Randomized algorithms for optimization: Statistical and computational guarantees

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Based on joint work with:

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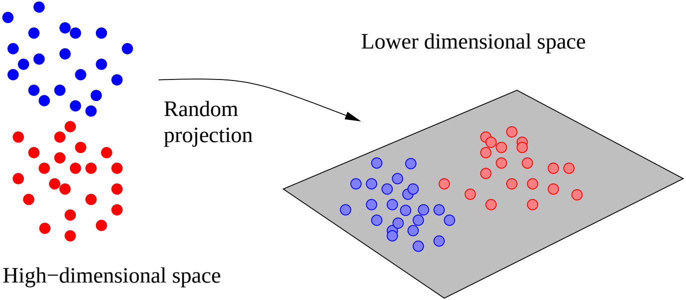
- Choose a random subspace of "low" dimension m.
- Project data into subspace, and solve reduced dimension problem.



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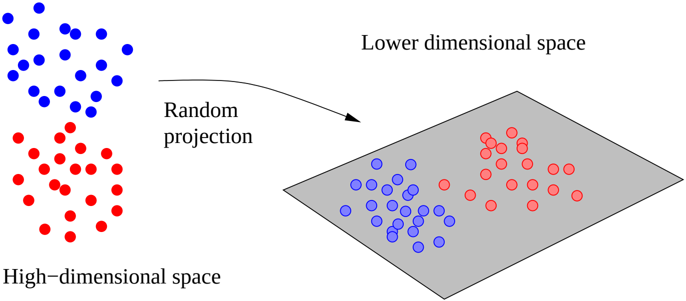
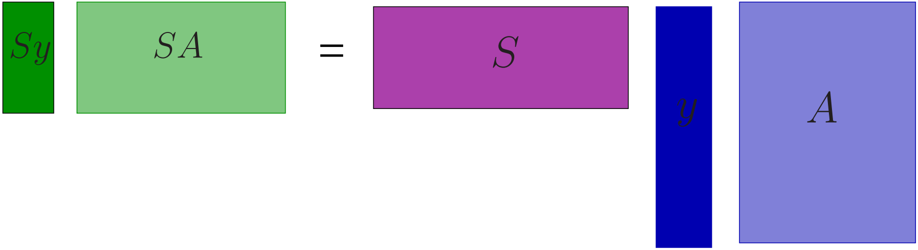


Basic underlying idea now widely used in practice:

- Johnson & Lindenstrauss (1984): for Hilbert spaces
- various surveys and books: Vempala, 2004; Mahoney et al., 2011 Cormode et al., 2012

Classical sketching for constrained least-squares



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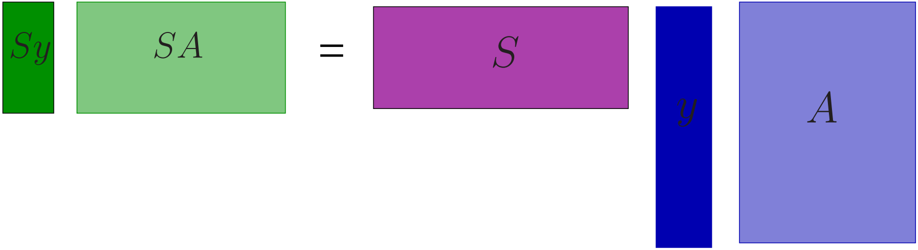

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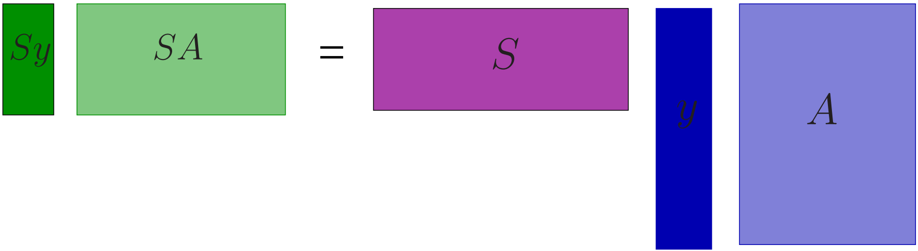

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Some history:

- random projections and Johnson-Lindenstrauss: 1980s onwards
- sketching for unconstrained least-squares: Sarlos, 2006
- leverage scores, cores sets: Drineas et al., 2010, 2011
- overview paper: Mahoney et al., 2011

Sketches based on randomized orthonormal systems

Step 1: Choose some fixed orthonormal matrix $H \in \mathbb{R}^{n \times n}$.
Example: Hadamard matrices

$$H_2 = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \qquad H_{2^t} = \underbrace{H_2 \otimes H_2 \otimes \cdots \otimes H_2}_{\text{Kronecker product } t \text{ times}}$$

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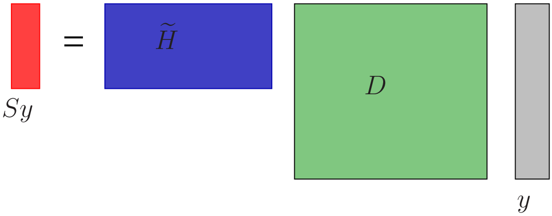

Step 2:

(A) Multiply data vector y with a diagonal matrix of random signs $\{-1, +1\}$

(B) Choose m rows of H to form sub-sampled matrix $\widetilde{H} \in \mathbb{R}^{m \times n}$

(C) Requires $\mathcal{O}(n \log m)$ time to compute sketched vector $Sy = \widetilde{H}\, Dy$.

(E.g., Ailon & Liberty, 2010)

Different notions of approximation

Given a convex set $\mathcal{C} \subseteq \mathbb{R}^d$:

Original least-squares problem

$$x_{\mathrm{LS}} = \arg\min_{x \in \mathcal{C}} \Big\{ \underbrace{\|Ax - y\|_2^2}_{f(x)} \Big\}$$

Sketched solution

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Sketched solution $\widehat{x} \in \mathcal{C}$ is a δ-accurate cost approximation if

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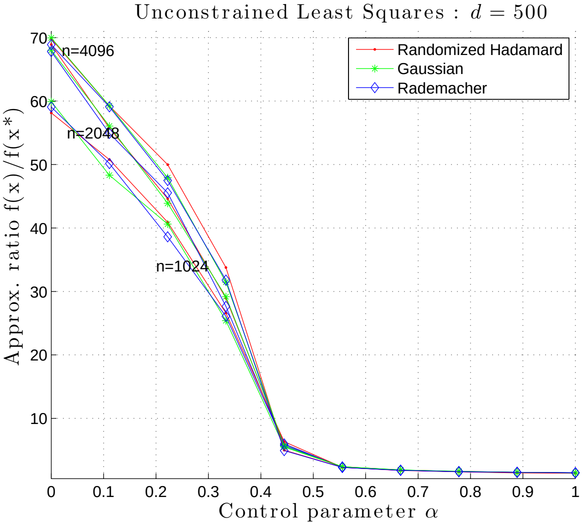
Solution approximation

Sketched solution $\widehat{x} \in \mathcal{C}$ is a δ-accurate solution approximation if

$$\underbrace{\|\widehat{x} - x_{\text{LS}}\|_A}_{\frac{1}{\sqrt{n}}\|A(\widehat{x} - x_{\text{LS}})\|_2} \;\leq \delta$$

Cost approx. for unconstrained LS



Sketch size $m = 4\alpha \, \mathrm{rank}(A)$

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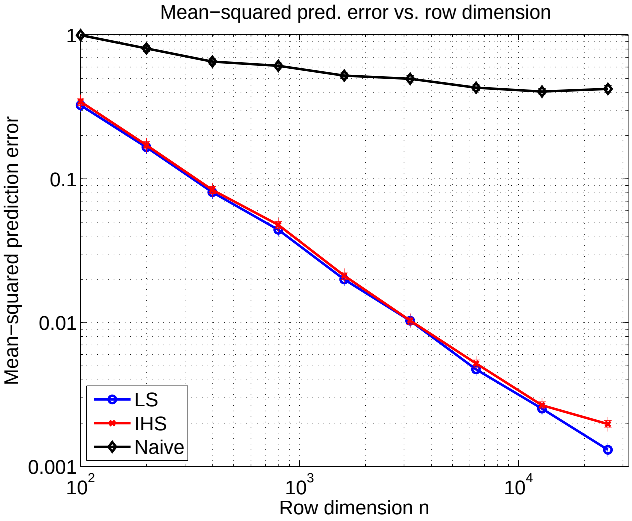
Least-squares solution x_{LS} has mean-squared error at most

$$\mathbb{E}\|x_{\mathrm{LS}} - x^*\|_A^2 \quad \precsim \quad \underbrace{\frac{\sigma^2 \ \mathrm{rank}(A)}{n}}_{\text{Nominal } \delta}$$

Unconstrained LS: Solution approximation



Sketch size $m \gtrsim \mathrm{rank}(A) \log n$.

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Theorem (Pilanci & W, 2014)

Any possible estimator $(Sy, SA) \mapsto \widetilde{x}$ *has error lower bounded as*

$$\sup_{x^* \in \mathcal{C}} \mathbb{E}_{S,w}\Big[\|\widetilde{x} - x_{LS}\|_A^2\Big] \succsim \sigma^2 \frac{\log P_{1/2}(\mathcal{C})}{\min\{n, m\}}$$

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Concretely: For unconstrained least-squares, we have

$$\sup_{x^* \in \mathcal{C}} \mathbb{E}_{S,w}\Big[\|\widetilde{x} - x_{\text{LS}}\|_A^2\Big] \succsim \sigma^2 \frac{\text{rank}(A)}{\min\{n, m\}}.$$

Consequently, we need $m \geq n$ to match least-squares performance in estimating x^*.

A slightly different approach: Hessian sketch

Observe that

$$x_{\text{LS}} = \arg\min_{x \in \mathcal{C}} \|Ax - y\|_2^2 \;=\; \arg\min_{x \in \mathcal{C}} \Big\{ \frac{1}{2} x^T A^T A x - \langle A^T y,\, x \rangle \Big\}.$$

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For a broad class of sketches, as long sketch dimension $m \gtrsim (1/\delta^2)\, \mathcal{W}^2(A\mathcal{K})$, can prove that

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...the construction can be iterated to obtain an optimal method.

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Given an iteration number $T \geq 1$:

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Intuition

- Step 1 returns the plain Hessian sketch $\widetilde{x} = x^1$.
- Step t is sketching a problem for which $x^t - x_{\mathrm{LS}}$ is the optimal solution.
- The error is thus successively "localized".

Theory for unconstrained least-squares

Theorem (Pilanci & W., 2014)

Given a sketch dimension $m \gtrsim \mathrm{rank}(A)$, *the error decays geometrically*

$$\|x^{t+1} - x_{LS}\|_A \leq \left(\frac{1}{2}\right)^t \|x_{LS}\|_A \qquad \textit{for all } t = 0, 1, \ldots, T-1$$

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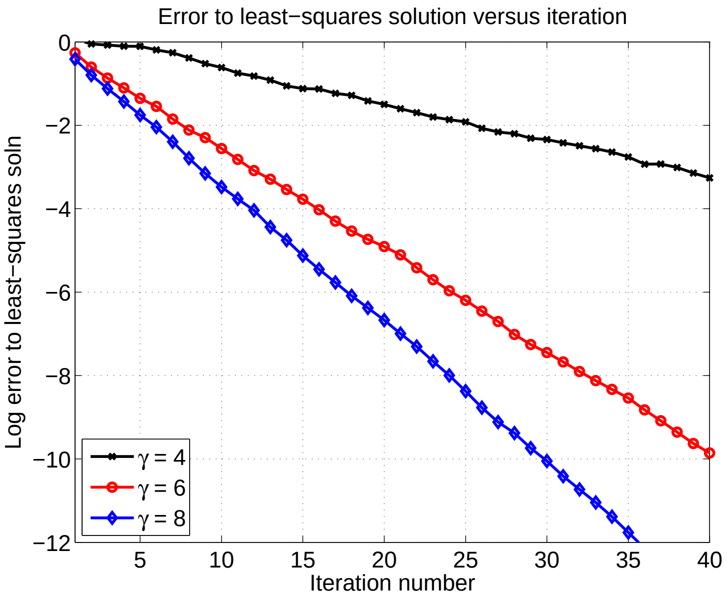
- applies to any sub-Gaussian sketch; same result for fast JL sketches with additional logarithmic factors
- total number of random projections scales as $T\, m$
- for any $\epsilon > 0$, taking $T = \log\left(\frac{2\|x_{\mathrm{LS}}\|_A}{\epsilon}\right)$ iterations yields ϵ-accurate solution.

Geometric convergence for unconstrained LS



Experiments for planted ensembles

Linear regression problems with $A \in \mathbb{R}^{n \times d}$ and $n > d$:

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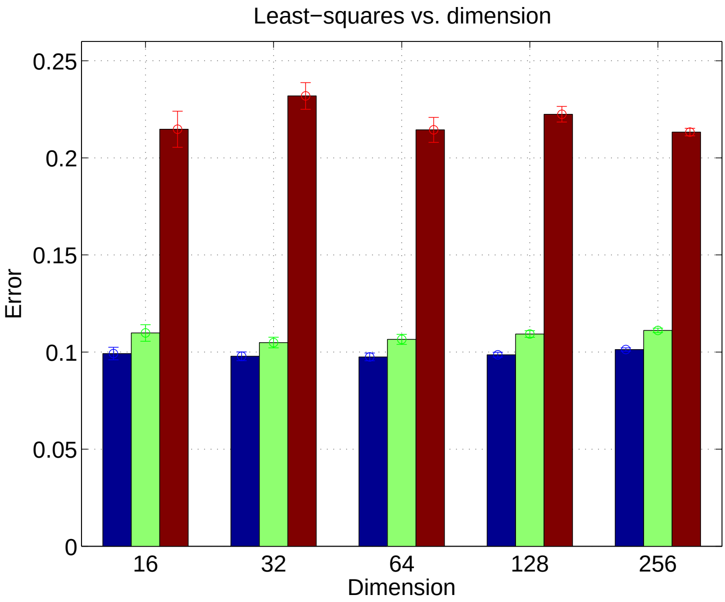
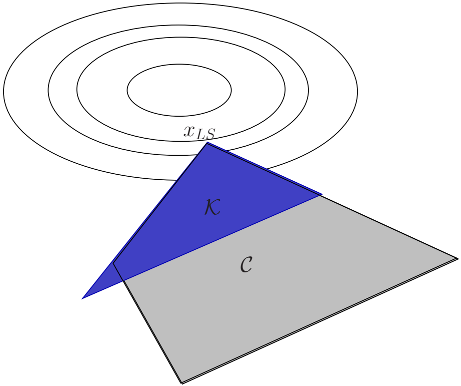
Scaling behavior:

- Fix $\sigma^2 = 1$ and sample size $n = 100d$, and vary $d \in \{16, 32, 64, 128, 256\}$.
- Run IHS with sketch size $m = 4d$ for $T = 4$ iterations.
- Compare to classical sketch with sketch size $16d$.

Sketched accuracy: IHS versus classical sketch



Extensions to constrained problems



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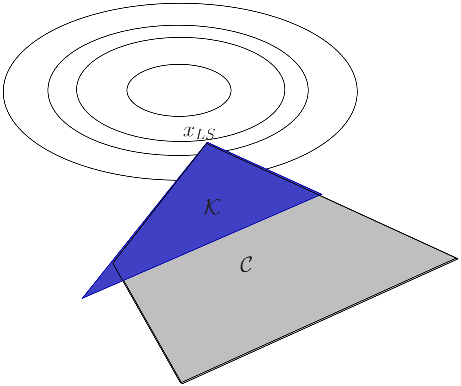

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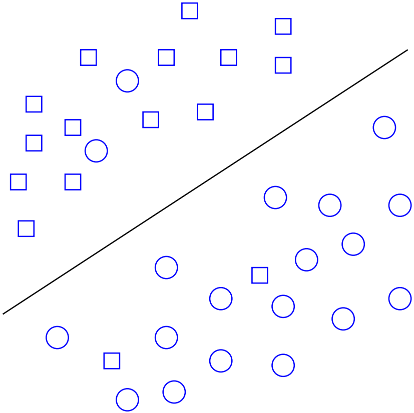
Tangent cone $\mathcal{K}$ at x_{LS}

Set of feasible directions at the optimum x_{LS}

$$\mathcal{K} = \left\{ \Delta \in \mathbb{R}^d \mid \Delta = t\,(x - x_{\text{LS}}) \quad \text{for some } x \in \mathcal{C}. \right\}.$$

Illustration: Binary classification with SVM

Observe labeled samples $(b_i, L_i) \in \mathbb{R}^D \times \{-1, +1\}$.



Goal: Find linear classifier $b \mapsto \text{sign}(\langle w,\, b\rangle)$ with low classification error.

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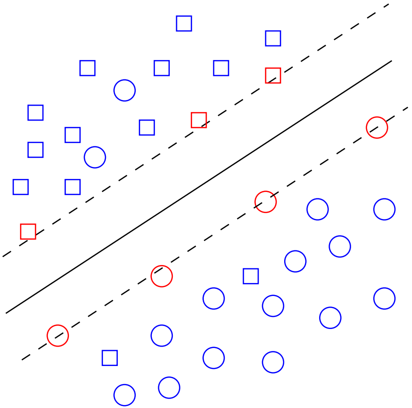

- Support vector machine: produces classifier that depends only on samples lying on the margin
- Number of support vectors k typically $\ll$ total number of samples n

Sketching the dual of the SVM

Primal form of SVM:

$$\widehat{w} = \arg\min_{w \in \mathbb{R}^n} \left\{ \frac{1}{2\gamma} \sum_{i=1}^{d} \max\left\{0, 1 - L_i \langle w,\, b_i \rangle \right\} + \frac{1}{2} \|w\|_2^2 \right\}.$$

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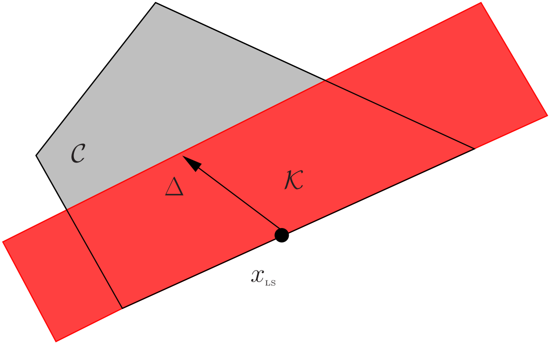
Unfavorable dependence on optimum x^*



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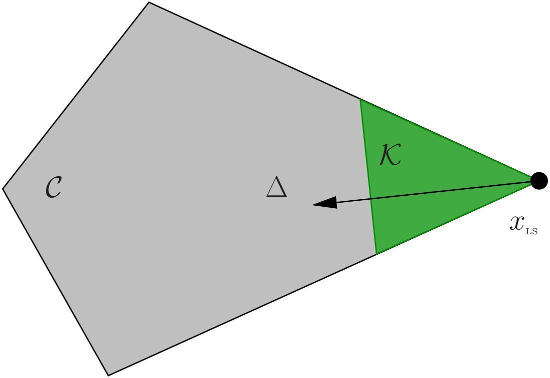
Favorable dependence on optimum x^*



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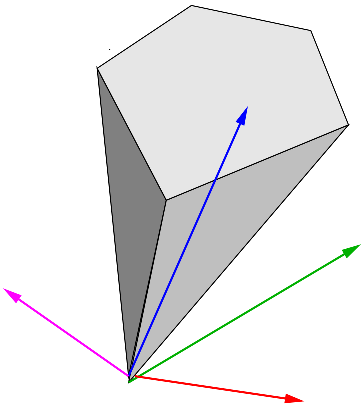
Gaussian width of transformed tangent cone

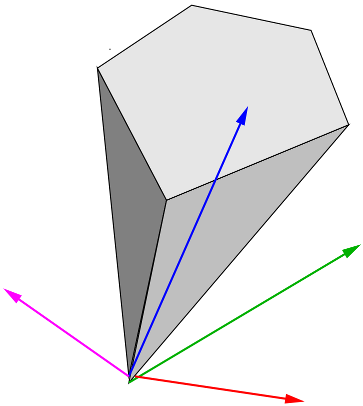


Gaussian width of set
$A\mathcal{K} \cap \mathcal{S}^{n-1} = \{A\Delta \mid \Delta \in \mathcal{K}, \|A\Delta\|_2 = 1\}$

$$\mathcal{W}(A\mathcal{K}) := \mathbb{E}\Big[\sup_{z \in A\mathcal{K} \cap \mathcal{S}^{n-1}} \langle g,\, z\rangle\Big]$$

where $g \sim N(0, I_{n\times n})$.

Gaussian width of transformed tangent cone



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Gaussian widths used in many areas:

- Banach space theory: Pisier, 1986
- Empirical process theory: Ledoux & Talagrand, 1991, Bartlett et al., 2002
- Compressed sensing: Mendelson et al., 2008; Chandrasekaran et al., 2012

A general guarantee

Tangent cone at x_{LS}:

$$\mathcal{K} = \{\Delta \in \mathbb{R}^d \mid \Delta = t(x - x_{\text{LS}}) \in \mathcal{C} \quad \text{for some } t \geq 0.$$

Width of transformed cone $A\mathcal{K} \cap \mathcal{S}^{n-1}$:

$$\mathcal{W}(A\mathcal{K}) = \mathbb{E}\Big[\sup_{z \in A\mathcal{K} \cap \mathcal{S}^{n-1}} \langle g,\, z \rangle\Big] \qquad \text{where } g \sim N(0, I_{n \times n}).$$

Theorem (Pilanci & W., 2014)

Given a sketch dimension $m \gtrsim \mathcal{W}^2(A\mathcal{K})$, the error decays geometrically

$$\|x^{t+1} - x_{LS}\|_A \leq \Big(\frac{1}{2}\Big)^t \|x_{LS}\|_A \qquad \textit{for all } t = 0, 1, \ldots, T-1$$

with probability at least $1 - c_1 T e^{-c_2 m}$.

Ilustration: Width calculation for dual SVM

- Relevant constraint set is simplex in $\mathbb{R}^n$:

$$\mathcal{P}^n := \Big\{x \in \mathbb{R}^n \mid x \geq 0 \text{ and } \sum_{i=1}^n x_i = \gamma\Big\}.$$

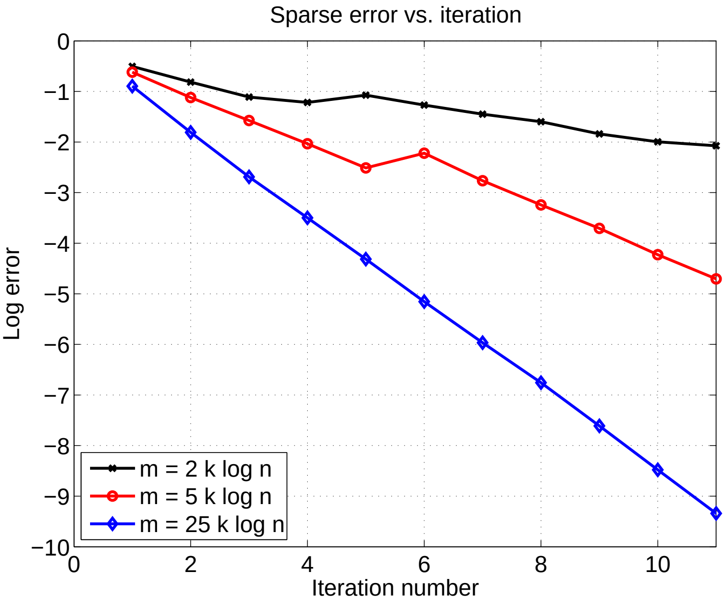
- in practice, SVM dual solution $\widehat{x}_{\text{dual}}$ is often sparse, with relatively few non-zeros
- under mild conditions on A, it can be shown that

$$\mathbb{E}\Big[\sup_{\substack{x \in \mathcal{P}^n \\ \|x\|_0 \leq k,\ \|Ax\|_2 \leq 1}} \langle g,\, Ax\rangle\Big] \precsim \sqrt{k \log n}.$$

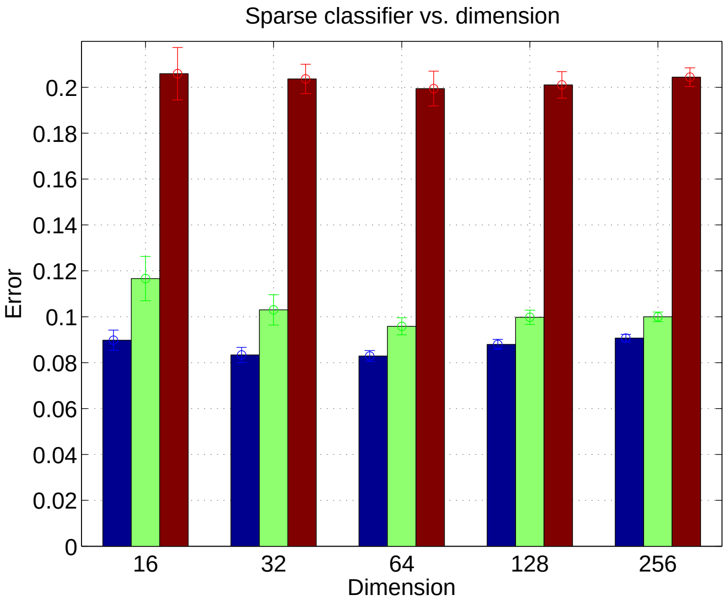
Conclusion

For a SVM solution with k support vectors, a sketch dimension $m \succsim k \log n$ is sufficient to ensure geometric convergence.

Geometric convergence for SVM



Sketched accuracy: IHS versus classical sketch



A more general story: Newton Sketch

Convex program over set $\mathcal{C} \subseteq \mathbb{R}^d$:

$$x_{\text{opt}} = \arg\min_{x \in \mathcal{C}} f(x), \quad \text{where } f : \mathbb{R}^d \to \mathbb{R} \text{ is twice-differentiable.}$$

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Ordinary Newton steps:

$$x^{t+1} = \arg\min_{x \in \mathcal{C}} \Big\{ \frac{1}{2} \|\nabla^2 f(x^t)^{1/2}(x - x^t)\|_2^2 + \langle \nabla f(x^t),\, x - x^t \rangle \Big\},$$

where $\nabla^2 f(x^t)^{1/2}$ is a matrix square of the Hessian at x^t.

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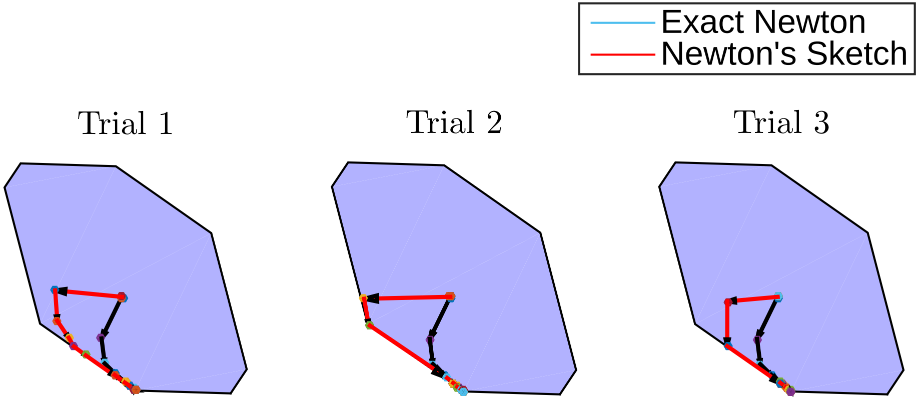
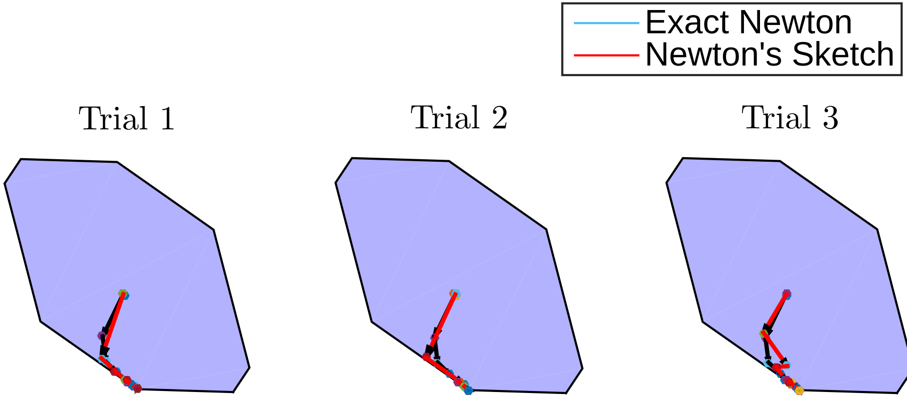
Question:

What is the minimal sketch dimension required to ensure that $\{\tilde{x}^t\}_{t=0}^T$ stays uniformly close to $\{x^t\}_{t=0}^T$?

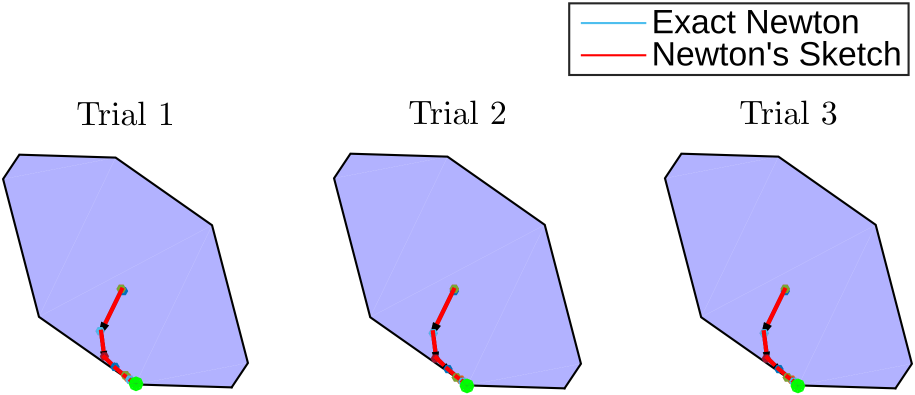
Sketching the central path: $m = d$



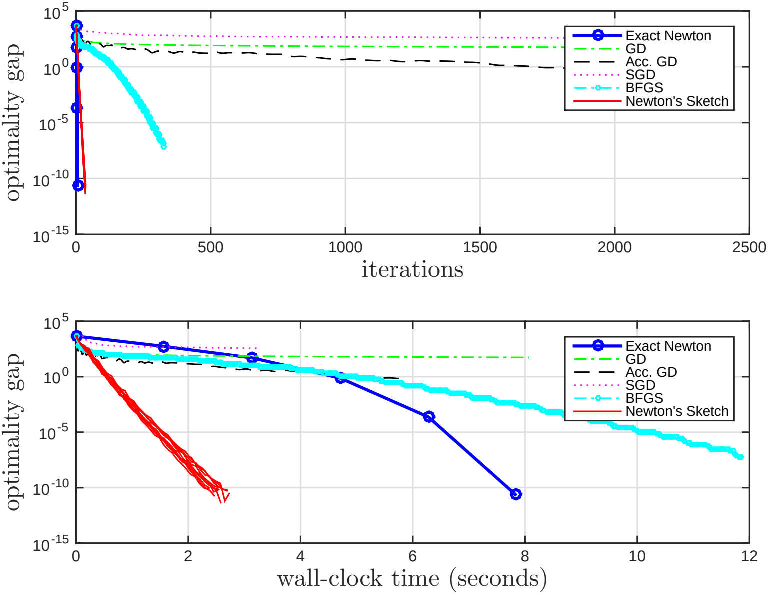
Sketching the central path: $m = 4d$



Sketching the central path: $m = 16d$



Running time comparisons



Summary

- important distinction: cost versus solution approximation
- classical least-squares sketch is provably sub-optimal for solution approximation
- iterative Hessian sketch: fast geometric convergence with guarantees in both cost/solution approximation
- sharp dependence of sketch dimension on geometry of solution and constraint set
- a more general perspective: sketched forms of Newton's method

Summary

- important distinction: cost versus solution approximation
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Papers/pre-prints:

- Pilanci & W. (2014a): Randomized sketches of convex programs with sharp guarantees, To appear in *IEEE Trans. Info. Theory*
- Pilanci & W. (2014b): Iterative Hessian Sketch: Fast and accurate solution approximation for constrained least-squares, Arxiv pre-print.
- Yang, Pilanci & W. (2015): Randomized sketches for kernels: fast and optimal non-parametric regression, Arxiv pre-print.
- Pilanci & W. (2015): Newton Sketch: A linear-time optimization algorithm with linear-quadratic convergence. Arxiv pre-print.