Improved Rates for Differentially Private Stochastic Convex Optimization with Heavy-Tailed Data

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Problem formulation

Stochastic convex optimization (SCO)

A fundamental optimization problem in machine learning.

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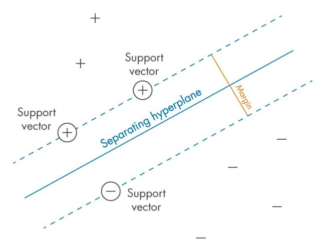
Goal: given n i.i.d. samples from an unknown distribution $\mathcal{D}$, find $\hat{w}$ to minimize

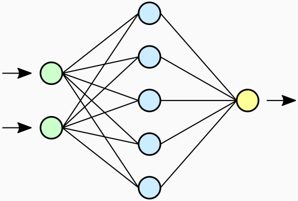
$$L_{\mathcal{D}}(\hat{w}) - \min_{w^* \in \mathcal{W}} L_{\mathcal{D}}(w^*).$$

Stochastic convex optimization (SCO)

Many applications in supervised machine learning and statistics.



(a) SVM



(b) Neural network

Privacy

Data may contain **sensitive** information.

(c) Navigation

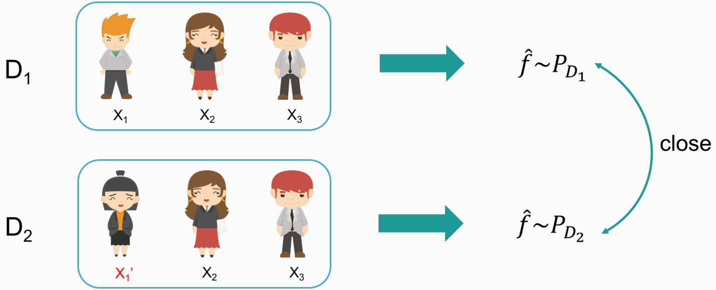
(d) Medical data

We want to protect the privacy while learning from samples.

Differential privacy (DP) [Dwork et al., 2006]

$\hat{f}$ is (ε, δ)-DP for any D_1 and D_2, with $d_{Ham}(D_1, D_2) \leq 1$, for all measurable S,

$$\forall S, \ \ \Pr\left(\hat{f}(D_1) \in S\right) \leq e^{\varepsilon} \cdot \Pr\left(\hat{f}(D_2) \in S\right) + \delta.$$



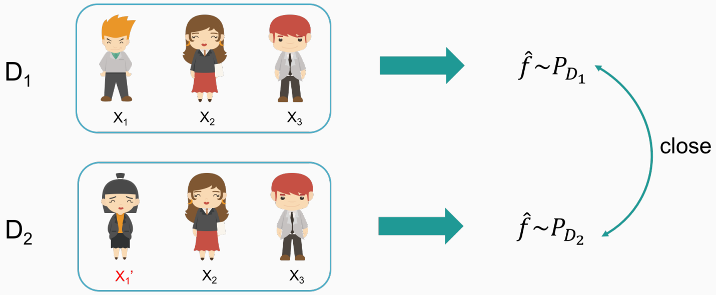
Pure DP: $\delta = 0$; **approximate DP:** $\delta \neq 0$

Concentrated Differential Privacy [Bun and Steinke, 2016]

$\hat{f}$ is ε^2-CDP if for any D_1 and D_2, with $d_{Ham}(D_1, D_2) \leq 1$,

$$\forall \alpha \in (1, \infty), D_\alpha\left(\hat{f}(D_1), \hat{f}(D_2)\right) \leq \varepsilon^2 \alpha,$$

where $D_\alpha\left(\hat{f}(D_1), \hat{f}(D_2)\right)$ is the α-Rényi divergence.



ε^2-CDP lies between $(O(\varepsilon), 0)$-DP and $(O(\varepsilon), \delta)$-DP.

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Let $\mathcal{D}$ be a distribution over $\mathbb{R}^d$. We assume for every $w \in W$,

$$\mathbb{E}_{x \in \mathcal{D}} \left[\left| \langle \nabla \ell(w, x), e_j \rangle \right|^k \right] \leq 1, \forall j \in [d],$$

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- We assume $k = 2$ for simplicity.

CDP SCO with heavy-tailed gradients

Goal: given n i.i.d. samples from an unknown distribution $\mathcal{D}$, and the gradient distribution satisfying the heavy-tailed assumption, we want to design a ε^2-CDP algorithm w^{priv} that minimizes

$$L_{\mathcal{D}}(w^{priv}) - \min_{w^* \in \mathcal{W}} L_{\mathcal{D}}(w^*).$$

Results

ε^2-CDP SCO with heavy-tailed gradients

Convex setting:

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- Tight up to a logarithmic factor.

Our techniques

CDP mean estimation

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- The first tight results for DP mean estimation with heavy-tailed data.

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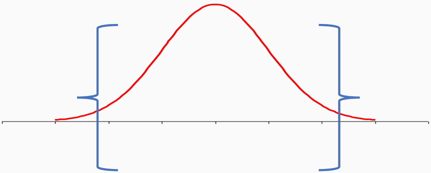

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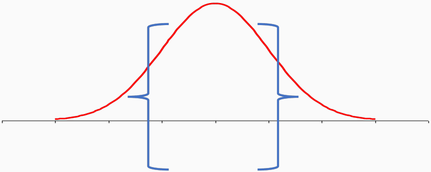

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- Wisely select the clipping range to balance the bias and variance!

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Proof: DP post-processing and composition.

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Theorem (utility, informal)

Suppose the mean estimation oracle guarantees that the bias is smaller than B and the variance is smaller than G^2, the algorithm outputs w^{priv} such that

$$\mathbb{E}\left[L_{\mathcal{D}}(w^{priv}) - L_{\mathcal{D}}(w^*)\right] \leq O\left(\frac{1}{\sqrt{T}} + \frac{G^2}{\sqrt{T}} + B\right).$$

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- However, it is sub-optimal for CDP SCO.
- Instead we set $B = \frac{G^2}{\sqrt{T}}$ to balance the second and third terms.
- This is achieved by a much more careful analysis of the mean estimation oracle.

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Theorem (ε^2-CDP Fano's inequality)

Let $\mathcal{V} = \{p_1, ..., p_M\}$ be a set of distributions, θ be a parameter of interest, and ℓ be a loss function. Suppose for all $i \neq j$, it satisfies (a) $\ell(\theta(p_i), \theta(p_j)) \geq r$, (b) $d_{TV}(p_i, p_j) \leq \alpha$. Then for any ε^2-CDP estimator $\hat{\theta}$,

$$\frac{1}{M} \sum_{i \in [M]} \mathbb{E}\left[\ell\Big(\hat{\theta}(X), \theta(p_i)\Big)\right] \geq \frac{r}{2}\left(1 - \frac{\varepsilon^2\big(n^2\alpha^2 + n\alpha(1-\alpha)\big) + \log 2}{\log M}\right).$$

Generalizations

Generalizing to $k > 2$

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- Estimating spherical Gaussians: $\Theta\left(\sqrt{\frac{d}{n}} + \frac{d}{\varepsilon n}\right)$ [Kamath et al., 2019, Acharya et al., 2021].

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- Our ε-DP result: $\Theta\left(\sqrt{\frac{d}{n}} + \frac{d^{\frac{3}{2}}}{\varepsilon n}\right)$.
- Estimating spherical Gaussians: $\Theta\left(\sqrt{\frac{d}{n}} + \frac{d}{\varepsilon n}\right)$ [Kamath et al., 2019, Acharya et al., 2021].
- The gap comes from the dependency across each dimension.

CDP SCO ($k > 2$)

All our analysis can be generalized to $k > 2$.

Convex setting:

- $\widetilde{O}\left(\frac{d}{\sqrt{n}} + \frac{d^2}{\varepsilon n} \cdot \left(\frac{\varepsilon n}{d^{1.5}}\right)^{\frac{1}{k}}\right)$

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Strongly convex setting:

- $\widetilde{O}\left(\frac{d}{n} + d \cdot \left(\frac{\sqrt{d}}{\varepsilon n}\right)^{\frac{2k-2}{k}}\right)$

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- $\Omega\left(\frac{d}{n} + d \cdot \left(\frac{\sqrt{d}}{\varepsilon n}\right)^{\frac{2k-2}{k}}\right)$
- Tight up to a logarithmic factor.

Summary

- Tight results for private mean estimation with heavy-tailed data.

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- Improved results for DP SCO. Our result is tight under strongly-convex setting.
- A new hammer for developing CDP lower bounds.

The End

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