

Algorithmic guarantees

1 General setting

We first introduce the regularity condition on the loss function \mathcal{L} and set \mathcal{S} .

Definition 1. Let f be a real-valued function. We say f satisfies $\text{RCG}(\alpha, \beta, \mathcal{S})$ condition for $\alpha, \beta > 0$ and the set \mathcal{S} if,

$$\langle \nabla f(x) - \nabla f(x'), x - x' \rangle \geq \alpha \|x - x'\|_2^2 + \beta \|\nabla f(x) - \nabla f(x')\|_2^2,$$

for any $x, x' \in \mathcal{S}$.

Define

$$\begin{aligned} \bar{\lambda} &:= \max \{ \sigma_{\max}(\mathcal{M}_1(\mathcal{B})), \sigma_{\max}(\mathcal{M}_2(\mathcal{B})), \sigma_{\max}(\mathcal{M}_3(\mathcal{B})) \}, \\ \underline{\lambda} &:= \min \{ \sigma_{\min}(\mathcal{M}_1(\mathcal{B})), \sigma_{\min}(\mathcal{M}_2(\mathcal{B})), \sigma_{\min}(\mathcal{M}_3(\mathcal{B})) \}, \end{aligned}$$

and $\kappa = \bar{\lambda}/\underline{\lambda}$ can be regarded as a tensor condition number. Here \mathcal{M}_i is the matricization operator with respect to i -th mode.

We define some constants related to side information $\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3$ as

$$\gamma := \prod_{k=1}^3 \sigma_{\max}(\mathbf{X}_k)^2, \quad \gamma_1 := \prod_{k=1}^3 \sigma_{\min}(\mathbf{X}_k)^2, \quad \text{and} \quad \gamma_2 := \prod_{k=1}^3 \|\mathbf{X}_k\|_F^2.$$

Without loss of generality, we scale the the side information matrices \mathbf{X}_k so that $\|\mathbf{X}_k\|_{\infty} \leq 1$ for all $k = 1, 2, 3$.

Lemma 1.1. Suppose $f: \mathbb{R}^{d_1 \times d_2 \times d_3} \rightarrow \mathbb{R}$ satisfies $\text{RCG}(\alpha, \beta, \mathcal{S})$ where $\mathcal{S} = \{\mathcal{T} \in \mathbb{R}^{d_1 \times d_2 \times d_3} : \text{rank}(\mathcal{T}) \leq (r_1, r_2, r_3)\}$. Define $g: \mathbb{R}^{p_1 \times p_2 \times p_3} \rightarrow \mathbb{R}$ as $g(\mathcal{B}) = f(\mathcal{B} \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\})$ for all $\mathcal{B} \in \mathbb{R}^{p_1 \times p_2 \times p_3}$ and $\mathcal{S}' = \{\mathcal{T} \in \mathbb{R}^{p_1 \times p_2 \times p_3} : \text{rank}(\mathcal{T}) \leq (r_1, r_2, r_3)\}$. Then, g satisfies $\text{RCG}(\alpha\gamma_1, \beta/\gamma_2, \mathcal{S}')$.

Proof. Notice that for any $\mathcal{B}_1, \mathcal{B}_2 \in \mathcal{S}'$,

$$\begin{aligned} &\langle \nabla g(\mathcal{B}_1) - \nabla g(\mathcal{B}_2), \mathcal{B}_1 - \mathcal{B}_2 \rangle \\ &= \langle (\nabla f(\mathcal{B}_1 \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\}) - \nabla f(\mathcal{B}_2 \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\})) \times \{\mathbf{X}_1^T, \mathbf{X}_2^T, \mathbf{X}_3^T\}, \mathcal{B}_1 - \mathcal{B}_2 \rangle \\ &= \langle \nabla f(\mathcal{B}_1 \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\}) - \nabla f(\mathcal{B}_2 \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\}), (\mathcal{B}_1 - \mathcal{B}_2) \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\} \rangle \\ &\geq \alpha \|(\mathcal{B}_1 - \mathcal{B}_2) \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\}\|_F^2 + \beta \|\nabla f(\mathcal{B}_1 \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\}) - \nabla f(\mathcal{B}_2 \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\})\|_F^2 \\ &\geq \alpha \gamma_1 \|\mathcal{B}_1 - \mathcal{B}_2\|_F^2 + \frac{\beta}{\gamma_2} \|\nabla g(\mathcal{B}_1) - \nabla g(\mathcal{B}_2)\|_F^2, \end{aligned}$$

where the first inequality uses the fact that f satisfies $\text{RCG}(\alpha, \beta, \mathcal{S})$ and the last inequality uses Cauch Schwartz inequality. \square

Since negative log-likelihoods of poisson and binomial distribution are not strongly convex and smooth in the unbounded domain. We thus introduce the following assumption on $\mathcal{B}_{\text{true}}$ to ensure that $\mathcal{B}_{\text{true}}$ is in a bounded set.

Assumption 1. Suppose $\mathcal{B}_{\text{true}} = \mathcal{C}^* \times \{\mathbf{M}_1^*, \mathbf{M}_2^*, \mathbf{M}_3^*\}$, where $\mathbf{M}_k^* \in \mathbb{R}^{p_k \times r_k}$ is a orthogonal matrix for $k = 1, 2, 3$. There exists some constants $\{\mu_k\}_{k=1}^3$, B such that $\|\mathbf{M}_k^*\|_{2,\infty}^2 \leq \frac{\mu_k r_k}{p_k}$ for $k = 1, 2, 3$ and $\bar{\lambda} \leq$

$B \sqrt{\frac{\prod_{k=1}^3 p_k}{\prod_{k=1}^3 \mu_k r_k}}$. Here $\|\mathbf{M}_k^*\|_{2,\infty}$ is the largest row-wise ℓ_2 norm of \mathbf{M}_k^* .

Remark 1. This condition guarantees that $\mathcal{B}_{\text{true}}$ is entry-wise upperbounded by B , which guarantees the local strong convexity and smoothness of the negative log-likelihood function.

We define searching space \mathcal{S} as follows:

$$\begin{aligned}\mathcal{S} &= \mathcal{S}_c \times \mathcal{S}_1 \times \mathcal{S}_2 \times \mathcal{S}_3, \text{ where} \\ \mathcal{S}_k &= \left\{ (\mathbf{M}_k \in \mathbb{R}^{p_k \times r_k} : \|\mathbf{M}_k\|_{2,\infty} \leq b \sqrt{\frac{\mu_k r_k}{p_k}} \right\} \text{ for } k = 1, 2, 3, \\ \mathcal{S}_c &= \left\{ \mathcal{C} \in \mathbb{R}^{r_1 \times r_2 \times r_3} : \max_k \|\mathcal{M}_k(\mathcal{C})\|_2 \leq b^{-3} B \sqrt{\frac{\prod_{k=1}^3 p_k}{\prod_{k=1}^3 \mu_k r_k}} \right\}.\end{aligned}$$

2 General tensor case from exponential family

Suppose we observe $\mathcal{Y} \in \mathbb{R}^{d_1 \times d_2 \times d_3}$ from exponential family with canonical parameter $\Theta = \mathcal{B}_{\text{true}} \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\}$ such that

$$\mathbb{P}(\mathcal{Y}_{ijk} | \Theta_{ijk}) = c(\mathcal{Y}_{ijk}, \phi) \exp \left(\frac{\mathcal{Y}_{ijk} \Theta_{ijk} - b(\Theta_{ijk})}{\phi} \right),$$

where $b(\cdot)$ is a known function, $\phi > 0$ is the dispersion parameter, and $c(\cdot)$ is a known normalization function. Then we consider the following negative log-likelihood to estimate $\mathcal{B}_{\text{true}}$,

$$\mathcal{L}(\mathcal{B} | \mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3) = -\langle \mathcal{Y}, \mathcal{B} \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\} \rangle + \sum_{ijk} b(\mathcal{B} \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\}).$$

Example 1 (Gaussian). Suppose we observe $\mathcal{Y} \in \mathbb{R}^{d_1 \times d_2 \times d_3}$ that satisfies

$$\mathcal{Y}_{ijk} \sim \text{Gaussian}(\mathcal{B}_{\text{true}} \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\}, \sigma) \text{ independently.}$$

Then the corresponding negative log-likelihood is,

$$\mathcal{L}(\mathcal{B} | \mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3) = \frac{1}{2} \|\mathcal{Y} - \mathcal{B}_{\text{true}} \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\}\|_F^2$$

Example 2 (Poisson). Suppose we observe $\mathcal{Y} \in \mathbb{N}^{d_1 \times d_2 \times d_3}$ that satisfies

$$\mathcal{Y}_{ijk} \sim \text{Poisson}(\exp(\mathcal{B}_{\text{true}} \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\})) \text{ independently.}$$

Then the corresponding negative log-likelihood is,

$$\mathcal{L}(\mathcal{B} | \mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3) = \sum_{ijk} \left(-\mathcal{Y}_{ijk} [\mathcal{B}_{\text{true}} \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\}]_{ijk} + \exp([\mathcal{B}_{\text{true}} \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\}]_{ijk}) \right).$$

Example 3 (Bernoulli). Suppose we observe $\mathcal{Y} \in \{0, 1\}^{d_1 \times d_2 \times d_3}$ that satisfies

$$\mathcal{Y}_{ijk} \sim \text{Bernoulli}(\text{logistic}(\mathcal{B}_{\text{true}} \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\})) \text{ independently,}$$

where $\text{logistic}(x) = (1 + e^{-x})^{-1}$. Then the corresponding negative log-likelihood is,

$$\mathcal{L}(\mathcal{B} | \mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3) = - \sum_{ijk} \left(\mathcal{Y}_{ijk} [\mathcal{B}_{\text{true}} \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\}]_{ijk} + \log \left(1 + \exp([\mathcal{B}_{\text{true}} \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\}]_{ijk}) \right) \right).$$

Theorem 2.1. Suppose Assumption 1 holds for Poisson and Bernoulli cases and

1. Initialization: $\|\mathcal{B}_{\text{true}} - \mathcal{B}^{(0)}\|_F^2 \leq c_1 \alpha \beta \kappa^{-2} \underline{\lambda}^2$
2. Signal to noise ratio: $\underline{\lambda}^2 \geq c_2 \frac{\kappa^4}{\alpha^3 \beta} \left(\frac{\prod_k r_k}{\max_k r_k} \gamma \sum_k p_k \right).$

where $c_1, c_2 > 0$ are universal constants. Then, with probability at least $1 - \exp(-c_3 \sum_k p_k)$, we have

$$\|\mathcal{B}^{(t)} - \mathcal{B}_{\text{true}}\|_F^2 \lesssim \underbrace{\left(\frac{\prod_k r_k}{\max_k r_k} \sum_k p_k \right)}_{\text{Statistical error}} + \underbrace{\rho^T \|\mathcal{B}^{(0)} - \mathcal{B}_{\text{true}}\|_F^2}_{\text{Algorithmic error}},$$

for all $t \geq 1$ where $\rho \in (0, 1)$ is a contraction parameter, and $c_1, c_2, c_3 > 0$ are some constants.

Remark 2. Combining Lemma 1.1 and proofs of the theorems in Han et al. [2020], we have

1. (Gaussian case) We have $\alpha = \frac{\gamma_1}{2}$ and $\beta = \frac{1}{2\gamma_2}$.
2. (Poisson case) We have $\alpha = \frac{\gamma_1}{e^B + e^{-B}}$ and $\beta = \frac{1}{\gamma_2(e^B + e^{-B})}$
3. (Bernoulli case) We have $\alpha = \frac{\gamma_1}{2(e^B + 3)}$ and $\beta = \frac{1}{2\gamma_2}$

Proof. We bound the statistical error and apply the result to Theorem 3.1. in Han et al. [2020]. We show that with probability at least $1 - \exp(-C_2 \sum_k p_k)$,

$$\xi = \sup_{\substack{\mathcal{T} \in \mathbb{R}^{p_1 \times p_2 \times p_3} \\ \text{rank}(\mathcal{T}) \leq (r_1, r_2, r_3) \\ \|\mathcal{T}\|_F^2 \leq 1}} \langle \nabla \mathcal{L}(\mathcal{B} | \mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3), \mathcal{T} \rangle \leq C_1 \sqrt{\frac{\prod_k r_k}{\max_k r_k} \gamma \sum_k p_k},$$

for some constants $C_1, C_2 > 0$. By definition of $\mathcal{L}(\mathcal{B} | \mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3)$, we have

$$\begin{aligned} \xi &= \sup_{\substack{\mathcal{T} \in \mathbb{R}^{p_1 \times p_2 \times p_3} \\ \text{rank}(\mathcal{T}) \leq (r_1, r_2, r_3) \\ \|\mathcal{T}\|_F^2 \leq 1}} \langle \nabla \mathcal{L}(\mathcal{B} | \mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3), \mathcal{T} \rangle \\ &= \sup_{\substack{\mathcal{T} \in \mathbb{R}^{p_1 \times p_2 \times p_3} \\ \text{rank}(\mathcal{T}) \leq (r_1, r_2, r_3) \\ \|\mathcal{T}\|_F^2 \leq 1}} \langle (\mathcal{Y} - b'(\mathcal{B}_{\text{true}} \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\})) \times \{\mathbf{X}_1^T, \mathbf{X}_2^T, \mathbf{X}_3^T\}, \mathcal{T} \rangle \\ &= \sup_{\substack{\mathcal{T} \in \mathbb{R}^{p_1 \times p_2 \times p_3} \\ \text{rank}(\mathcal{T}) \leq (r_1, r_2, r_3) \\ \|\mathcal{T}\|_F^2 \leq 1}} \langle \mathcal{E} \times \{\mathbf{X}_1^T, \mathbf{X}_2^T, \mathbf{X}_3^T\}, \mathcal{T} \rangle, \end{aligned} \tag{1}$$

where $\mathcal{E} \stackrel{\text{def}}{=} \mathcal{Y} - b'(\mathcal{B}_{\text{true}} \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\})$. Based on Proposition 3, the boundedness of $b''(\cdot)$ implies that \mathcal{E} is a sub-Gaussian- (ϕU) tensor. Let $\check{\mathcal{E}} \stackrel{\text{def}}{=} \mathcal{E} \times \{\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\}$. By proposition 2, $\check{\mathcal{E}}$ is a (p_1, p_2, p_3) -dimensional sub-Gaussian tensor with parameter bounded by $\phi U \sqrt{\gamma}$. Applying Cauchy-Schwartz inequality to (1) yields

$$\xi \leq \|\check{\mathcal{E}}\|_2 \sup_{\substack{\mathcal{T} \in \mathbb{R}^{p_1 \times p_2 \times p_3} \\ \text{rank}(\mathcal{T}) \leq (r_1, r_2, r_3) \\ \|\mathcal{T}\|_F^2 \leq 1}} \|\mathcal{T}\|_*, \tag{2}$$

where $\|\cdot\|_2$ denotes the tensor spectral norm and $\|\cdot\|_*$ denotes the tensor nuclear norm. The nuclear norm $\|\mathcal{T}\|_*$ is bounded by $\|\mathcal{T}\|_* \leq \sqrt{\frac{\prod_{k=1}^3 r_k}{\max_k r_k}} \|\mathcal{T}\|_F$ [Wang et al., 2017, Wang and Li, 2018]. The spectral norm $\|\check{\mathcal{E}}\|_2$ is bounded by $\|\check{\mathcal{E}}\|_2 \leq C_1 \sqrt{\gamma \sum_k p_k}$ with probability at least $1 - \exp(-C_2 \log K \sum_k p_k)$ [Tomioka and Suzuki, 2014]. Combining these two bounds with (2), we have, with probability at least $1 - \exp(-C_2 \sum_k p_k)$,

$$\xi \leq C_1 \sqrt{\frac{\prod_k r_k}{\max_k r_k} \gamma \sum_k p_k}.$$

Applying the upper bound of ξ to Theorem 3.1 in Han et al. [2020] completes the proof. \square

References

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