for Turbulence Research (Stanford)

[Austin et al., '16] consider tensor data produced by high-fidelity combustion simulations with the following properties:

- ▶ 3-dimensional spatial grid with 512 points per dimension
- ▶ 64 variables are tracked per grid point
- ▶ 128 time steps $512 \times 512 \times 512 \times 64 \times 128$ (8 TB)



This is a **dense tensor**

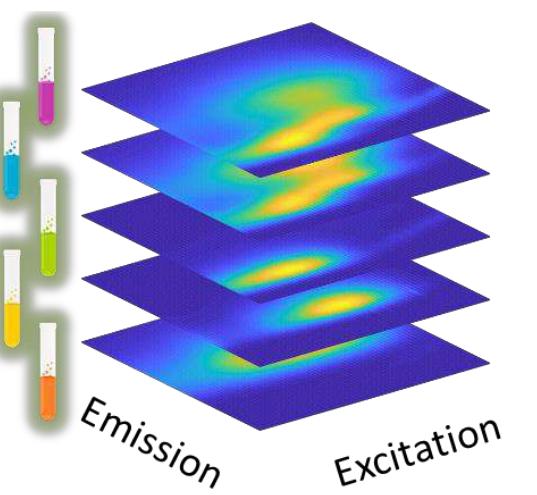
... we'll want methods that work with both sparse and dense tensors

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Examples of tensors

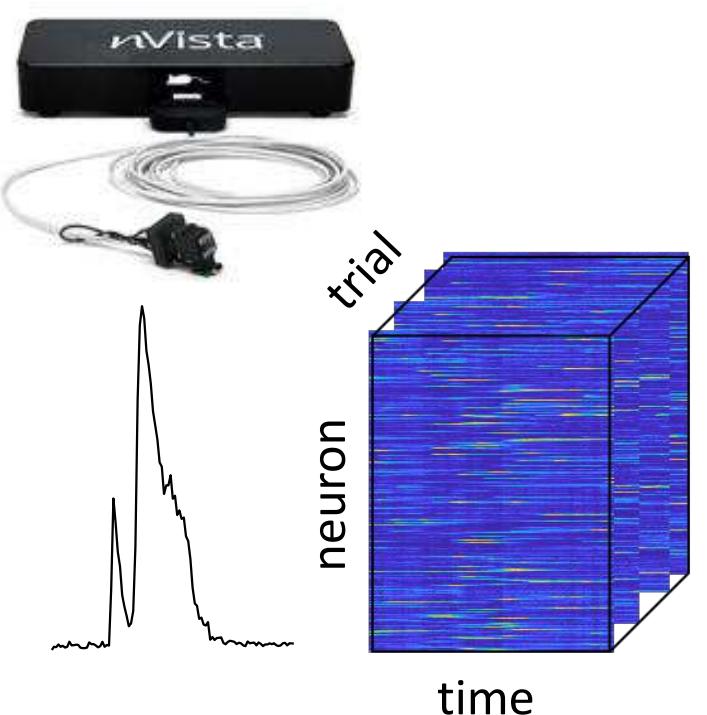
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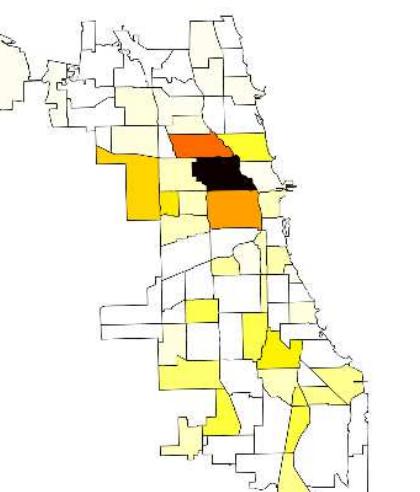
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Others:

- ▶ Chemometrics (emission \times excitation \times samples, for fluorescence spectroscopy)
- ▶ Neuroscience (neuron \times time \times trial/stimulus, for calcium imaging)
- ▶ Criminology (day \times hour \times location \times crime, e.g., Chicago crime dataset)



Images: Tamara Kolda

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Examples of tensors

For example, [Kolda & Sun, '08] consider these datasets:

- ▶ **The Enron dataset**

consists of
Element (i, j, k)
keyword k

- ▶ **The DBLP dataset**

elements of
 (i, j, k) is
containing

[Austin et al.,
combustion sim]

- ▶ 3-dimensional
- ▶ 64 variables
- ▶ 128 time steps

One-pass methods

All these tensors have a **time or sample index**

As time/samples increase, we don't want to store old ones

i.e., want a **streaming/one-pass method**

THIS IS A BIG MOTIVATION FOR SKETCHING

$512 \times 512 \times 512 \times 04 \times 128$ (8 TB)

Others:

- ▶ Chemometrics (emission \times excitation \times samples, for fluorescence spectroscopy)
- ▶ Neuroscience (neuron \times time \times trial/stimulus, for calcium imaging)
- ▶ Criminology (day \times hour \times location \times crime, e.g., Chicago crime dataset)

Tensor operations 1: matricization

Matricization (i.e., flattening) turns a tensor \mathcal{X} into a matrix $\mathbf{X}_{(n)}$

Same idea as turning a matrix (e.g., an image) into a vector

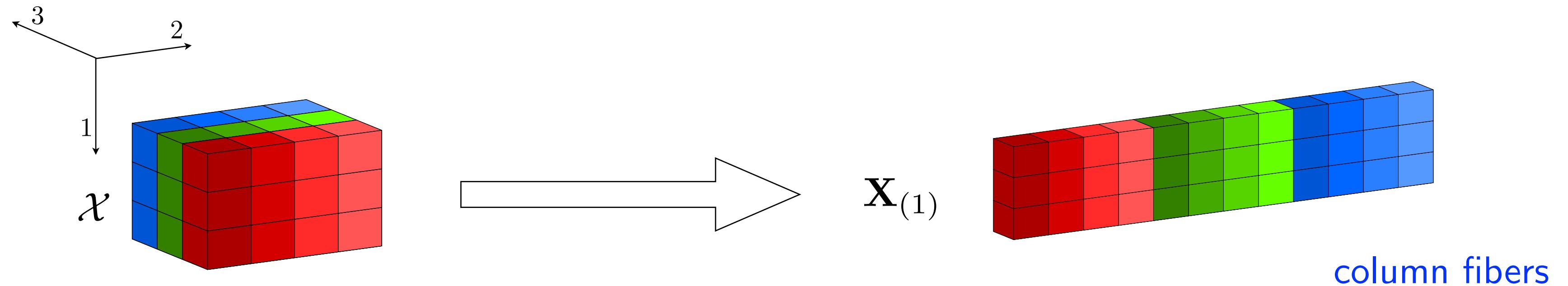
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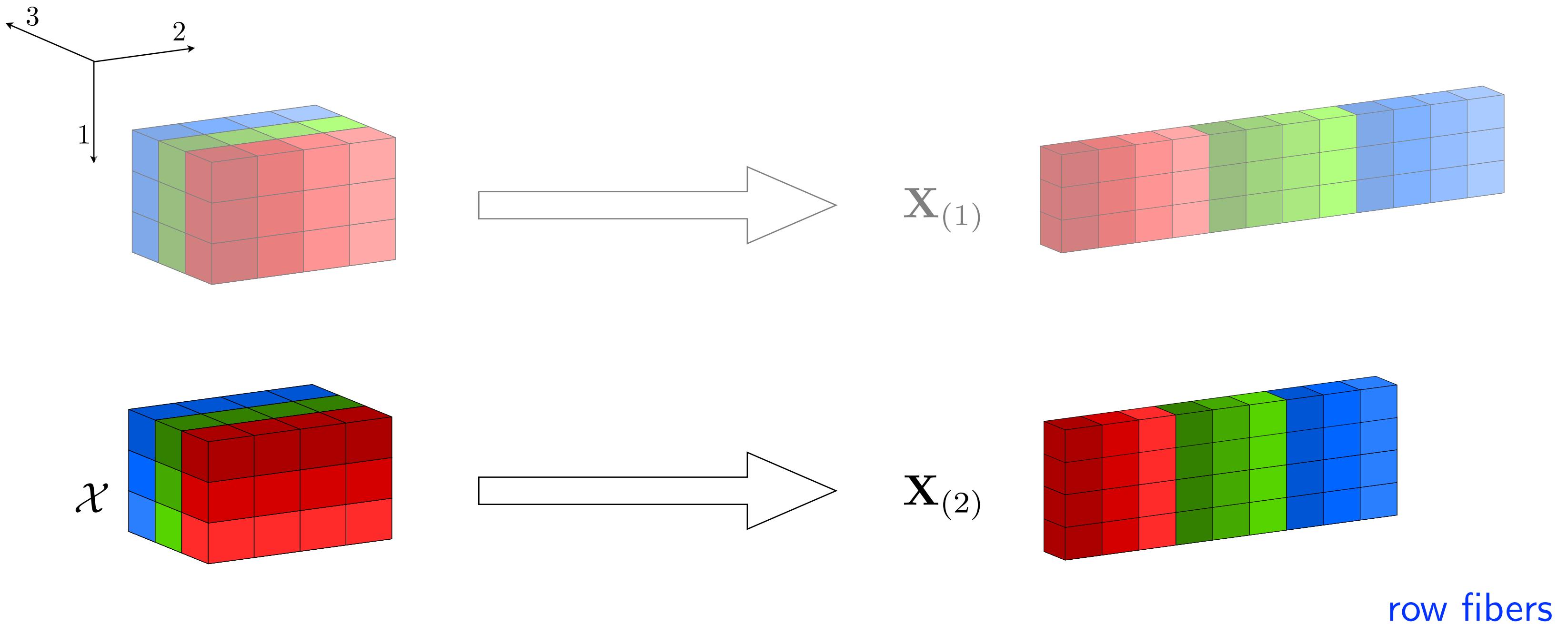


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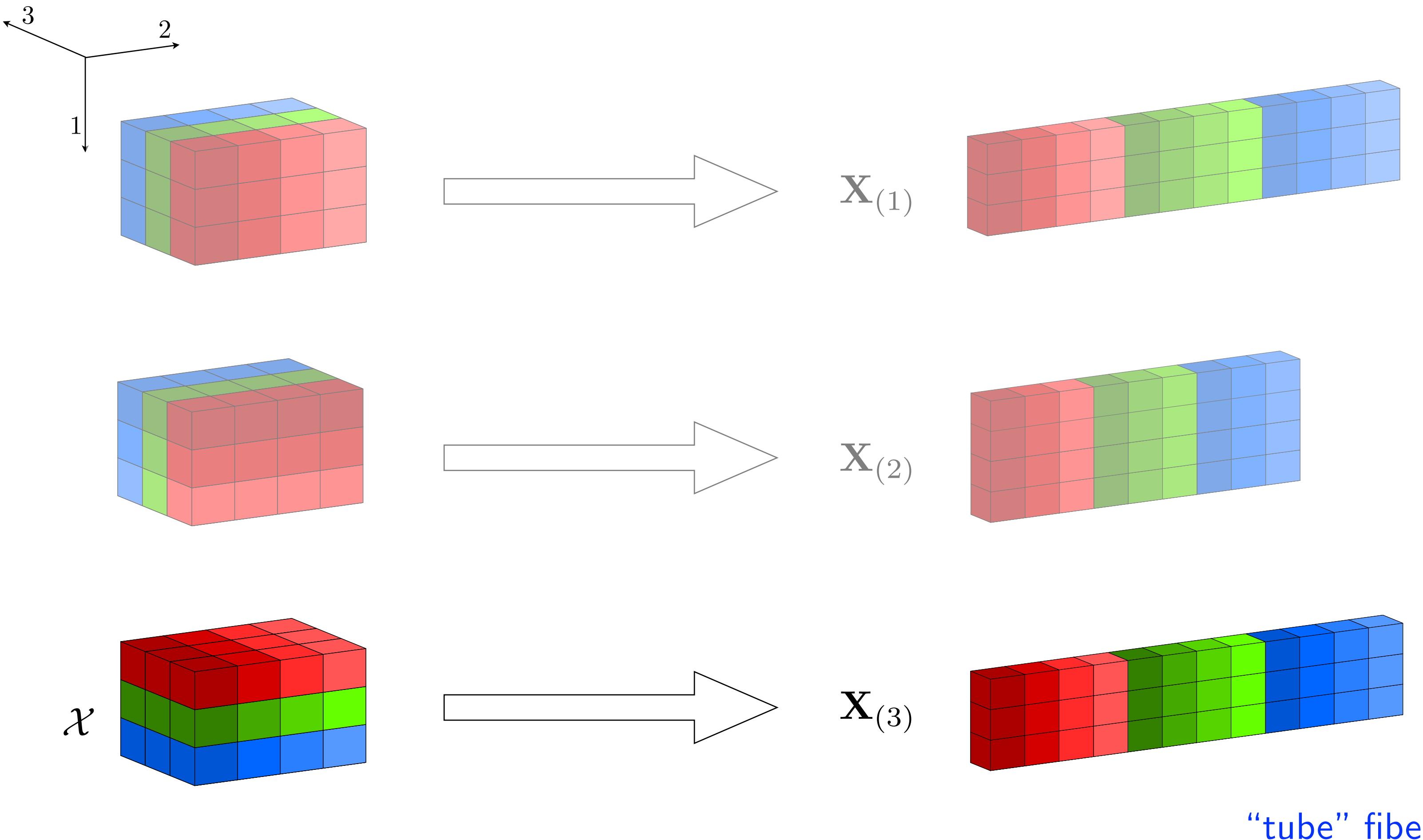


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Tensor operations 2: tensor-times-matrix

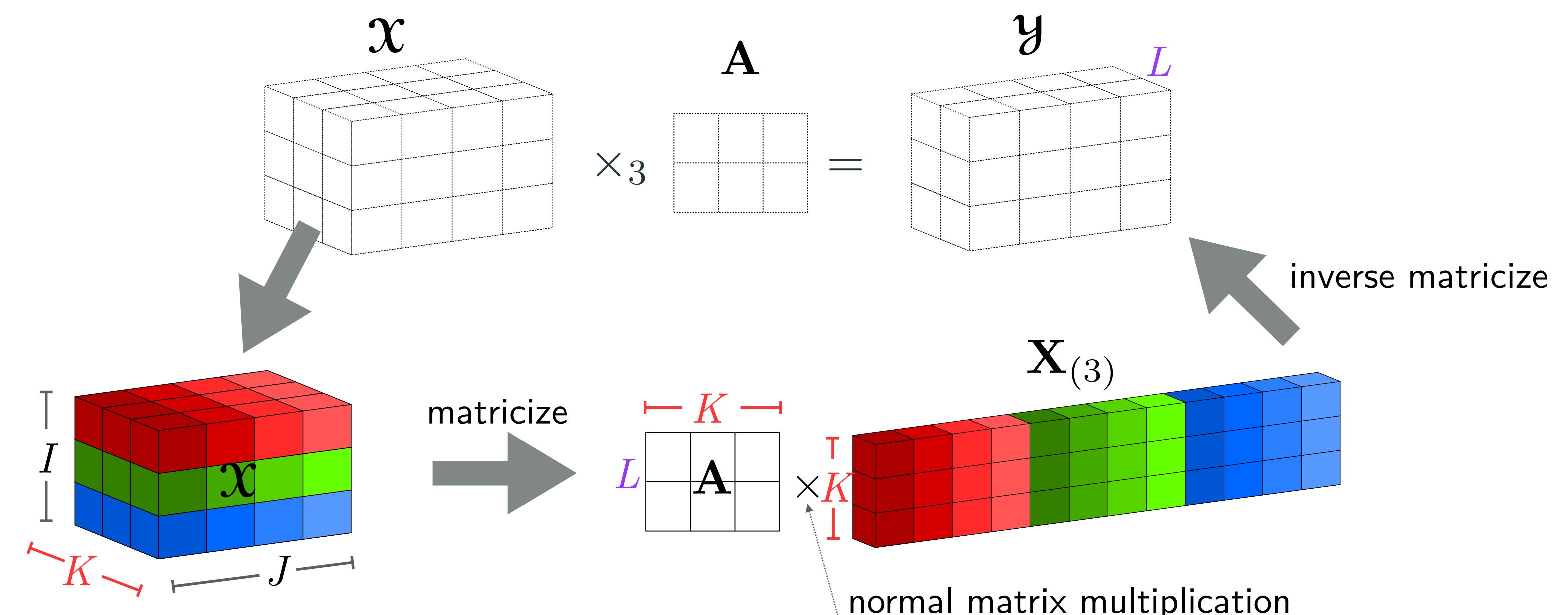
Example:

- Let $\mathcal{X} \in \mathbb{R}^{I \times J \times K}$ and $\mathbf{A} \in \mathbb{R}^{L \times K}$.
- We define $\mathcal{Y} \stackrel{\text{def}}{=} \mathcal{X} \times_3 \mathbf{A} \in \mathbb{R}^{I \times J \times L}$ elementwise by

$$y_{ijl} = \sum_{k=1}^K x_{ijk} a_{kl}.$$

- In matrix terms, $\mathbf{Y}_{(3)} = \mathbf{AX}_{(3)}$.

Conveniently, order doesn't matter*

$$\mathcal{X} \times_1 \mathbf{A}_1 \times_2 \mathbf{A}_2 = \mathcal{X} \times_2 \mathbf{A}_2 \times_1 \mathbf{A}_1$$


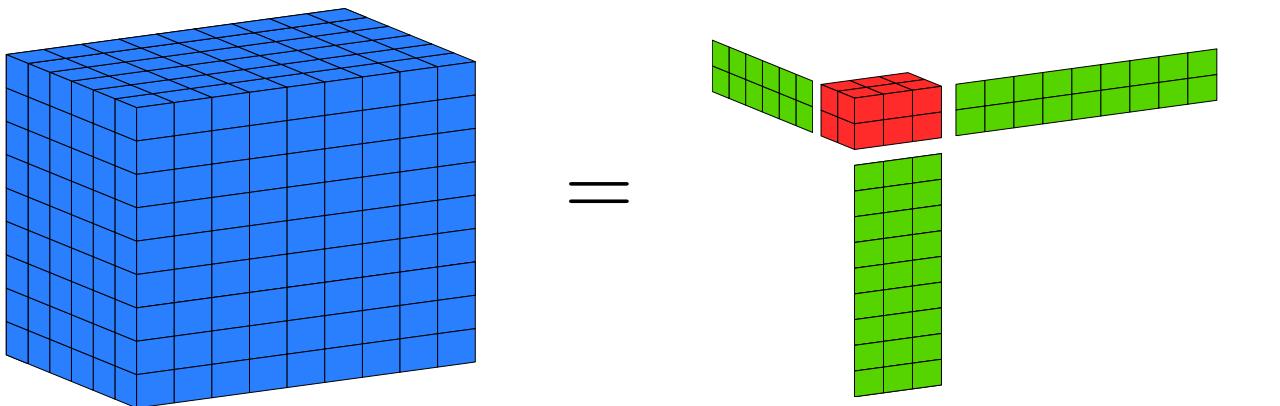
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The Tucker decomposition

A Tucker decomposition of $\mathcal{X} \in \mathbb{R}^{I_1 \times I_2 \times \dots \times I_N}$ is of the form

$$\mathcal{X} = \mathcal{G} \times_1 \mathbf{A}^{(1)} \times_2 \mathbf{A}^{(2)} \dots \times_N \mathbf{A}^{(N)} =: [\![\mathcal{G}; \mathbf{A}^{(1)}, \mathbf{A}^{(2)}, \dots, \mathbf{A}^{(N)}]\!] \text{ (shorthand notation)}$$

where $\mathcal{G} \in \mathbb{R}^{R_1 \times R_2 \times \dots \times R_N}$ and each $\mathbf{A}^{(n)} \in \mathbb{R}^{I_n \times R_n}$.



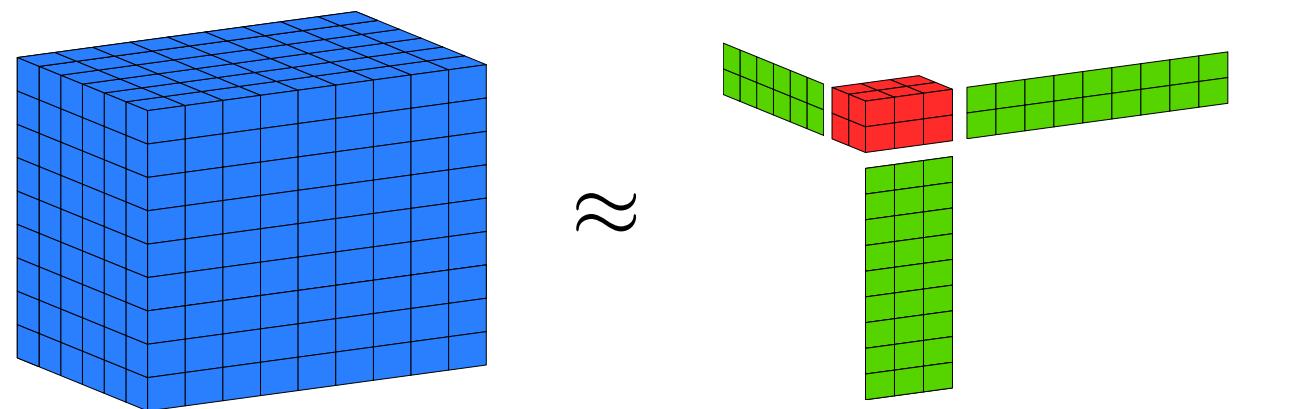
\mathcal{G} is the *core tensor* and $\mathbf{A}^{(n)}$, $n = 1, 2, \dots, N$, are *factor matrices*.

We say that \mathcal{X} is a rank- (R_1, R_2, \dots, R_N) tensor.

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Applications of the Tucker decomposition

- **Data compression.** Storing the **red** and **green** objects require less storage than the full **blue** tensor.
- **Data analysis.** Use rows of factor matrices as feature vectors—*unsupervised learning*.



Computing the Tucker decomposition

Given a data tensor $\mathcal{X} \in \mathbb{R}^{I_1 \times I_2 \times \dots \times I_N}$, we can find a decomposition $\mathcal{X} \approx [\mathcal{G}; \mathbf{A}^{(1)}, \dots, \mathbf{A}^{(N)}]$ by solving the optimization problem

$$\min_{\mathcal{G}, \mathbf{A}^{(1)}, \dots, \mathbf{A}^{(N)}} \|\mathcal{X} - [\mathcal{G}; \mathbf{A}^{(1)}, \mathbf{A}^{(2)}, \dots, \mathbf{A}^{(N)}]\|^2, \quad (4)$$

where $\mathcal{G} \in \mathbb{R}^{R_1 \times R_2 \times \dots \times R_N}$ and $\mathbf{A}^{(n)} \in \mathbb{R}^{I_n \times R_n}$ for $n = 1, 2, \dots, N$.

- Nonlinear!
- A common approach to this issue is to use *alternating least squares (ALS)*: Minimize with respect to each $\mathbf{A}^{(n)}$ and \mathcal{G} one at a time. Repeat! i.e., Gauss-Siedel style
- With ALS, each subproblem is linear and easily solved.

ALS same as *higher-order orthogonal iteration (HOOI)*
and if you do just one iteration, it's *higher-order SVD (HOSVD)*

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Computing the Tucker decomposition

The algorithm looks like this. Repeat the following until convergence:

Repeat until convergence

1. For $n = 1, \dots, N$, update (10)

$$\mathbf{A}^{(n)} = \arg \min_{\mathbf{A} \in \mathbb{R}^{I_n \times R_n}} \left\| \left(\bigotimes_{\substack{i=1 \\ i \neq n}}^N \mathbf{A}^{(i)} \right) \mathbf{G}_{(n)}^\top \mathbf{A}^\top - \mathbf{X}_{(n)}^\top \right\|_F^2. \quad (11)$$

2. Update $\mathcal{G} = \mathcal{X} \times_1 \mathbf{A}^{(1)\top} \times_2 \mathbf{A}^{(2)\top} \cdots \times_N \mathbf{A}^{(N)\top}$. (12)

$$= \arg \min_{\mathbf{Z} \in \mathbb{R}^{R_1 \times \cdots \times R_N}} \left\| \left(\bigotimes_{i=1}^N \mathbf{A}^{(i)} \right) \mathbf{Z}(:, :) - \mathbf{X}(:, :) \right\|_2^2.$$

(Line 12 follows if the factor matrices are orthogonalized)

Make extensive use of this identity:

$$\mathcal{Y} = \mathcal{X} \times_1 \mathbf{A}^{(1)} \times_2 \mathbf{A}^{(2)} \cdots \times_N \mathbf{A}^{(N)} \iff$$

$$\mathbf{Y}_{(n)} = \mathbf{A}^{(n)} \mathbf{X}_{(n)} \left(\mathbf{A}^{(N)} \otimes \cdots \otimes \mathbf{A}^{(n+1)} \otimes \mathbf{A}^{(n-1)} \otimes \cdots \otimes \mathbf{A}^{(1)} \right)^\top$$

Computing the Tucker decomposition

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2. Update $\mathcal{G} = \mathcal{X} \times_1 \mathbf{A}^{(1)\top} \times_2 \mathbf{A}^{(2)\top} \cdots \times_N \mathbf{A}^{(N)\top}$. (12)

Issues when dealing with large, sparse tensors:

- The Kronecker product matrix is huge.
- The series of tensor-times-matrix products is very costly, and can require lots of additional memory when \mathcal{X} is sparse.
- We address this problem by using *TensorSketch*.

Aside: we initially thought that **solving** the least-squares problem would be an issue, and something to fix with sketching, but this is not exactly the case

(partly because of many clever tricks due to orthogonality of \mathbf{A})

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Our modified algorithm: Tucker-TS

We simply sketch each of these least-squares problems with TensorSketch operators $\mathbf{S}^{(n)}$, $n = 1, \dots, N + 1$, which are defined at the start of the algorithm:

Repeat until convergence

1. For $n = 1, \dots, N$, update

$$\mathbf{A}^{(n)} = \arg \min_{\mathbf{A} \in \mathbb{R}^{I_n \times R_n}} \left\| \left(\mathbf{S}^{(n)} \bigotimes_{\substack{i=1 \\ i \neq n}}^N \mathbf{A}^{(i)} \right) \mathbf{G}_{(n)}^\top \mathbf{A}^\top - \mathbf{S}^{(n)} \mathbf{x}_{(n)}^\top \right\|_F^2. \quad (18)$$

(and orthogonalize)

2. Update

$$\mathbf{G} = \arg \min_{\mathbf{z} \in \mathbb{R}^{R_1 \times \dots \times R_N}} \left\| \left(\mathbf{S}^{(N+1)} \bigotimes_{i=1}^N \mathbf{A}^{(i)} \right) \mathbf{z}_{(:)} - \mathbf{S}^{(N+1)} \mathbf{x}_{(:)} \right\|_2^2. \quad (19)$$

Tricks:

- don't draw new sketches each iteration
- the TensorSketches have CountSketches/hashes in common $\mathbf{S}^{(n)}, \mathbf{S}^{(n')}$
- G update solved via conjugate gradient (CG) algo, and can prove it is well-conditioned
- advanced tricks and variants in the paper

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Numerical experiment: sparse 3D tensor

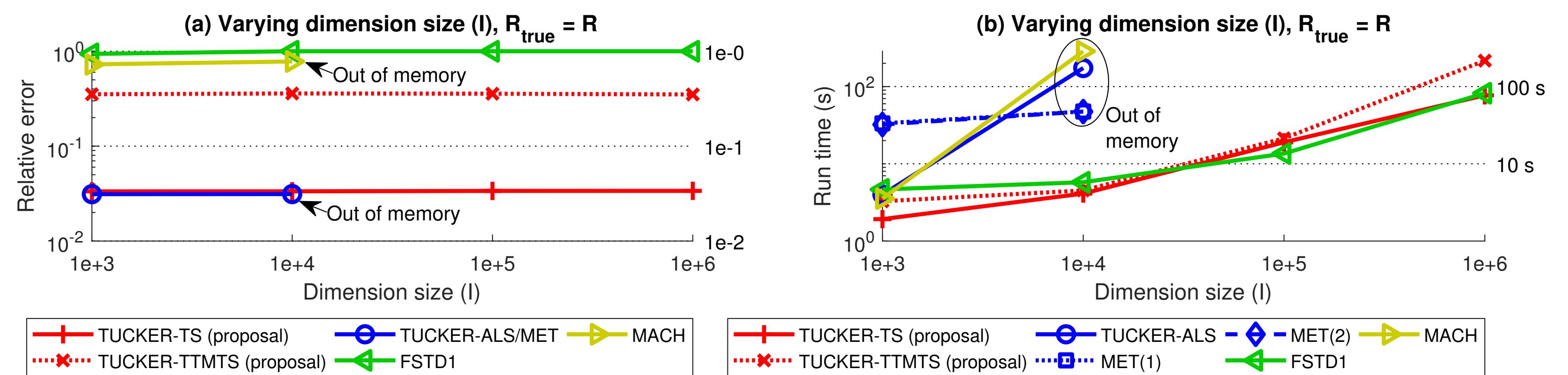


Figure 3: Relative error and run time for random sparse 3-way tensors with varying dimension size I and $\text{nnz}(\mathcal{Y}) \approx 1e+6$. Both the true and target ranks are $(10, 10, 10)$.

Tucker-TS approximates least-squares like this:

$$\begin{aligned} \operatorname{argmin}_x \frac{1}{2} \|Ax - b\|_2^2 &\approx \operatorname{argmin}_x \frac{1}{2} \|\Phi(Ax - b)\|_2^2 \\ &= (A^\top \Phi^\top \Phi A)^{-1} A^\top \Phi^\top \Phi b \end{aligned}$$

Tucker-TTMTS approximates least-squares like this:

$$\begin{aligned} \operatorname{argmin}_x \frac{1}{2} \|Ax - b\|_2^2 &= (A^\top A)^{-1} A^\top b \\ &\approx (A^\top A)^{-1} A^\top \Phi^\top \Phi b \end{aligned}$$

Video

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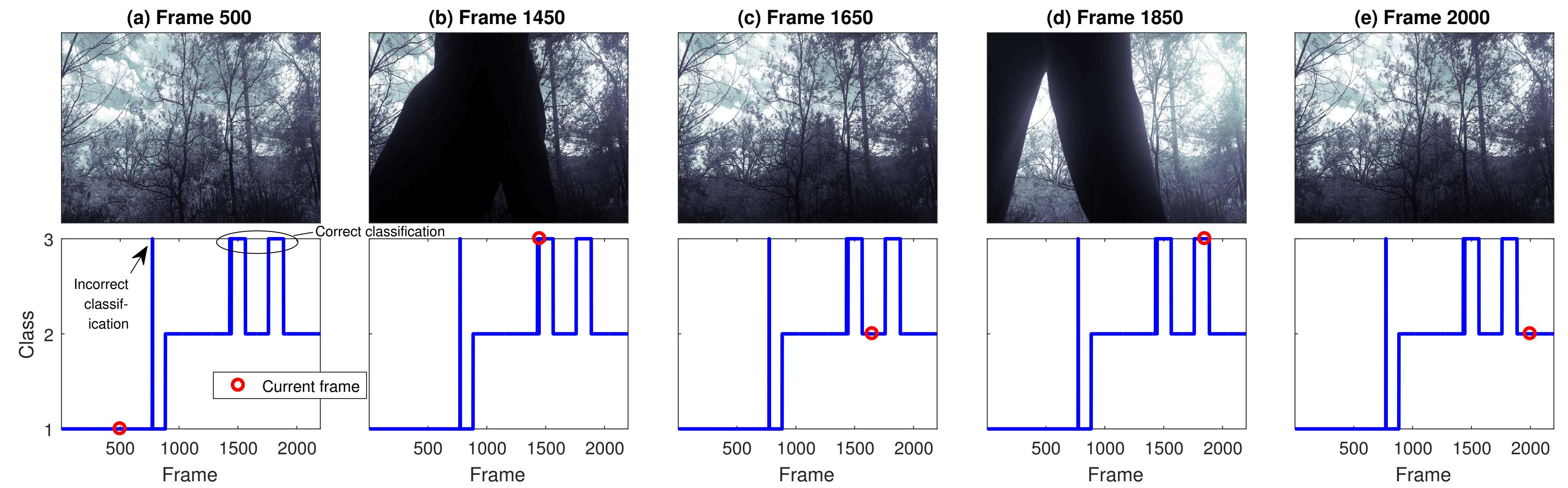


Figure 6: Five sample frames with their assigned classes. The frames (b) and (d) contain a disturbance.

38 GB video (can't all fit into RAM): 2,200 frames, each of size 1,080 by 1,980 pixels

Compute rank (10,10,10) factorization, 30 iterations max

Find 3 factor matrices — take the one corresponding to time and run k-means clustering

(used Tucker-TTMTS variant)

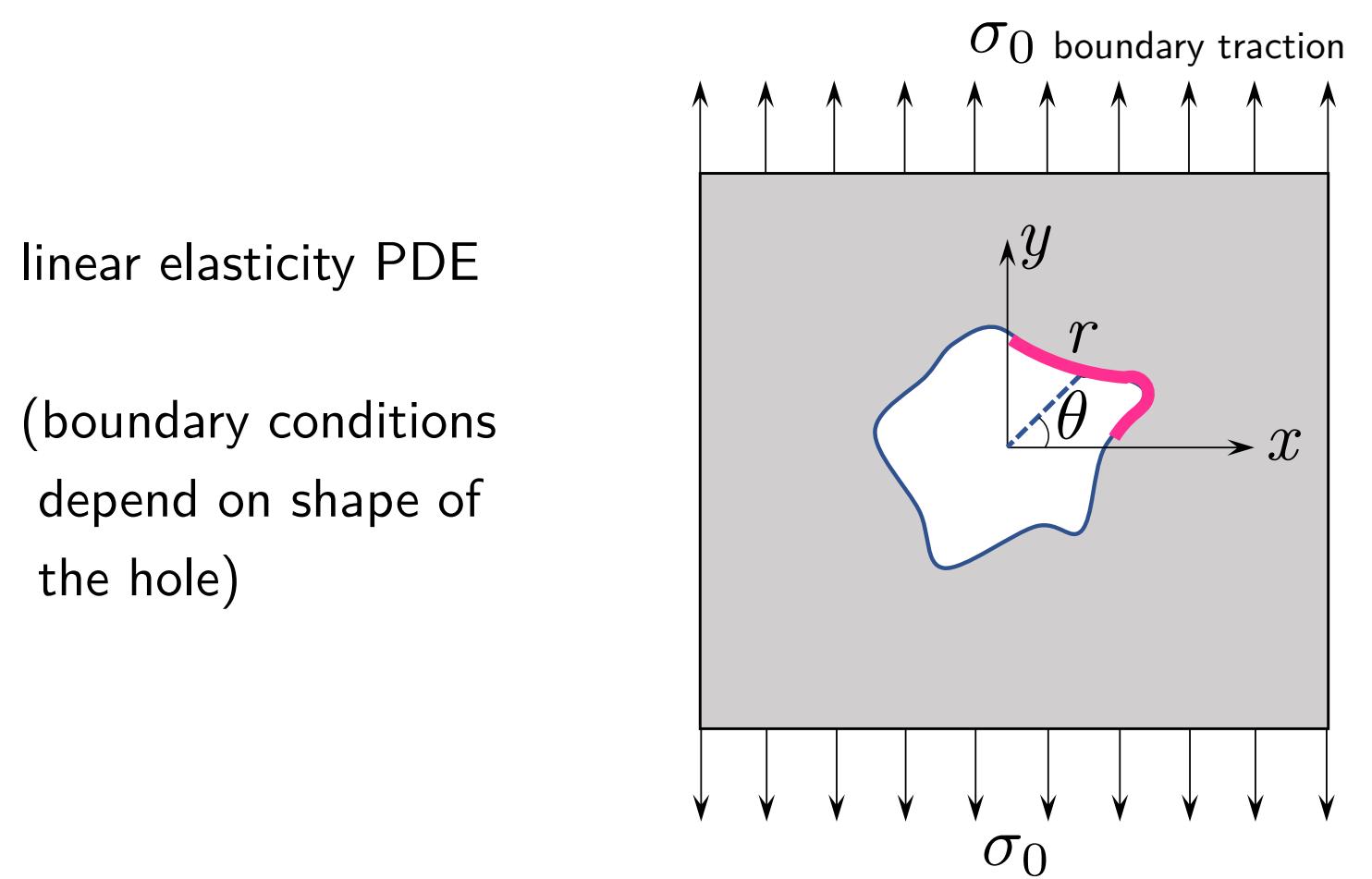
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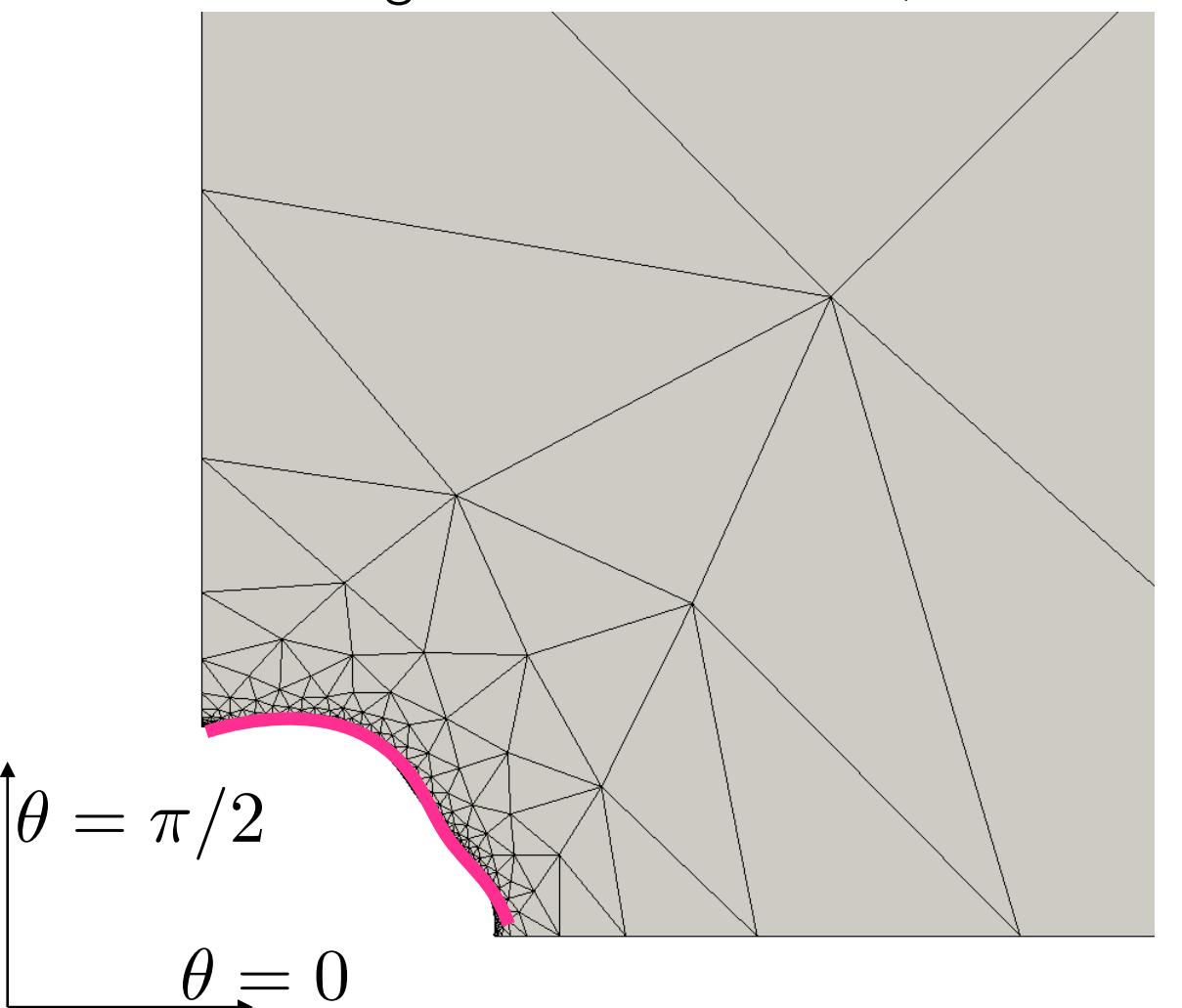
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Motivating Application: shape optimization

Forward problem: find vertical stress σ_y



conforming finite element mesh, used in FEniCS

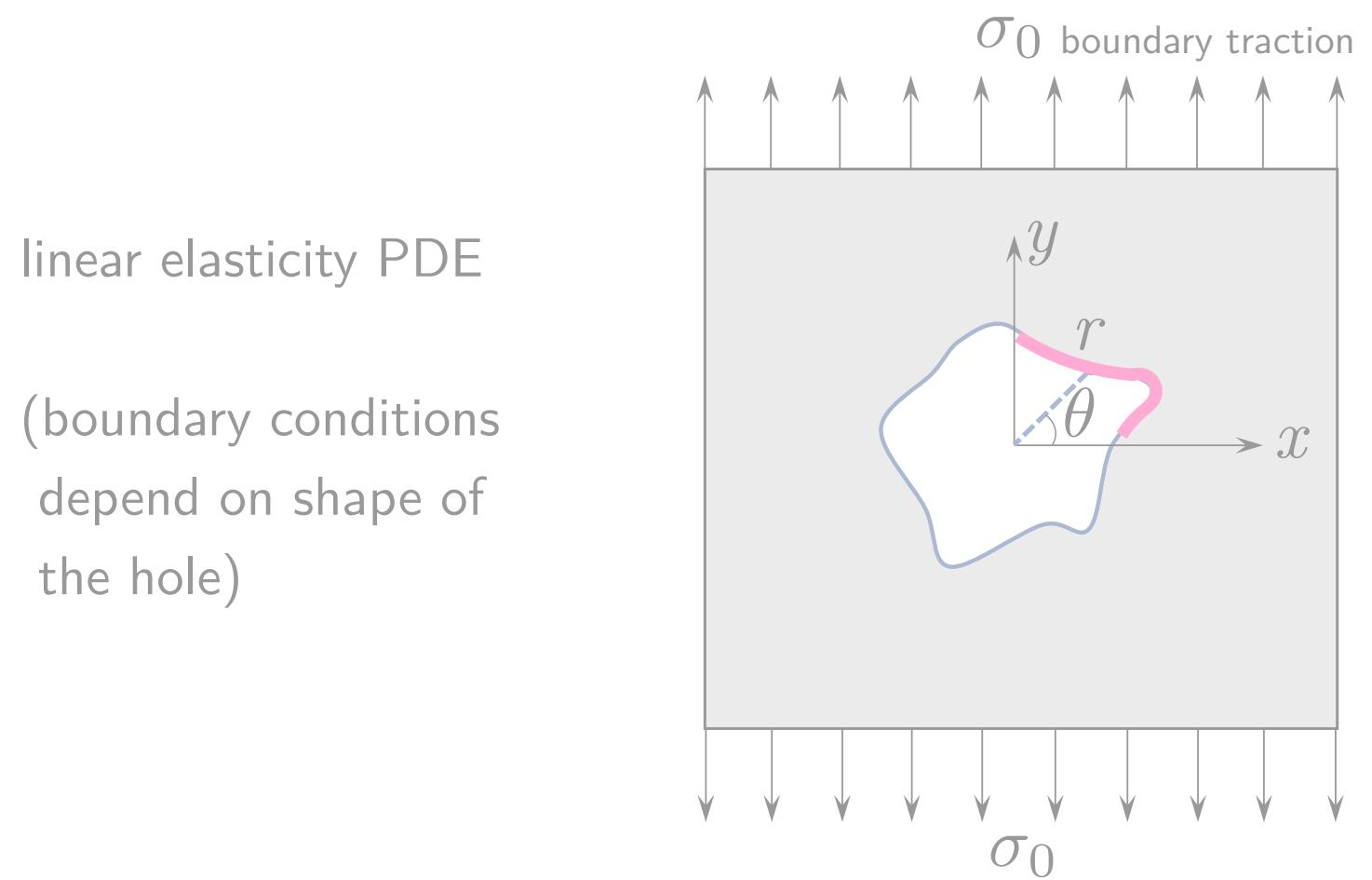


Change in notation temporarily

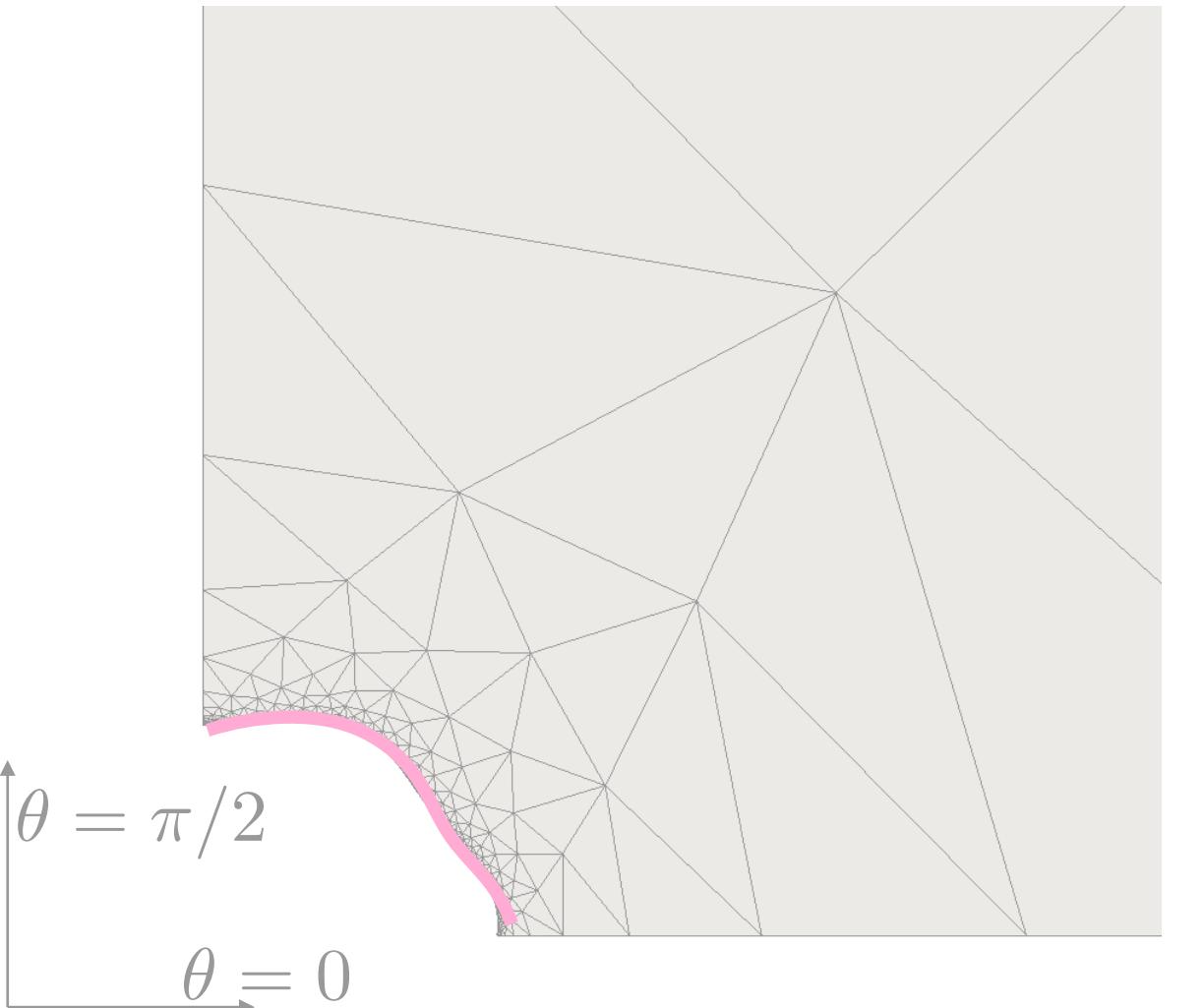
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Motivating Application: shape optimization

Forward problem: find vertical stress σ_y



conforming finite element mesh, used in FEniCS



Inverse problem: what shape minimizes the vertical stress?

parameterize the shape of the hole as follows, which automatically enforces a constant area constraint

$$r(\theta) = \frac{1}{2\pi} + \delta \sum_{k=0}^{d/2-1} \frac{1}{\sqrt{2k+1}} (\textcolor{red}{x}_{2k+1} \sin((2k+1) \cdot \theta) + \textcolor{red}{x}_{2k+2} \cos((2k+1) \cdot \theta))$$

optimization variable:

$$\textcolor{red}{x} \in \mathbb{R}^d$$

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Generic PDE-constrained optimization

implicitly saying that u solves the PDE

$$\boxed{\min_{u,x} \mathcal{L}(u) \quad \text{subject to} \quad \phi(u, x) = 0}$$

Examples:

$$\dot{u} = \Delta u, \quad u(0) = \textcolor{red}{h} \quad "x" \text{ is the initial condition}$$

$$\ddot{u} = \textcolor{red}{c}^2 \Delta u, \quad u(0) = h \quad "x" \text{ is a parameter}$$

$$\Delta u = 0, \quad u(\Gamma) = \textcolor{red}{h} \quad "x" \text{ is the boundary condition}$$

$\mathcal{L}(u)$ is the loss which penalizes something like:

- deviation from observations
- drag
- mass
- cost of materials
- compliance
- etc.

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$$\phi(u, x) = 0 \implies u = u(x)$$

Rewrite:

$$\boxed{\min_x f(x) \stackrel{\text{def}}{=} \mathcal{L}(u(x))}$$

... but finding the gradient is tricky:

$$\nabla f(x) = \frac{\partial \mathcal{L}}{\partial u} \cdot \frac{\partial u}{\partial x}$$

Why not just find gradients automatically?

✓ The **adjoint state method** and **reverse-mode automatic differentiation** can automatically calculate gradients in about the same time ($\sim 4x$) as a function evaluation

- ... so if we can evaluate $f(x)$ numerically, we can find the gradient
- (this applies if $f : \mathbb{R}^d \rightarrow \mathbb{R}$; $f : \mathbb{R}^d \rightarrow \mathbb{R}^q$ with $q \gg 1$ is another story)

Note: we're assuming derivative exists, just hard to actually calculate

This is *not* non-smooth optimization

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Why not just find gradients automatically?



The **adjoint state method** and **reverse-mode automatic differentiation** can automatically calculate gradients in about the same time ($\sim 4x$) as a function evaluation



Requires specialized/restricted libraries/code (`dolfin-adjoint/FEniCS`, `autograd`)

`Jax`, `PyTorch`, `Tensorflow`, ...

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Adjoint state method requires a method to solve adjoint PDE

(and have to parallelize for HPC)

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- difficult to maintain in large code bases, e.g., 4D-var for weather codes



Slow if used for intermediate calculations involving some

$$f : \mathbb{R}^d \rightarrow \mathbb{R}^q$$

- e.g., seismic inversion with many observations

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- ✗ Slow if used for intermediate calculations involving some $f : \mathbb{R}^d \rightarrow \mathbb{R}^q$
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- ✗ Possible memory explosion
 - e.g., time-dependent problems. Check-pointing schemes somewhat helpful

Example: hyper-parameter optimization in deep learning

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- ✗ Requires access to original source code
- ✗ Assumes a computational structure
 - inapplicable for physical observations (wind farms; *rollout* in AI)

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Baseline Algorithms (for comparison)

$$f : \mathbb{R}^d \rightarrow \mathbb{R}$$

Algorithm Gradient Descent via Finite Differences

```

1: for  $k = 1, 2, \dots$  do
2:   Estimate  $g_k \approx \nabla f(x_k)$      $\triangleright$  Use finite differences
3:    $x_{k+1} \leftarrow x_k - \eta_k g_k$      $\triangleright$  For appropriate step-size  $\eta_k$ 
  
```

ignoring finite-difference error, enjoys well-understood convergence

requires $d+1$ function evaluations per iter.

Why not use traditional Derivative Free Optimization (DFO) methods?

Answer: most classical DFO methods don't scale well with dimension

Note: there are many other DFO methods... but we won't discuss in this talk

From heuristics to theoretically based, from local to global

- Heuristics: Nelder-Mead, genetic algorithms, particle swarm optimization
 - e.g., CMA-ES, Covariance matrix adaptation evolution strategy
- Simulated Annealing (typical as heuristic)
- Bayesian Optimization
 - Model is Gaussian Process, with acquisition function (exploration/exploitation tradeoff)
- DFO-TR (Trust-region)
 - Model is polynomial

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requires $d+1$ function evaluations per iter.

Algorithm Randomized Coordinate Descent (CD)

```

1: for  $k = 1, 2, \dots$  do
2:   Choose  $j \in \{1, 2, \dots, d\}$  at random
3:    $g_k = e_j e_j^T \nabla f(x_k)$ 
4:    $x_{k+1} \leftarrow x_k - \eta_k g_k$         $\triangleright$  For appropriate step-size  $\eta_k$  (or exact minimization... depends on structure)
  
```

just 1 function evaluation per iteration

poor convergence properties, slow rates

Stochastic Subspace Descent

directional derivative $qq^T \nabla f(x_k) = \left(\lim_{h \rightarrow 0} \frac{f(x_k + h \cdot q) - f(x_k)}{h} \right) q$

Assume we can compute this!

e.g.,

- 1) forward finite diff
- 2) forward-mode AD

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$$Q = [q_1, q_2, \dots, q_\ell] \sim \text{Haar}(d \times \ell) \quad Q^T Q = I_{\ell \times \ell}, \quad \mathbb{E} \left(\frac{d}{\ell} Q Q^T \right) = I_{d \times d}$$

One benefit: in the limit $\ell = d$, $Q Q^T = I_{d \times d}$, and so we'll recover the full gradient
(for Gaussians, this is only true in expectation)

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Algorithm “Stochastic Subspace Descent” (SSD)

```

1: for  $k = 1, 2, \dots$  do
2:   Draw  $Q \sim \text{Haar}(d \times \ell)$  or any generic SSD
3:    $x_{k+1} \leftarrow x_k - \eta_k \frac{d}{\ell} Q Q^T \nabla f(x_k)$ 

```

Generic SSD

$$Q^T Q = I_{\ell \times \ell}, \quad \mathbb{E} \left(\frac{d}{\ell} Q Q^T \right) = I_{d \times d}$$

Both **Haar** and **Coordinate Descent** methods are valid generic SSD

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Algorithm “Stochastic Subspace Descent” (SSD)

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1: for  $k = 1, 2, \dots$  do
2:   Draw  $Q \sim \text{Haar}(d \times \ell)$ 
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```

We call Q a “Haar” distributed r.v. (i.e., the Haar measure over orthogonal matrices), but really care about QQ^T which is a projection matrix (onto $\text{col}(Q)$).

We get Q via Gram-Schmidt (or appropriately modified QR) on a Gaussian G , and note $\text{col}(Q) = \text{col}(G)$ w.p. 1, so our update is equivalent to

$$x_{k+1} \leftarrow x_k - \eta_k \frac{d}{\ell} \mathcal{P}_{\text{col}(G)}(\nabla f(x_k))$$

and hence the term “stochastic subspace”.

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First theory results (for generic SSD)



Theorem (Kozak, Becker, Tenorio, Doostan '20)

Assume: minimizer attained, gradient Lipschitz, stepsize η_k chosen appropriately.

1. If f is **convex**,

$$\mathbb{E}f(x_k) - f^* \leq 2\frac{\ell}{d}\frac{L}{k}R^2 = \mathcal{O}(k^{-1})$$

$$\text{constant } L \quad \eta = \frac{\ell}{d} \frac{1}{L}$$

constant μ

2. If f is **not convex** but satisfies the **Polyak-Lojasiewicz** inequality,

$$\mathbb{E}f(x_k) - f^* \leq \rho^k(f(x_0) - f^*) = \mathcal{O}(\rho^k) \quad \text{and} \quad f(x_k) \xrightarrow{\text{a.s.}} f^*$$

3. If f is **strongly convex**, statements of 2 above hold, and also

$$x_k \xrightarrow{\text{a.s.}} \operatorname{argmin}_x f(x)$$

4. If f is **not convex** (nor PL),

$$\min_{k' \in \{0, \dots, k\}} \mathbb{E}\|\nabla f(x_{k'})\|^2 \leq \frac{d}{\ell} \frac{2L(f(x_0) - f^*)}{k + 1}$$

Generic SSD

$$Q^T Q = I_{\ell \times \ell}, \quad \mathbb{E} \left(\frac{d}{\ell} Q Q^T \right) = I_{d \times d}$$

$$f^* \stackrel{\text{def}}{=} \min_x f(x)$$

$$\rho = 1 - \frac{\mu}{L} \frac{\ell}{d}$$

d = ambient dimension

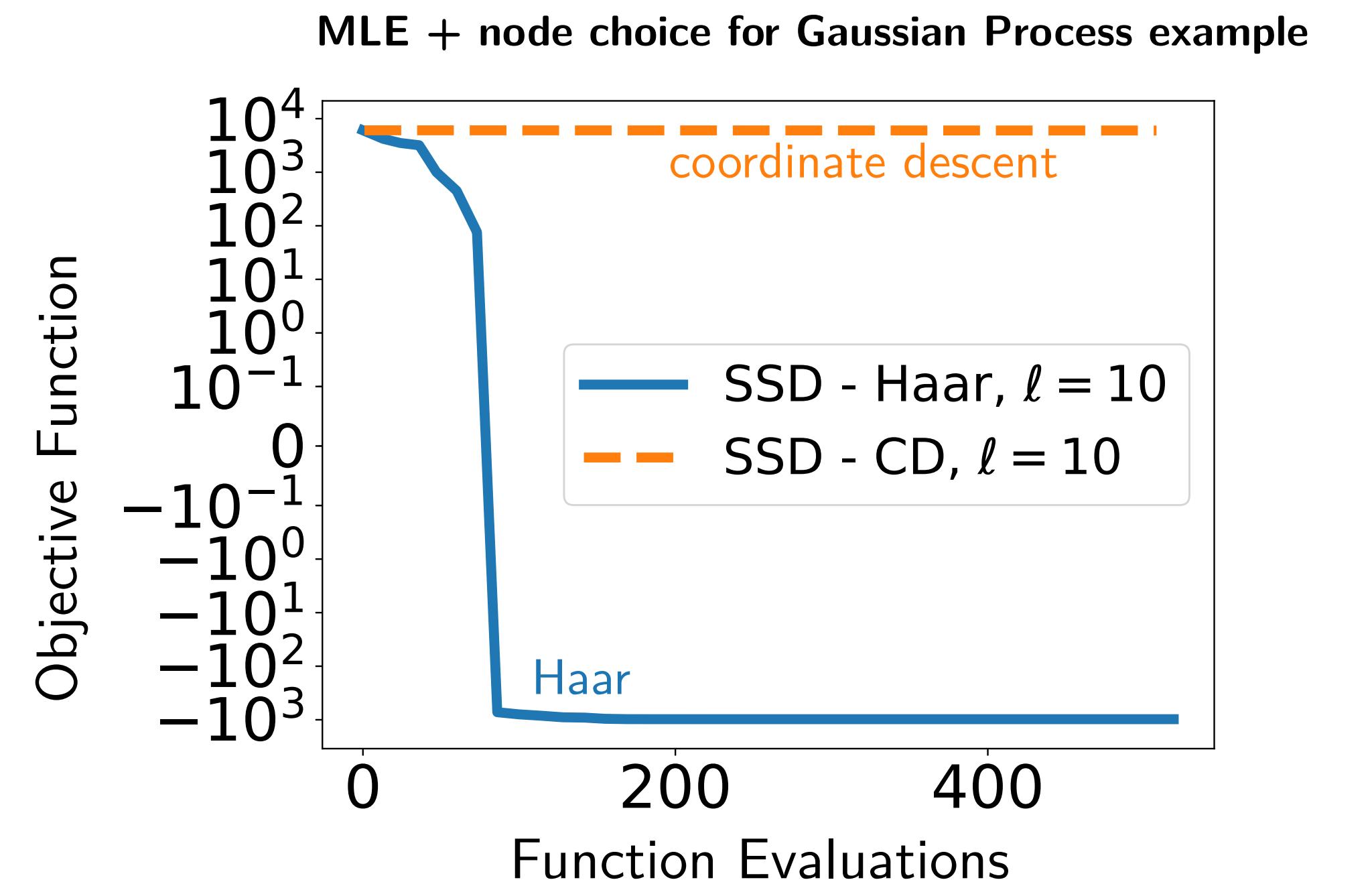
ℓ = # directional derivs

$\frac{d}{\ell} = 1$ is gradient descent

SSD is a **special type of SGD**,
but results are much better
than generic SGD analysis

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Numerical Results: better than expected



Observation: sometimes SSD (with Haar) drastically outperforms randomized coordinate descent (CD)

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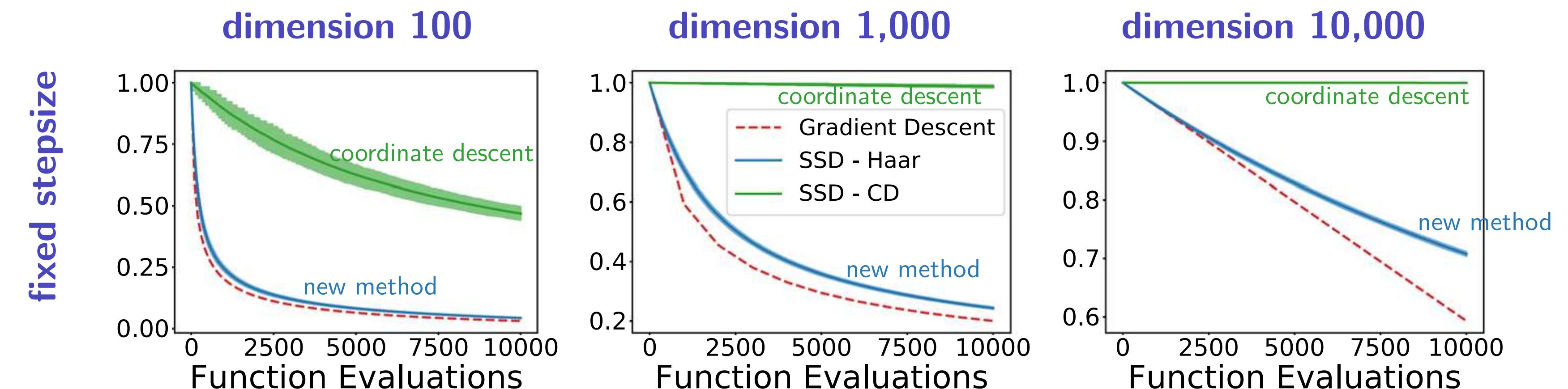
Haar SSD drastically outperforms randomized coordinate descent (CD)



We can force it to happen by making a problem with low “intrinsic” dimension, e.g., Nesterov’s “worst function in the world”

$$f_{\lambda,r}(\mathbf{x}) = \lambda((x_1^2 + \sum_{i=1}^{r-1} (x_i - x_{i+1})^2 + x_r^2)/2 - x_1)/4,$$

This has **intrinsic dimension** of r



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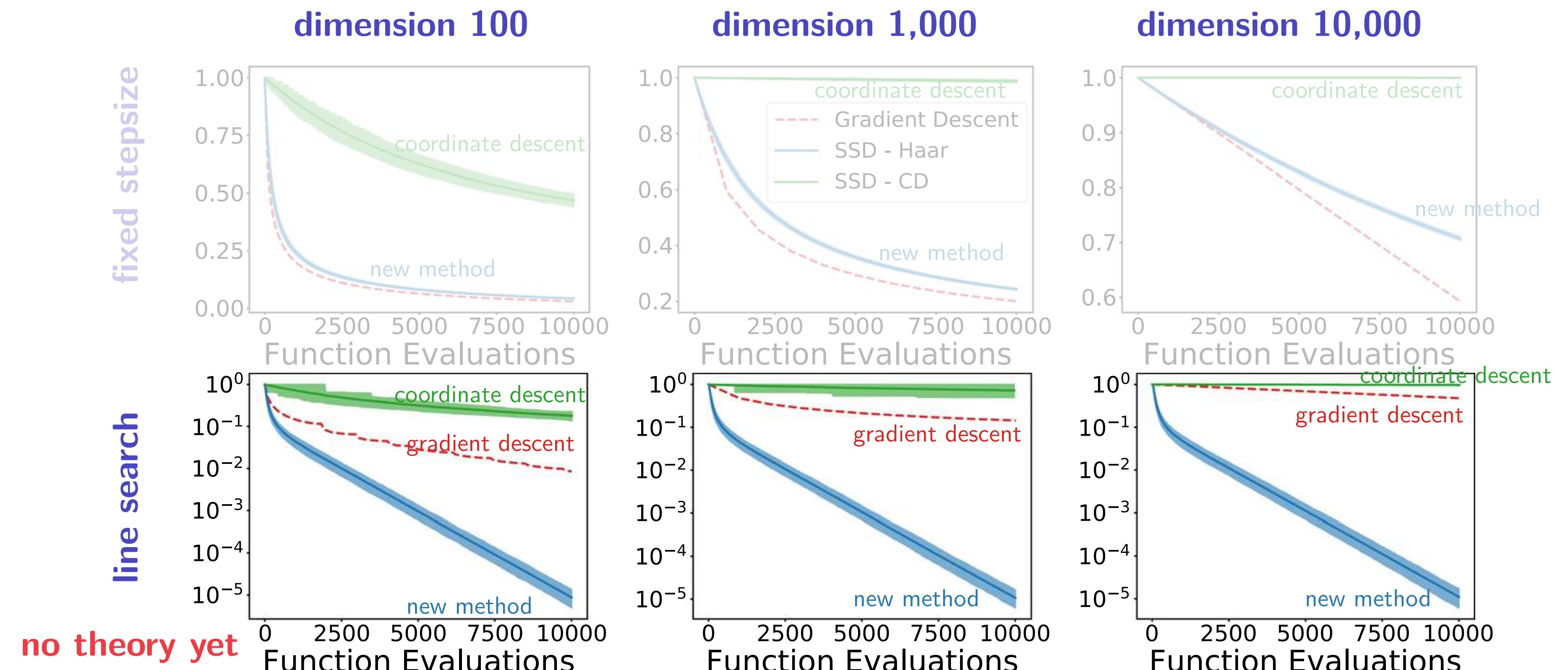


$r = 20$
 $\ell = 3$

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Theory: explain better-than-expected results

Previous theorem didn't actually rely on properties of Haar distribution, just generic Q :

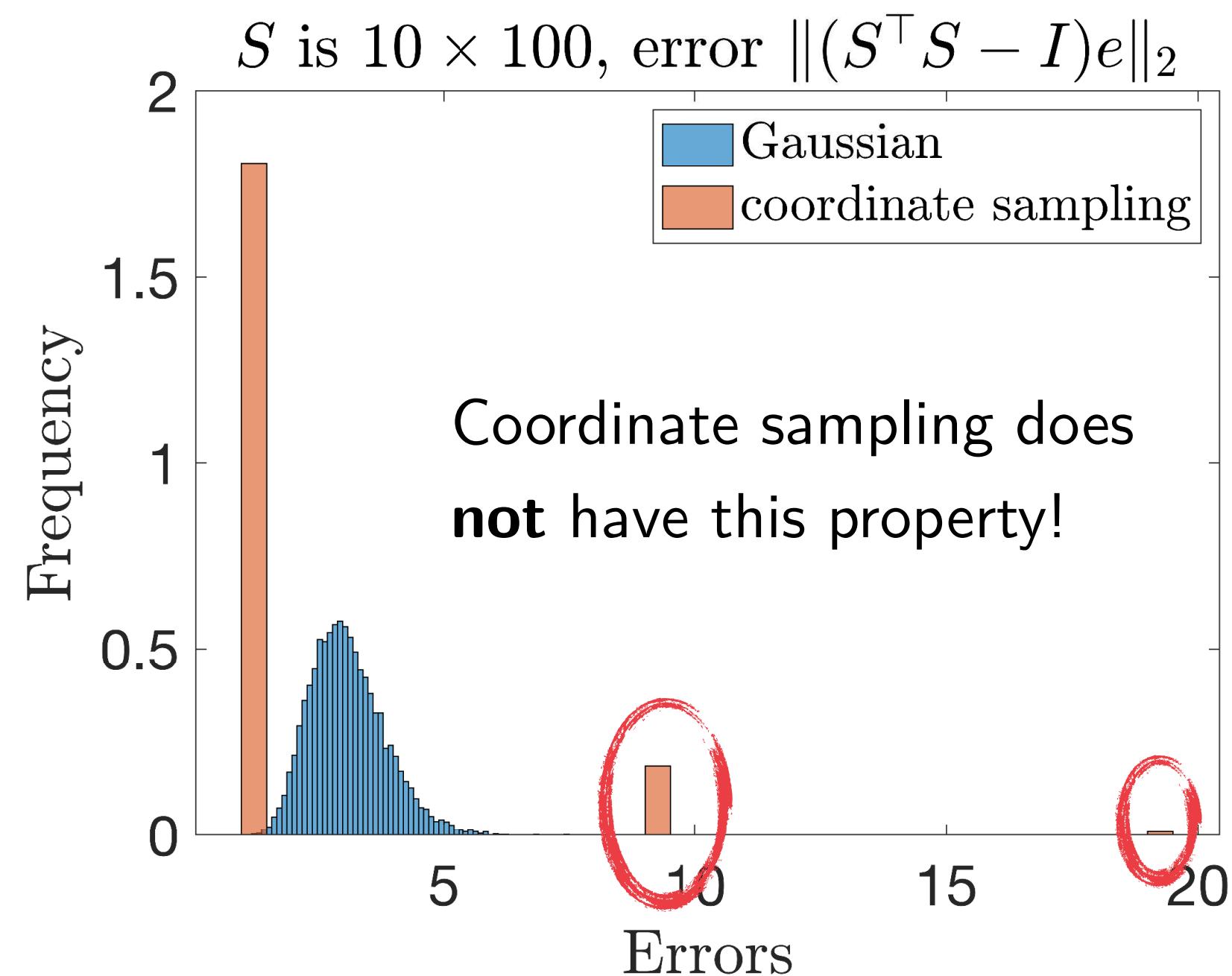
Tighter analysis using concentration-of-measure:

$$Q^T Q = I_{\ell \times \ell}, \quad \mathbb{E} \left(\frac{d}{\ell} Q Q^T \right) = I_{d \times d}$$

Lemma 2 (Johnson-Lindenstrauss style embedding, from Kozak, Becker, Tenorio '19, Lemma 1).

$\forall \epsilon \in (0, 1)$, if $\ell \gtrsim \epsilon^{-2}$, $Q \sim \text{Haar}(d \times \ell)$, then $\forall 0 \neq g \in \mathbb{R}^d$,

$$1 - \epsilon \leq \frac{d}{\ell} \frac{\|Q^T g\|^2}{\|g\|^2} \leq 1 + \epsilon \text{ w/ prob. } \delta \geq 0.8$$



Recall...
 d = ambient dimension
 ℓ = # directional derivs

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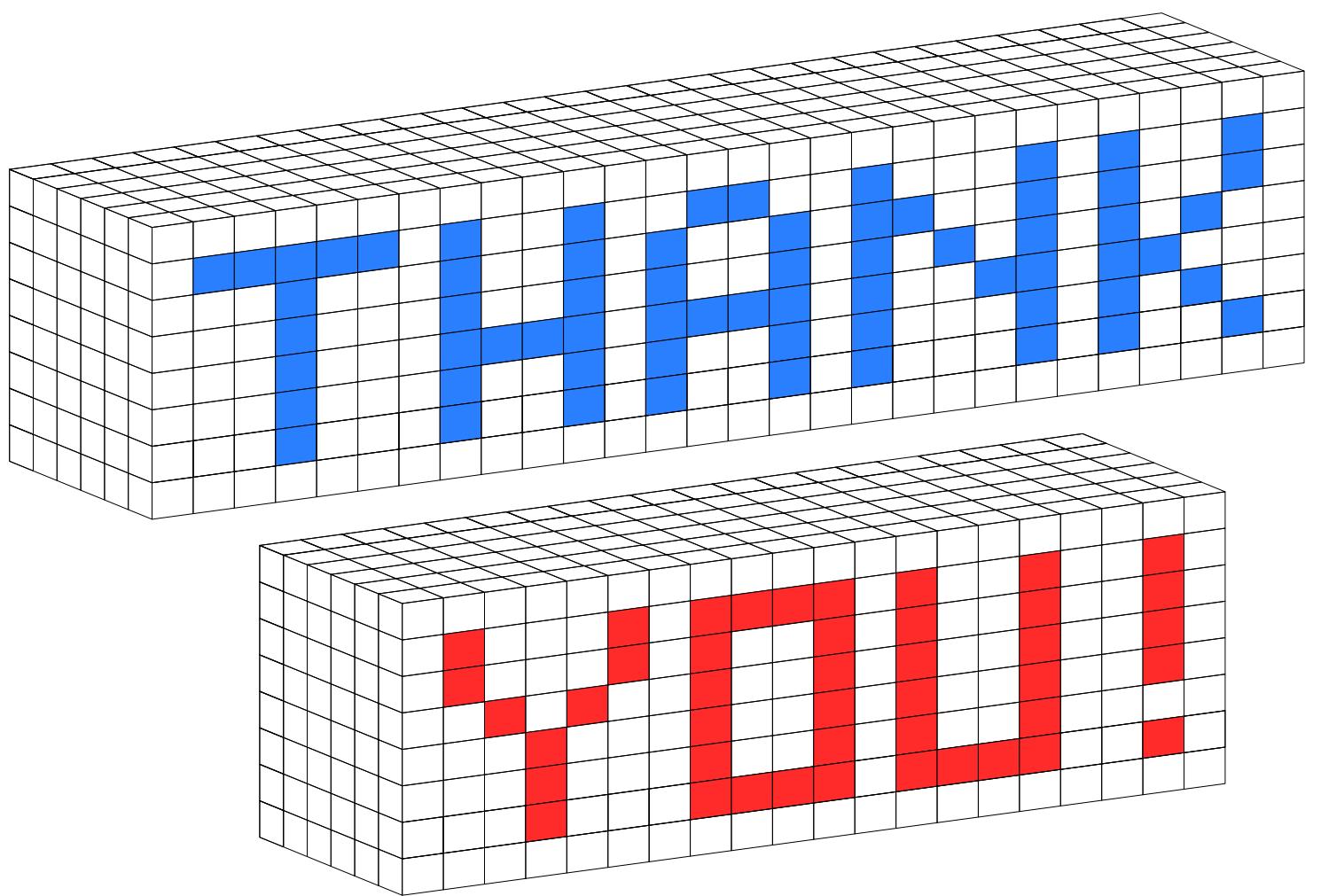
Theorem 3 (Kozak, Becker, Tenorio '19, Thm. 1). *If f is strongly convex and ∇f is Lipschitz continuous, then for an appropriate stepsize η_k , the sequence (x_k) generated by SSD (with $Q \sim \text{Haar}$), for $k > 100$, satisfies*

$$f(x_k) - f^* \leq (1 + (1 - \epsilon)\rho)^{k/2} (f(x_0) - f^*) \quad \text{with probability } \geq 0.998,$$

where $\rho < 1$ depends on ℓ , d and the Lipschitz and strong convexity parameters.

error in JL embedding

due to possibility of failure of JL



Papers and code available at <https://amath.colorado.edu/faculty/becker/>

Method 7: CountSketch

$\mathcal{S} : \mathbb{R}^n \rightarrow \mathbb{R}^m$ linear operator

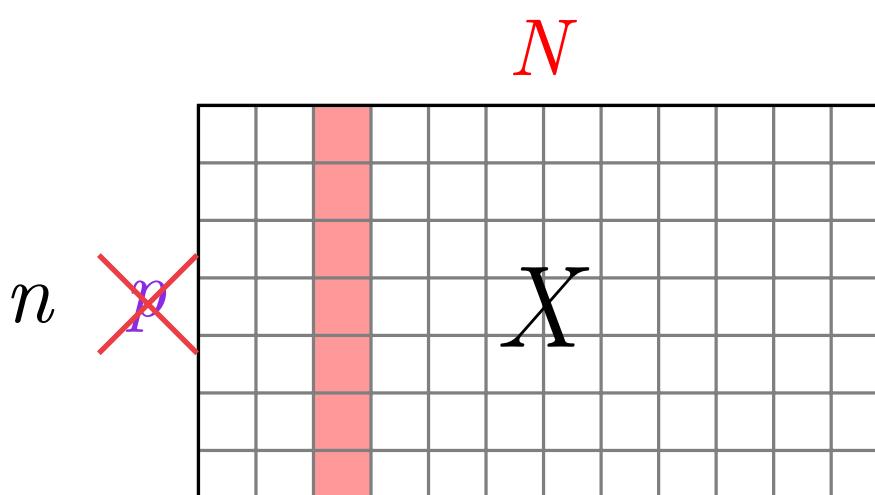
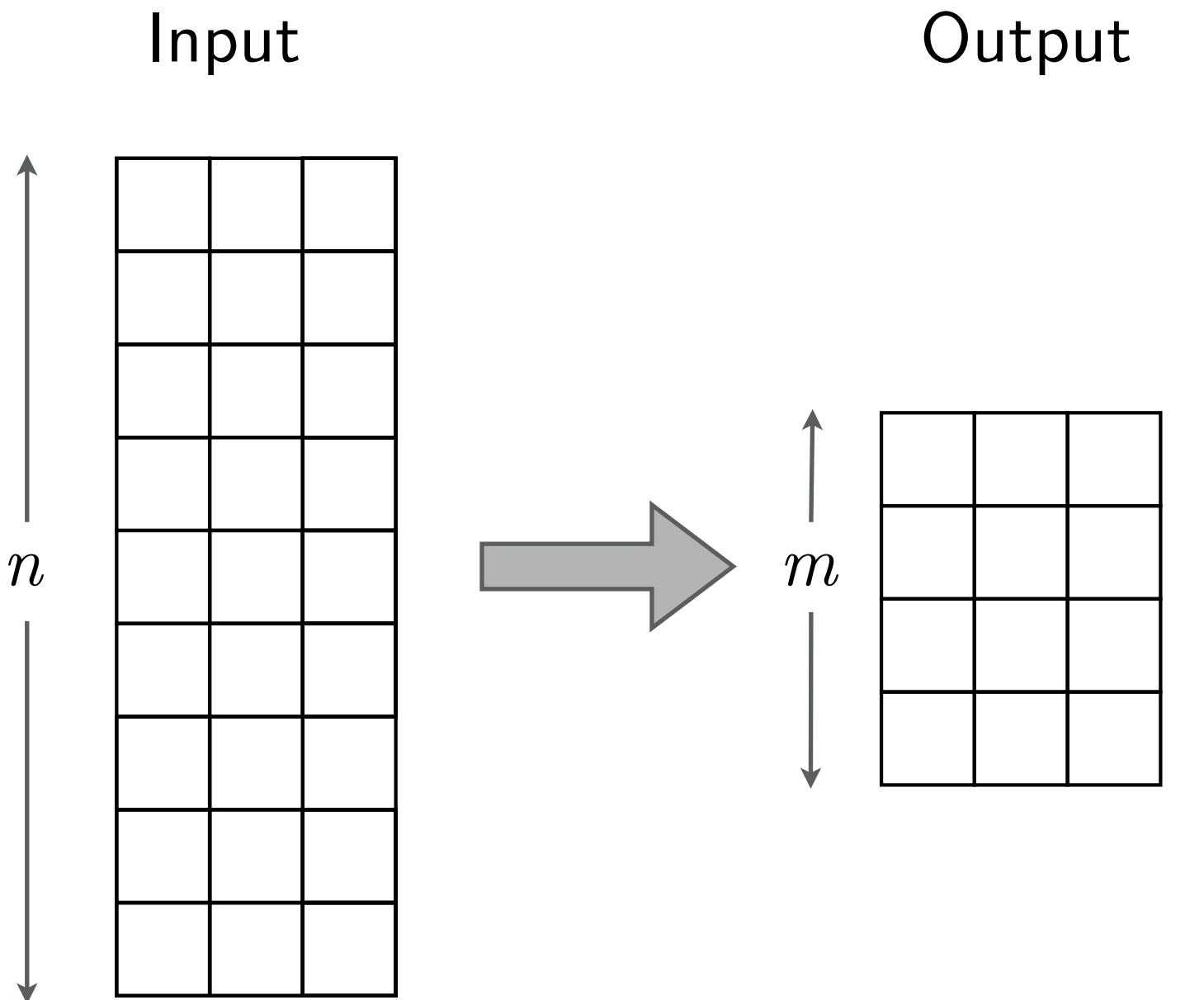
Introduced in [Charikar et al. \(2004\)](#), more analysis in, e.g., [Clarkson and Woodruff \(2017\)](#)

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Change in notation temporarily

$$\begin{aligned}\Phi &\rightarrow \mathcal{S} \\ p &\rightarrow n \\ p_{\text{small}} &\rightarrow m\end{aligned}$$



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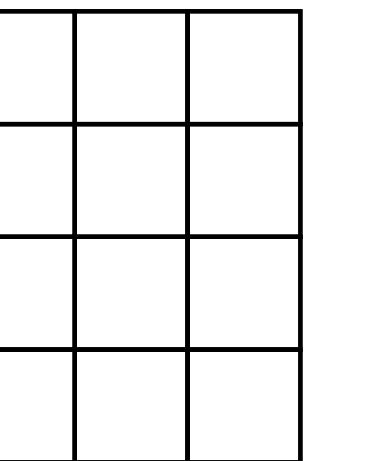
Step 1:

Multiply by random sign*

$s : [n] \rightarrow \{\pm 1\}$
(uniform)

+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

Notation: $[n] = (0, 1, \dots, n - 1)$
(use 0-based indexing)



* technically doesn't have to be fully random, but must be 2-wise independent

$$s(i) \perp s(j) \quad \text{if } i \neq j$$

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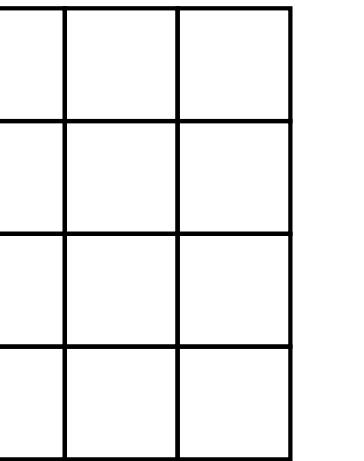
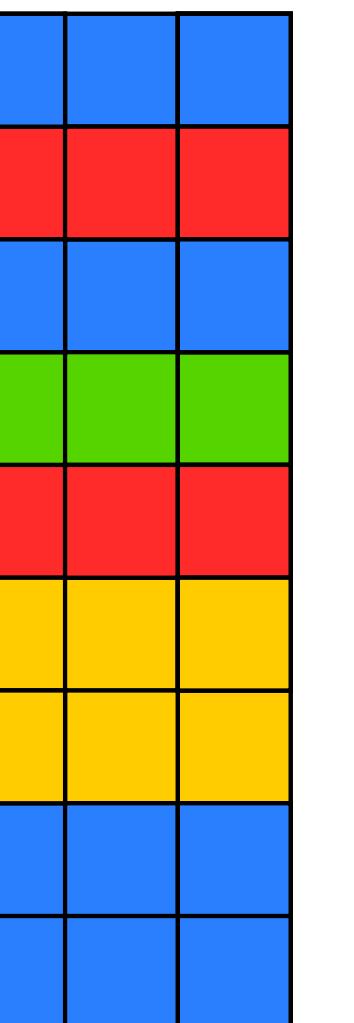
$$\mathcal{S} : \mathbb{R}^n \rightarrow \mathbb{R}^m \text{ linear operator}$$

Step 2:

Assign an output row to
every input row (randomly
or with a hash function)

$$h : [n] \rightarrow [m]$$

(uniform)



Again, don't need *all* of $h[i]$ to be independent, only pairwise independent
(but easy enough to make them all independent)

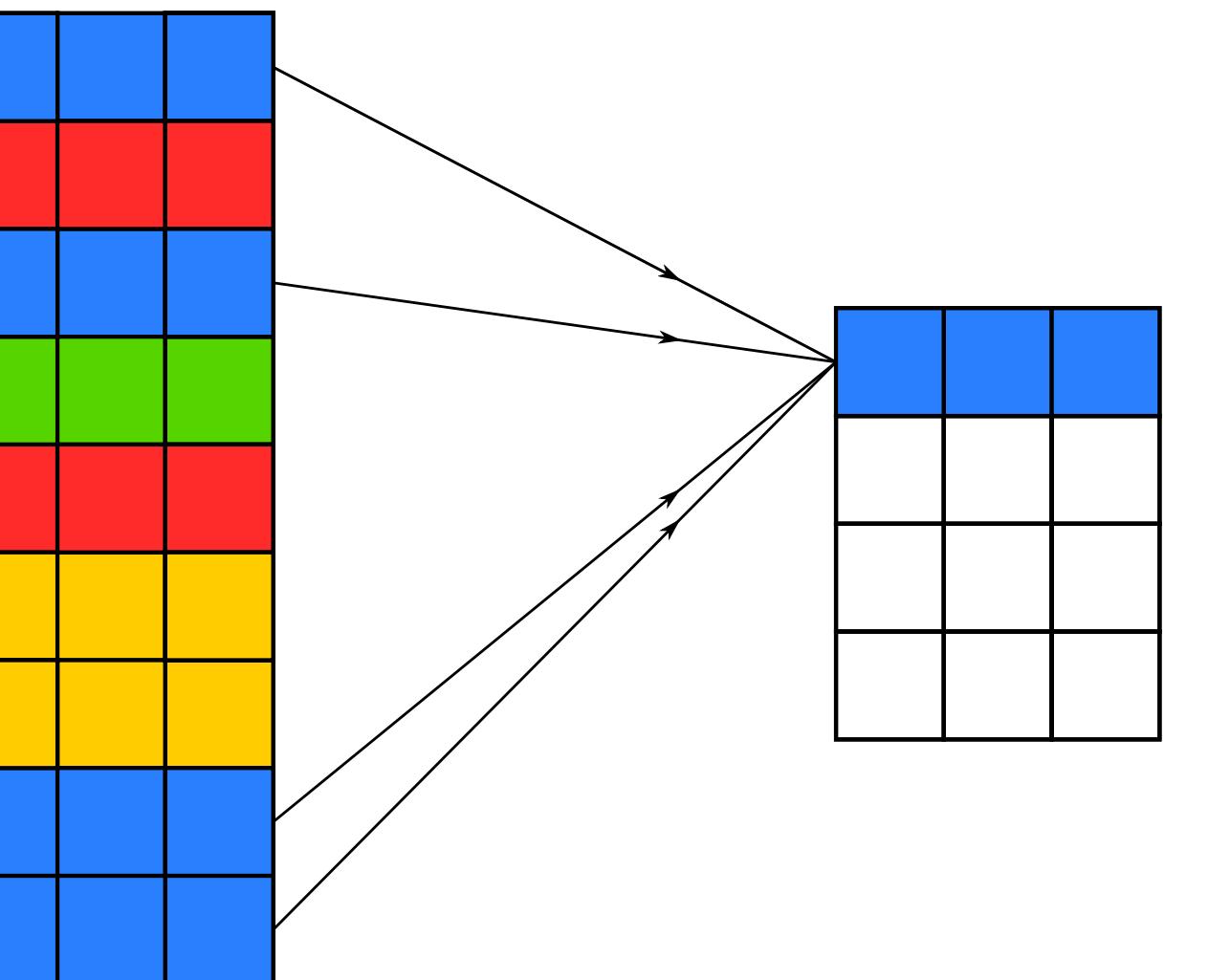
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Method 7: CountSketch

$$\mathcal{S} : \mathbb{R}^n \rightarrow \mathbb{R}^m \text{ linear operator}$$

Step 3:

Each output row is the sum
of corresponding input rows



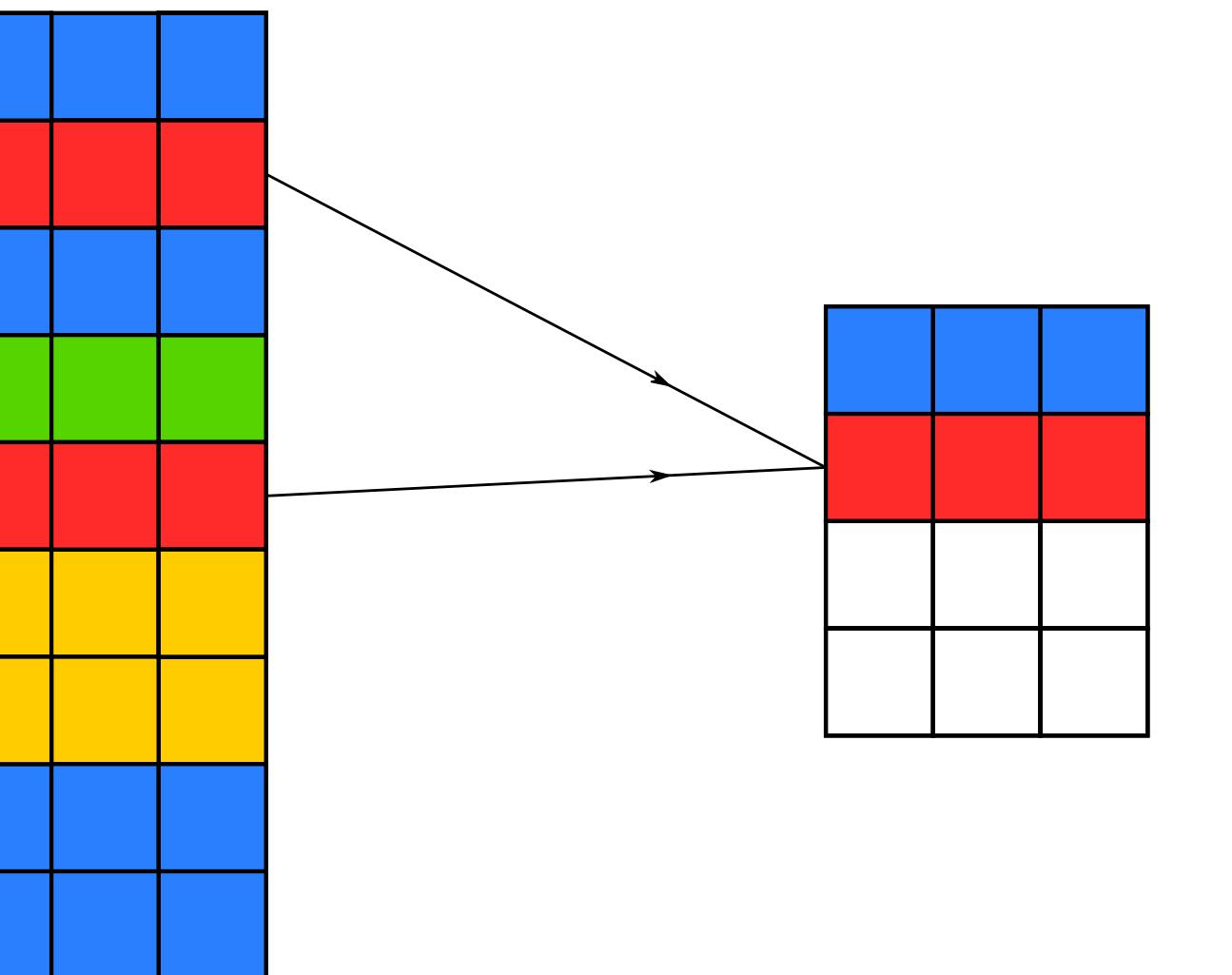
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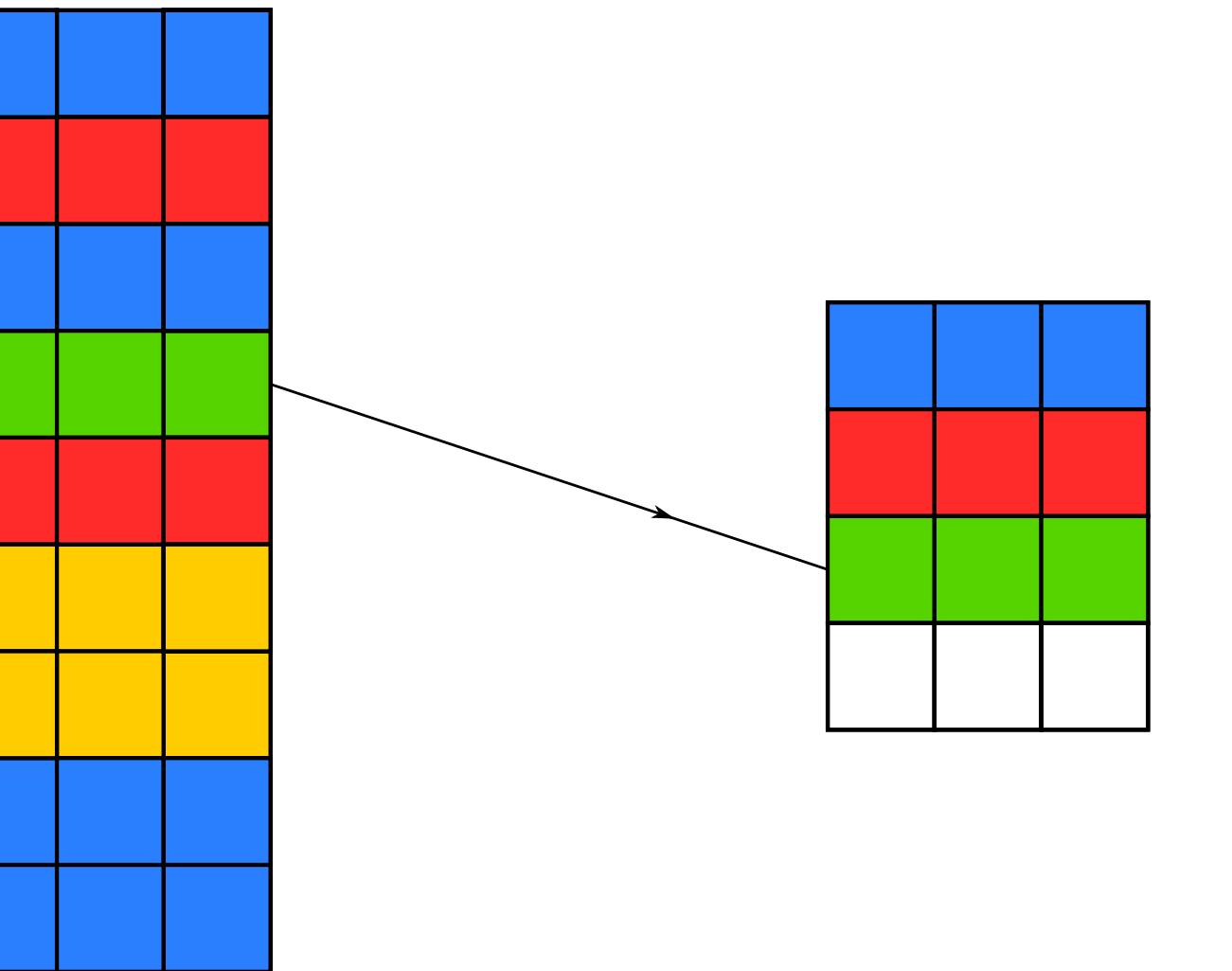
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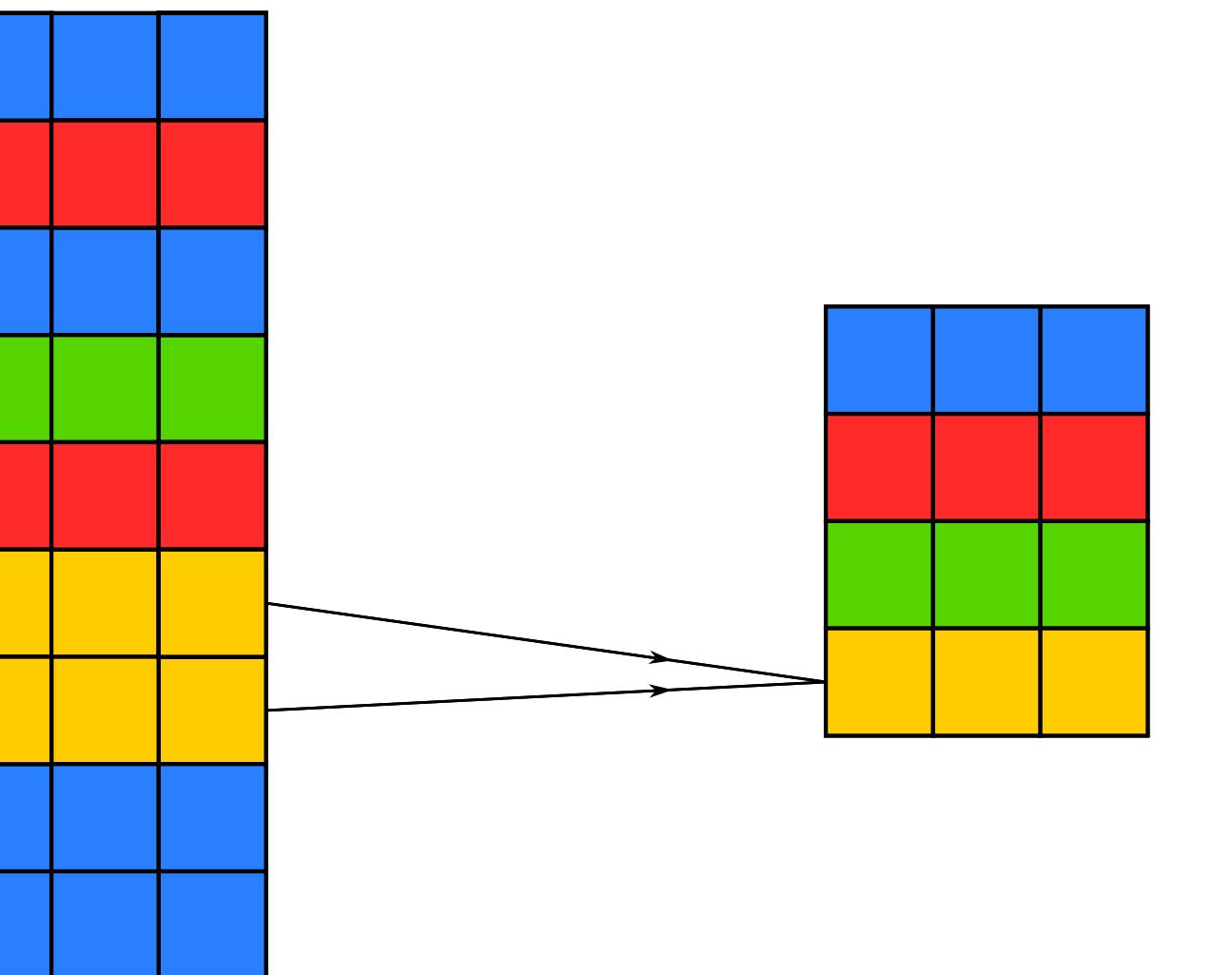
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Method 7: CountSketch

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Complexity analysis: every input element is touched once
... so linear complexity
(and can exploit sparsity)

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Method 7: CountSketch

$\mathcal{S} : \mathbb{R}^n \rightarrow \mathbb{R}^m$ linear operator

A formula for the output:

$$\mathbf{u} = \mathcal{S}(\mathbf{v}), \quad u_i = \sum_{j|h(j)=i} s(j)v_j \quad \begin{aligned} s : [n] &\rightarrow \{\pm 1\} \\ h : [n] &\rightarrow [m] \end{aligned}$$

... and note that the following polynomial has the output as its coefficients:

$$p(\mathbf{x}) \stackrel{\text{def}}{=} \sum_{j \in [n]} s(j) \cdot v_j \cdot \mathbf{x}^{h(j)} = \sum_{i \in [m]} \mathbf{x}^i \left(\sum_{j|h(j)=i} s(j)v_j \right) = \sum_{i \in [m]} u_i \cdot \mathbf{x}^i$$

Method 8: TensorSketch

Introduced in Pagh (2013), more analysis
in, e.g., Diao, Zong, Sun, Woodruff (2018)

TensorSketch is just CountSketch when the input can be written as a tensor product
(for a special choice of the hash and sign functions)



Change in notation temporarily

$$\Phi \rightarrow \mathcal{S}$$

$$p \rightarrow n$$

$$p_{\text{small}} \rightarrow m$$

$$\mathcal{T} : \mathbb{R}^n \rightarrow \mathbb{R}^m$$

$$\mathbf{v} = \mathbf{v}^{(1)} \otimes \mathbf{v}^{(2)}$$

where size is

$$n = n^{(1)} \cdot n^{(2)}$$

Not (yet!) related to tensors

TensorSketch

Introduced in Pagh (2013), more analysis
in, e.g., Diao, Zong, Sun, Woodruff (2018)

TensorSketch is just CountSketch when the input can be written as a tensor product
(for a special choice of the hash and sign functions)

$$\mathcal{T} : \mathbb{R}^n \rightarrow \mathbb{R}^m$$

$$\mathbf{v} = \mathbf{v}^{(1)} \otimes \mathbf{v}^{(2)} \quad \text{where size is} \quad n = n^{(1)} \cdot n^{(2)}$$

Kronecker/tensor product

$$\mathbf{a} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}, \quad \mathbf{b} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}$$

$$\mathbf{a} \otimes \mathbf{b} = \begin{bmatrix} a_1 \mathbf{b} \\ a_2 \mathbf{b} \\ a_3 \mathbf{b} \end{bmatrix} =$$

$$\begin{bmatrix} a_1 b_1 \\ a_1 b_2 \\ a_1 b_3 \\ a_2 b_1 \\ a_2 b_2 \\ a_2 b_3 \\ a_3 b_1 \\ a_3 b_2 \\ a_3 b_3 \end{bmatrix}$$

TensorSketch

Introduced in Pagh (2013), more analysis
in, e.g., Diao, Zong, Sun, Woodruff (2018)

TensorSketch is just CountSketch when the input can be written as a tensor product
(for a special choice of the hash and sign functions)

$$\mathcal{T} : \mathbb{R}^n \rightarrow \mathbb{R}^m$$

$$\mathbf{v} = \mathbf{v}^{(1)} \otimes \mathbf{v}^{(2)} \quad \text{where size is} \quad n = n^{(1)} \cdot n^{(2)}$$

Kronecker/tensor product

$$\mathbf{a} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}, \quad \mathbf{b} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}$$

$$\mathbf{a} \otimes \mathbf{b} = \begin{bmatrix} \mathbf{a}_1 \mathbf{b} \\ \mathbf{a}_2 \mathbf{b} \\ \mathbf{a}_3 \mathbf{b} \end{bmatrix}$$

$$= \begin{bmatrix} a_1 b_1 \\ a_1 b_2 \\ a_1 b_3 \\ a_2 b_1 \\ a_2 b_2 \\ a_2 b_3 \\ a_3 b_1 \\ a_3 b_2 \\ a_3 b_3 \end{bmatrix}$$

another equivalent definition:

$$\mathbf{a} \otimes \mathbf{b} = \text{vec}_{\text{col}} (\mathbf{b} \mathbf{a}^T)$$

$$\mathbf{b} \mathbf{a}^T = \begin{bmatrix} b_1 a_1 & b_1 a_2 & b_1 a_3 \\ b_2 a_1 & b_2 a_2 & b_2 a_3 \\ b_3 a_1 & b_3 a_2 & b_3 a_3 \end{bmatrix} = \begin{bmatrix} a_1 b_1 & a_2 b_1 & a_3 b_1 \\ a_1 b_2 & a_2 b_2 & a_3 b_2 \\ a_1 b_3 & a_2 b_3 & a_3 b_3 \end{bmatrix}$$

$$\begin{aligned} \text{vec} : [n^{(1)}] \times [n^{(2)}] &\rightarrow [n^{(1)} \cdot n^{(2)}] \\ \text{vec}^{-1} = \text{mat} : [n^{(1)} \cdot n^{(2)}] &\rightarrow [n^{(1)}] \times [n^{(2)}] \end{aligned}$$

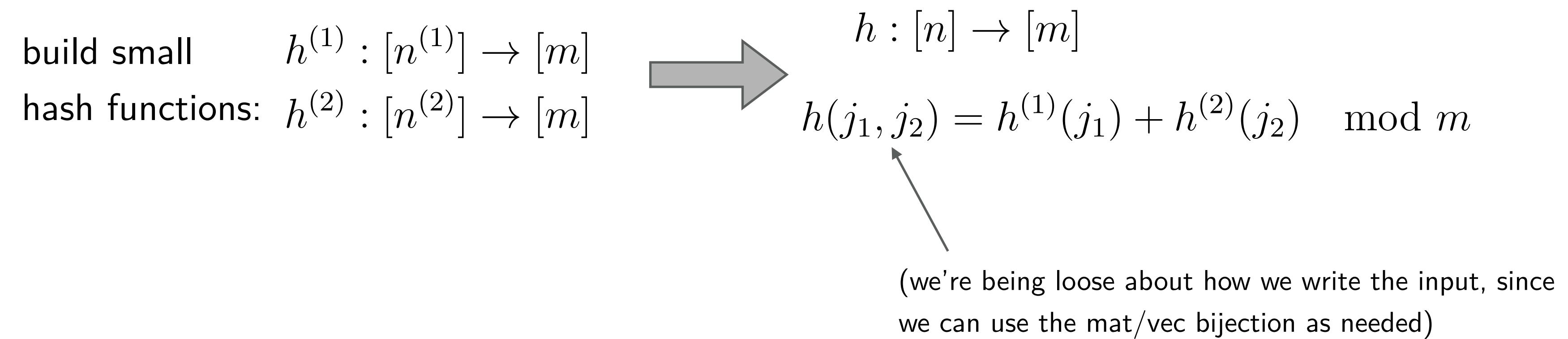
more generally,

$$(\mathbf{A} \otimes \mathbf{B}) \text{vec}_{\text{col}} (\mathbf{X}) = \text{vec}_{\text{col}} (\mathbf{B} \mathbf{X} \mathbf{A}^T)$$

TensorSketch

Pick hash functions in a decomposable way:

Input has structure $\mathbf{v} = \mathbf{v}^{(1)} \otimes \mathbf{v}^{(2)}$ with sizes $n = n^{(1)} \cdot n^{(2)}$



Fact: as long as $h^{(i)}$ is fully independent (or at least 3-wise independent), then h is 2-wise independent

TensorSketch

Pick hash functions in a decomposable way:

Input has structure $\mathbf{v} = \mathbf{v}^{(1)} \otimes \mathbf{v}^{(2)}$ with sizes $n = n^{(1)} \cdot n^{(2)}$

build small hash functions: $h^{(1)} : [n^{(1)}] \rightarrow [m]$

$h^{(2)} : [n^{(2)}] \rightarrow [m]$



$h : [n] \rightarrow [m]$

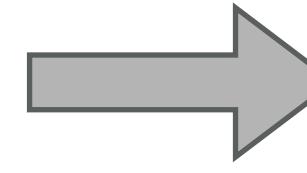
$h(j_1, j_2) = h^{(1)}(j_1) + h^{(2)}(j_2) \pmod m$

Fact: h is 2-wise independent

(we're being loose about how we write the input, since we can use the mat/vec bijection as needed)

same trick for sign functions: $s^{(1)} : [n^{(1)}] \rightarrow \{\pm 1\}$

$s^{(2)} : [n^{(2)}] \rightarrow \{\pm 1\}$



$s : [n] \rightarrow \{\pm 1\}$

$s(j_1, j_2) = s^{(1)}(j_1) \cdot s^{(2)}(j_2)$

still pairwise independent, as needed for theory!

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TensorSketch

what's the point? Huge computational speedup.

$$h^{(1)} : [n^{(1)}] \rightarrow [m]$$

$$h^{(2)} : [n^{(2)}] \rightarrow [m]$$

$$p^{(1)}(\textcolor{red}{x}) \stackrel{\text{def}}{=} \sum_{j \in [n^{(1)}]} s^{(1)}(j) \cdot v_j^{(1)} \cdot \textcolor{red}{x}^{h^{(1)}(j)} = \sum_{i \in [m]} u_i^{(1)} \cdot \textcolor{red}{x}^i$$

$$p^{(2)}(\textcolor{red}{x}) \stackrel{\text{def}}{=} \sum_{j \in [n^{(2)}]} s^{(2)}(j) \cdot v_j^{(2)} \cdot \textcolor{red}{x}^{h^{(2)}(j)} = \sum_{i \in [m]} u_i^{(2)} \cdot \textcolor{red}{x}^i$$

Let's compute this: $p^{(1)}(\textcolor{red}{x}) \cdot p^{(2)}(\textcolor{red}{x}) \pmod{x^m - 1}$

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TensorSketch

what's the point? Huge computational speedup.

$$p^{(1)}(\textcolor{red}{x}) \cdot p^{(2)}(\textcolor{red}{x}) = \left(\sum_{j_1 \in [n^{(1)}]} s^{(1)}(j_1) \cdot v_{j_1}^{(1)} \cdot \textcolor{red}{x}^{h^{(1)}(j_1)} \right) \cdot \left(\sum_{j_2 \in [n^{(2)}]} s^{(2)}(j_2) \cdot v_{j_2}^{(2)} \cdot \textcolor{red}{x}^{h^{(2)}(j_2)} \right)$$

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TensorSketch

what's the point? Huge computational speedup.

$$\begin{aligned}
 p^{(1)}(\textcolor{red}{x}) \cdot p^{(2)}(\textcolor{red}{x}) &= \left(\sum_{j_1 \in [n^{(1)}]} s^{(1)}(j_1) \cdot v_{j_1}^{(1)} \cdot \textcolor{red}{x}^{h^{(1)}(j_1)} \right) \cdot \left(\sum_{j_2 \in [n^{(2)}]} s^{(2)}(j_2) \cdot v_{j_2}^{(2)} \cdot \textcolor{red}{x}^{h^{(2)}(j_2)} \right) \\
 &= \sum_{j_1 \in [n^{(1)}], j_2 \in [n^{(2)}]} s^{(1)}(j_1) \cdot s^{(2)}(j_2) \cdot v_{j_1}^{(1)} \cdot v_{j_2}^{(2)} \cdot \textcolor{red}{x}^{h^{(1)}(j_1)} \cdot \textcolor{red}{x}^{h^{(2)}(j_2)}
 \end{aligned}$$

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TensorSketch

what's the point? Huge computational speedup.

$$\begin{aligned}
 p^{(1)}(\textcolor{red}{x}) \cdot p^{(2)}(\textcolor{red}{x}) &= \left(\sum_{j_1 \in [n^{(1)}]} s^{(1)}(j_1) \cdot v_{j_1}^{(1)} \cdot \textcolor{red}{x}^{h^{(1)}(j_1)} \right) \cdot \left(\sum_{j_2 \in [n^{(2)}]} s^{(2)}(j_2) \cdot v_{j_2}^{(2)} \cdot \textcolor{red}{x}^{h^{(2)}(j_2)} \right) \\
 &= \sum_{j_1 \in [n^{(1)}], j_2 \in [n^{(2)}]} s^{(1)}(j_1) \cdot s^{(2)}(j_2) \cdot v_{j_1}^{(1)} \cdot v_{j_2}^{(2)} \cdot \textcolor{red}{x}^{h^{(1)}(j_1)} \cdot \textcolor{red}{x}^{h^{(2)}(j_2)} \\
 &= \sum_{j_1 \in [n^{(1)}], j_2 \in [n^{(2)}]} \mathcal{S}(j_1, j_2) \cdot v_{j_1 j_2} \cdot \textcolor{red}{x}^{h^{(1)}(j_1)h^{(2)}(j_2)}
 \end{aligned}$$

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TensorSketch

what's the point? Huge computational speedup.

$$\begin{aligned}
 p^{(1)}(\textcolor{red}{x}) \cdot p^{(2)}(\textcolor{red}{x}) &= \left(\sum_{j_1 \in [n^{(1)}]} s^{(1)}(j_1) \cdot v_{j_1}^{(1)} \cdot \textcolor{red}{x}^{h^{(1)}(j_1)} \right) \cdot \left(\sum_{j_2 \in [n^{(2)}]} s^{(2)}(j_2) \cdot v_{j_2}^{(2)} \cdot \textcolor{red}{x}^{h^{(2)}(j_2)} \right) \\
 &= \sum_{j_1 \in [n^{(1)}], j_2 \in [n^{(2)}]} s^{(1)}(j_1) \cdot s^{(2)}(j_2) \cdot v_{j_1}^{(1)} \cdot v_{j_2}^{(2)} \cdot \textcolor{red}{x}^{h^{(1)}(j_1)} \cdot \textcolor{red}{x}^{h^{(2)}(j_2)} \\
 &= \sum_{j_1 \in [n^{(1)}], j_2 \in [n^{(2)}]} \mathcal{S}(j_1, j_2) \cdot v_{j_1 j_2} \cdot \textcolor{red}{x}^{h^{(1)}(j_1)h^{(2)}(j_2)} \\
 &\equiv \sum_{j_1 \in [n^{(1)}], j_2 \in [n^{(2)}]} \mathcal{S}(j_1, j_2) \cdot v_{j_1 j_2} \cdot \textcolor{red}{x}^{h(j_1, j_2)} \mod \textcolor{red}{x}^m - 1
 \end{aligned}$$



$$\begin{aligned}
 \textcolor{red}{x}^{k\ell} &= \textcolor{red}{x}^{dm + (k\ell \mod m)} = \textcolor{red}{x}^{dm + (k\ell \mod m)} = (\textcolor{red}{x}^m)^d \textcolor{red}{x}^{k\ell \mod m} \equiv \textcolor{red}{x}^{k\ell \mod m} \mod \textcolor{red}{x}^m - 1
 \end{aligned}$$

Recall $\textcolor{red}{x}^m \equiv 1 \mod \textcolor{red}{x}^m - 1$

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TensorSketch

what's the point? Huge computational speedup.

$$\begin{aligned}
 p^{(1)}(\mathbf{x}) \cdot p^{(2)}(\mathbf{x}) &= \left(\sum_{j_1 \in [n^{(1)}]} s^{(1)}(j_1) \cdot v_{j_1}^{(1)} \cdot \mathbf{x}^{h^{(1)}(j_1)} \right) \cdot \left(\sum_{j_2 \in [n^{(2)}]} s^{(2)}(j_2) \cdot v_{j_2}^{(2)} \cdot \mathbf{x}^{h^{(2)}(j_2)} \right) \\
 &= \sum_{j_1 \in [n^{(1)}], j_2 \in [n^{(2)}]} s^{(1)}(j_1) \cdot s^{(2)}(j_2) \cdot v_{j_1}^{(1)} \cdot v_{j_2}^{(2)} \cdot \mathbf{x}^{h^{(1)}(j_1)} \cdot \mathbf{x}^{h^{(2)}(j_2)} \\
 &= \sum_{j_1 \in [n^{(1)}], j_2 \in [n^{(2)}]} \mathcal{S}(j_1, j_2) \cdot v_{j_1 j_2} \cdot \mathbf{x}^{h^{(1)}(j_1) h^{(2)}(j_2)} \\
 &\equiv \sum_{j_1 \in [n^{(1)}], j_2 \in [n^{(2)}]} \mathcal{S}(j_1, j_2) \cdot v_{j_1 j_2} \cdot \mathbf{x}^{h(j_1, j_2)} \mod \mathbf{x}^m - 1 \\
 &= p(\mathbf{x})
 \end{aligned}$$

coefficients are the output
of the CountSketch!



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TensorSketch

How to multiply polynomials?

$$(2\cancel{x}^2 + 3\cancel{x} + 4) \cdot (\cancel{x}^2 - \cancel{x} + 5)$$

$p(x) \qquad q(x)$

$$p(x) \quad \begin{matrix} \cancel{x}^0 & \cancel{x}^1 & \cancel{x}^2 \\ \boxed{4} & 3 & 2 \end{matrix} \quad \begin{matrix} 1 & -1 & 5 \\ \cancel{x}^2 & \cancel{x}^1 & \cancel{x}^0 \end{matrix} \quad q(x)$$

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TensorSketch

How to multiply polynomials?

$$(2x^2 + 3x + 4) \cdot (x^2 - x + 5)$$

$$\begin{array}{c}
 x^0 \quad x^1 \quad x^2 \\
 \boxed{4} \quad 3 \quad \boxed{2} \\
 \qquad \boxed{1} \quad -1 \quad 5 \\
 x^2 \quad x^1 \quad x^0
 \end{array}
 = 2x^4$$

$$2 \cdot 1$$

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TensorSketch

How to multiply polynomials?

$$(2x^2 + 3x + 4) \cdot (x^2 - x + 5)$$

$$\begin{array}{ccc} x^0 & x^1 & x^2 \\ \hline 4 & \boxed{3} & 2 \\ & 1 & -1 \\ \hline x^2 & x^1 & x^0 \end{array} = 2x^4 + x^3$$

$$3 \cdot 1 + 2 \cdot (-1) = 1$$

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TensorSketch

How to multiply polynomials?

$$(2x^2 + 3x + 4) \cdot (x^2 - x + 5)$$

$$\begin{array}{ccc}
 x^0 & x^1 & x^2 \\
 \boxed{\begin{array}{ccc} 4 & 3 & 2 \\ 1 & -1 & 5 \end{array}} \\
 x^2 & x^1 & x^0
 \end{array}
 = 2x^4 + x^3 + 11x^2$$

$$4 \cdot 1 + 3 \cdot (-1) + 2 \cdot 5 = 11$$

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TensorSketch

How to multiply polynomials?

$$(2x^2 + 3x + 4) \cdot (x^2 - x + 5)$$

$$\begin{array}{ccc}
 x^0 & x^1 & x^2 \\
 \boxed{\begin{array}{cc} 4 & 3 \\ 1 & -1 \end{array}} & 2 \\
 \hline
 1 & -1 & 5 \\
 x^2 & x^1 & x^0
 \end{array}
 = 2x^4 + x^3 + 11x^2 + 11x$$

$$4 \cdot (-1) + 3 \cdot 5 = 11$$

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TensorSketch

How to multiply polynomials?

$$(2x^2 + 3x + 4) \cdot (x^2 - x + 5)$$

$$\begin{array}{ccc}
 & x^0 & x^1 & x^2 \\
 & | & | & | \\
 \begin{matrix} 4 \\ 3 \\ 2 \end{matrix} & \boxed{4} & 3 & 2 \\
 \hline
 1 & -1 & \boxed{5} \\
 \hline
 x^2 & x^1 & x^0
 \end{array}
 = 2x^4 + x^3 + 11x^2 + 11x + 20$$

$$4 \cdot 5 = 20$$

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TensorSketch

How to multiply polynomials?

$$(2x^2 + 3x + 4) \cdot (x^2 - x + 5)$$

x^0	x^1	x^2			
4	3	2			
1	-1	5			
x^2	x^1	x^0			

$= 2x^4 + x^3 + 11x^2 + 11x + 20$
 $\equiv 11x^2 + 13x + 21 \pmod{x^3 - 1}$

$$4 \cdot 5 = 20$$

... this is circular convolution!

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TensorSketch: complexity analysis

Convolution Theorem (for circular convolutions $*$)

$$\mathcal{F}(g * h) = \mathcal{F}(g)\mathcal{F}(h) \quad \text{i.e.} \quad g * h = \mathcal{F}^{-1}(\mathcal{F}(g)\mathcal{F}(h))$$

Discrete Fourier Transform (implemented via FFT)

pointwise multiplication

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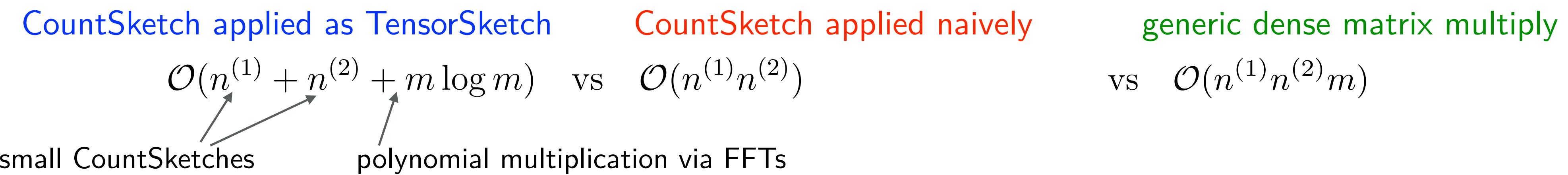
TensorSketch: complexity analysis

Convolution Theorem (for circular convolutions $*$)

$$\mathcal{F}(g * h) = \mathcal{F}(g)\mathcal{F}(h) \quad \text{i.e.} \quad g * h = \mathcal{F}^{-1}(\mathcal{F}(g)\mathcal{F}(h))$$

Complexity:

$$\begin{aligned}\mathcal{T} : \mathbb{R}^n &\rightarrow \mathbb{R}^m \\ n &= n^{(1)} \cdot n^{(2)}\end{aligned}$$



Savings grow as we have more tensor products

If $n = n^{(1)}n^{(2)} \dots n^{(q)}$

$$\mathcal{O}(n^{(1)} + n^{(2)} + \dots + n^{(q)} + m \log m) \quad \text{vs} \quad \mathcal{O}(n^{(1)}n^{(2)} \dots n^{(q)})$$

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TensorSketch: applying to matrices

From vector case $\mathbf{v} = \mathbf{v}^{(1)} \otimes \mathbf{v}^{(2)}$ to matrix case $\mathbf{A} = \mathbf{A}^{(1)} \otimes \mathbf{A}^{(2)} \otimes \cdots \otimes \mathbf{A}^{(N)}$

Recall the **Kronecker** product:

$$\begin{aligned} \mathbf{A} \otimes \mathbf{B} &= \begin{bmatrix} a_{11}\mathbf{B} & a_{12}\mathbf{B} & \cdots & a_{1J}\mathbf{B} \\ a_{21}\mathbf{B} & a_{22}\mathbf{B} & \cdots & a_{2J}\mathbf{B} \\ \vdots & \vdots & \ddots & \vdots \\ a_{I1}\mathbf{B} & a_{I2}\mathbf{B} & \cdots & a_{IJ}\mathbf{B} \end{bmatrix} \\ &= [\mathbf{a}_1 \otimes \mathbf{b}_1 \quad \mathbf{a}_1 \otimes \mathbf{b}_2 \quad \mathbf{a}_1 \otimes \mathbf{b}_3 \quad \cdots \quad \mathbf{a}_J \otimes \mathbf{b}_{L-1} \quad \mathbf{a}_J \otimes \mathbf{b}_L] \end{aligned}$$

Khatri-Rao product

$$\mathbf{A} \odot \mathbf{B} = [\mathbf{a}_1 \otimes \mathbf{b}_1 \quad \mathbf{a}_2 \otimes \mathbf{b}_2 \quad \cdots \quad \mathbf{a}_K \otimes \mathbf{b}_K]$$

Observe

pointwise multiplication (aka Hadamard product)

$$\mathbf{a} \circ \mathbf{b} = (\mathbf{a}^\top \odot \mathbf{b}^\top)^\top$$

and with some work,

$$\mathbf{T}\mathbf{A} = \text{FFT}^{-1} \left(\left(\bigodot_{n=1}^N \left(\text{FFT} \left(\mathbf{S}^{(n)} \mathbf{A}^{(n)} \right) \right)^\top \right)^\top \right)$$