
Supplementary Materials for Interaction Screening: Efficient and Sample-Optimal Learning of Ising Models

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We provide in Section 1 detailed proofs of Lemma 1, 2, 3 and 4 related to the gradient concentration of the Interaction-Screening Objective (ISO). Detailed proofs of Lemma 5, 6, 7 and 8 related to the restricted strong-convexity of the ISO can be found in Section 2.

1 Gradient Concentration

Lemma 1. *For any Ising model with p spins and for all $l \neq u \in V$*

$$\mathbb{E} [X_{ul}(\underline{\theta}_u^*)] = 0. \quad (1)$$

Proof. By direct computation, we find that

$$\begin{aligned} \mathbb{E} [X_{ul}(\underline{\theta}_u^*)] &= \mathbb{E} \left[-\sigma_u \sigma_l \exp \left(- \sum_{i \in \partial u} \theta_{ui}^* \sigma_u \sigma_i \right) \right] \\ &= \frac{-1}{Z} \sum_{\underline{\sigma}} \sigma_u \sigma_l \exp \left(\sum_{(i,j) \in E} \theta_{ij}^* \sigma_i \sigma_j - \sum_{i \in \partial u} \theta_{ui}^* \sigma_u \sigma_i \right) = 0, \end{aligned} \quad (2)$$

where in the last line we use the fact that the exponential terms involving σ_u cancel, implying that the sum over $\sigma_u \in \{-1, +1\}$ is zero. \square

Lemma 2. *For any Ising model with p spins and for all $l \neq u \in V$*

$$\mathbb{E} [X_{ul}(\underline{\theta}_u^*)^2] = 1. \quad (3)$$

Proof. As a result of direct evaluation one derives

$$\begin{aligned}
\mathbb{E} \left[X_{ul} (\underline{\theta}_u^*)^2 \right] &= \mathbb{E} \left[\exp \left(-2 \sum_{i \in \partial u} \theta_{ui}^* \sigma_u \sigma_i \right) \right] \\
&= \frac{1}{Z} \sum_{\underline{\sigma}} \exp \left(\sum_{(i,j) \in E, i,j \neq u} \theta_{ij}^* \sigma_i \sigma_j - \sum_{i \in \partial u} \theta_{ui}^* \sigma_u \sigma_i \right) \\
&= \frac{1}{Z} \sum_{\underline{\sigma}} \exp \left(\sum_{(i,j) \in E, i,j \neq u} \theta_{ij}^* \sigma_i \sigma_j + \sum_{i \in \partial u} \theta_{ui}^* \sigma_u \sigma_i \right) \\
&= 1.
\end{aligned} \tag{4}$$

Notice that in the second line the first sum over edges (under the exponential) does not depend on σ_u . Furthermore, the first sum is invariant under the change of variables, $\sigma_u \rightarrow -\sigma_u$, while the second sum changes sign. This transformation results in appearance of the partition function in the numerator. \square

Lemma 3. *For any Ising model with p spins, with maximum degree d and maximum coupling intensity β , it is guaranteed that for all $l \neq u \in V$*

$$|X_{ul} (\underline{\theta}_u^*)| \leq \exp(\beta d). \tag{5}$$

Proof. Observe that components of $\underline{\theta}_u^*$ are smaller than β and at most d of them are non-zero. Recall that spins are binary, $\{-1, +1\}$, which results in the following estimate

$$\begin{aligned}
|X_{ul} (\underline{\theta}_u^*)| &= \left| -\sigma_u \sigma_l \exp \left(- \sum_{i \in \partial u} \theta_{ui}^* \sigma_u \sigma_i \right) \right| \\
&\leq \exp \left(- \sum_{i \in \partial u} \theta_{ui}^* \sigma_u \sigma_i \right) \\
&\leq \exp(\beta d).
\end{aligned} \tag{6}$$

\square

Lemma 4. *For any Ising model with p spins, with maximum degree d and maximum coupling intensity β . For any $\epsilon_3 > 0$, if the number of observation satisfies $n \geq \exp(2\beta d) \ln \frac{2p}{\epsilon_3}$, then the following bound holds with probability at least $1 - \epsilon_3$:*

$$\|\nabla \mathcal{S}_n (\underline{\theta}_u^*)\|_\infty \leq 2 \sqrt{\frac{\ln \frac{2p}{\epsilon_3}}{n}}. \tag{7}$$

Proof. Let us first show that every term is individually bounded by the RHS of (7) with high-probability. We further use the union bound to prove that all components are uniformly bounded with high-probability. Utilizing Lemma 1, Lemma 2 and Lemma 3 we apply the Bernstein's Inequality

$$\mathbb{P} \left[\left| \frac{\partial}{\partial \theta_{ul}} \mathcal{S}_n (\underline{\theta}_u^*) \right| > t \right] \leq 2 \exp \left(- \frac{\frac{1}{2} t^2 n}{1 + \frac{1}{3} \exp(\beta d) t} \right). \tag{8}$$

Inverting the following relation

$$s = \frac{\frac{1}{2} t^2 n}{1 + \frac{1}{3} \exp(\beta d) t}, \tag{9}$$

and substituting the result in the Eq. (8) one derives

$$\mathbb{P} \left[\left| \frac{\partial}{\partial \theta_{ul}} \mathcal{S}_n (\underline{\theta}_u^*) \right| > \frac{1}{3} \left(u + \sqrt{\frac{18}{\exp(\beta d)} u + u^2} \right) \right] \leq 2 \exp(-s), \tag{10}$$

where $u = \frac{s}{n} \exp(\beta d)$.

For $n \geq s \exp(2\beta d)$, we can simplify Eq. (10) to have an expression independent of β and d

$$\mathbb{P} \left[\left| \frac{\partial}{\partial \theta_{ul}} \mathcal{S}_n(\theta_u^*) \right| > 2\sqrt{\frac{s}{n}} \right] \leq 2 \exp(-s). \quad (11)$$

Using $s = \ln \frac{2p}{\epsilon_3}$ and the union bound on every component of the gradient leads to the desired result. \square

2 Restricted Strong-Convexity

We recall that the remainder of the first-order Taylor-expansion of the ISO, is the following quantity

$$\delta \mathcal{S}_n(\Delta_u, \theta^*) = \frac{1}{n} \sum_{k=1}^n \exp \left(- \sum_{i \in \partial u} \theta_{ui}^* \sigma_u^{(k)} \sigma_i^{(k)} \right) f \left(\sum_{i \in V \setminus u} \Delta_{ui} \sigma_u^{(k)} \sigma_i^{(k)} \right), \quad (12)$$

where the function $f(z)$ appearing in Eq. (12) reads

$$f(z) := e^{-z} - 1 + z. \quad (13)$$

Lemma 5. *For all $\Delta_u \in \mathbb{R}^{p-1}$, the remainder of the first-order Taylor expansion admits the following lower-bound*

$$\delta \mathcal{S}_n(\Delta_u, \theta^*) \geq \frac{e^{-\beta d}}{2 + \|\Delta_u\|_1} \Delta_u^\top H^n \Delta_u \quad (14)$$

where the matrix H^n is an empirical covariance matrix with elements $i, j \in V \setminus u$

$$H_{ij}^n = \frac{1}{n} \sum_{k=1}^n \sigma_i^{(k)} \sigma_j^{(k)}. \quad (15)$$

Proof. We start to prove a lower-bound on the function $f(z)$ valid for all $z \in \mathbb{R}$,

$$f(z) \geq \frac{z^2}{2 + |z|}. \quad (16)$$

To see this, define an auxiliary function $g(z)$ as follows

$$\begin{aligned} g(z) &:= (2 + |z|) f(z) - z^2 \\ &= (2 + |z|) (e^{-z} - 1 + z) - z^2. \end{aligned} \quad (17)$$

We show that $g(z)$ achieves its minimum at $g(0) = 0$. Observe that the first derivative of $g(z)$ vanishes at zero from both the negative and positive side

$$\lim_{z \rightarrow 0_+} \frac{d}{dz} g(z) = \lim_{z \rightarrow 0_-} \frac{d}{dz} g(z) = 0. \quad (18)$$

Moreover for all $z > 0$ the second derivative of $g(z)$ is non-negative

$$\frac{d^2}{dz^2} g(z) = ze^{-z} > 0. \quad (19)$$

A similar result holds for $z < 0$

$$\frac{d^2}{dz^2} g(z) = 4(e^{-z} - 1) - ze^{-z} > 0, \quad (20)$$

proving that for all z , $g(z) \geq g(0) = 0$.

Combining Eq. (16) with the straightforward inequalities

$$\left| \sum_{i \in V \setminus u} \Delta_{ui} \sigma_u^{(k)} \sigma_i^{(k)} \right| \leq \|\Delta_u\|_1, \quad (21)$$

and

$$\exp\left(-\sum_{i \in \partial u} \theta_{ui}^* \sigma_u^{(k)} \sigma_i^{(k)}\right) \geq \exp(-\beta d), \quad (22)$$

leads us to the following lower-bound on the remainder of the first-order Taylor expansion of the ISO

$$\begin{aligned} \delta \mathcal{S}_n(\Delta_u, \theta^*) &\geq \frac{e^{-\beta d}}{2 + \|\Delta_u\|_1} \frac{1}{n} \sum_{k=1}^n \left(\sum_{i \in V \setminus u} \Delta_{ui} \sigma_u^{(k)} \sigma_i^{(k)} \right)^2 \\ &= \frac{e^{-\beta d}}{2 + \|\Delta_u\|_1} \Delta_u^\top H^n \Delta_u, \end{aligned} \quad (23)$$

where in the last line we used the trivial identity $\sigma_u^{(k)} \cdot \sigma_u^{(k)} = 1$. \square

Lemma 6. *Consider an Ising model with p spins, with maximum degree d and maximum coupling intensity β . Let $\delta > 0$, $\epsilon_4 > 0$ and $n \geq \frac{2}{\delta^2} \ln \frac{p^2}{\epsilon_4}$. Then with probability greater than $1 - \epsilon_4$, we have for all $i, j \in V \setminus u$*

$$|H_{ij}^n - H_{ij}| \leq \delta, \quad (24)$$

where the matrix H is the covariance matrix with elements $i, j \in V \setminus u$

$$H_{ij} = \mathbb{E}[\sigma_i \sigma_j]. \quad (25)$$

Proof. We recall that the matrix elements of the empirical covariance matrix read

$$H_{ij}^n = \frac{1}{n} \sum_{k=1}^n \sigma_i^{(k)} \sigma_j^{(k)}. \quad (26)$$

Since $|\sigma_i^{(k)} \sigma_j^{(k)}| \leq 1$ using Hoeffding's inequality, we have

$$\mathbb{P}[|H_{ij}^n - H_{ij}| \geq \delta] \leq 2 \exp\left(-\frac{n\delta^2}{2}\right). \quad (27)$$

As H_{ij}^n is symmetric we use the union bound over the elements $i < j \in V \setminus u$ to get

$$\mathbb{P}[|H_{ij}^n - H_{ij}| \geq \delta \quad \forall i, j \in V \setminus u] \leq 1 - p^2 \exp\left(-\frac{n\delta^2}{2}\right). \quad (28)$$

\square

Lemma 7. *Consider an Ising model with p spins, with maximum degree d and maximum coupling intensity β . For all $\Delta_u \in \mathbb{R}^{p-1}$ the following bound holds*

$$\Delta_u^\top H \Delta_u \geq \frac{e^{-2\beta d}}{d+1} \|\Delta_u\|_2^2. \quad (29)$$

Proof. Our proof strategy here follows [1, Cor. 3.1]. Notice that the probability measure of the Ising model is symmetric with respect to the sign flip, i.e. $\mu(\sigma_1, \dots, \sigma_p) = \mu(-\sigma_1, \dots, -\sigma_p)$. Thus any spin has zero mean, which implies that for every $\Delta_u \in \mathbb{R}^{p-1}$

$$\mathbb{E}\left[\left(\sum_{i \in V \setminus u} \Delta_{ui} \sigma_i\right)\right] = 0. \quad (30)$$

This allows to reinterpret the left-hand side of Eq. (29) as a variance, using that $\sigma_u^2 = 1$,

$$\begin{aligned} \Delta_u^\top H \Delta_u &= \sum_{i, j \in V \setminus u} \Delta_{ui} \mathbb{E}[\sigma_i \sigma_j] \Delta_{uj} \\ &= \mathbb{E}\left[\left(\sum_{i \in V \setminus u} \Delta_{ui} \sigma_i\right)^2\right] \\ &= \text{Var}\left[\sum_{i \in V \setminus u} \Delta_{ui} \sigma_i\right]. \end{aligned} \quad (31)$$

Construct a subset $A \subset V$ recursively as follows: (i) let $i_0 = \operatorname{argmax}_{j \in V \setminus u} \Delta_{uj}^2$ and define $A_0 = \{i_0\}$, (ii) given $A_t = \{i_0, \dots, i_t\}$, let $B_t = \{j \in V \setminus A_t \mid \partial j \cap A_t = \emptyset\}$ and $i_{t+1} = \operatorname{argmax}_{j \in B_t \setminus u} \Delta_{uj}^2$ and set $A_{t+1} = A_t \cup \{i_{t+1}\}$, (iii) terminate when $B_t \setminus u = \emptyset$ and declare $A = A_t$.

The set A possesses the following two main properties. First, every node $i \in A$ does not have any neighbors in A and, second,

$$(d+1) \sum_{i \in A} \Delta_{ui}^2 \geq \sum_{i \in V \setminus u} \Delta_{ui}^2. \quad (32)$$

We apply the law of total variance to (31) by conditioning on the set of spins $\underline{\sigma}_{A^c}$ with indexes belonging to the complementary set A^c ,

$$\begin{aligned} \operatorname{Var} \left[\sum_{i \in V \setminus u} \Delta_{ui} \sigma_i \right] &\geq \mathbb{E} \left[\operatorname{Var} \left[\sum_{i \in V \setminus u} \Delta_{ui} \sigma_i \mid \underline{\sigma}_{A^c} \right] \right] \\ &= \sum_{i \in A} \Delta_{ui}^2 \mathbb{E} [\operatorname{Var} [\sigma_i \mid \underline{\sigma}_{A^c}]], \end{aligned} \quad (33)$$

where in the last line one uses that the spins in A are conditionally independent given their neighbors $\underline{\sigma}_{A^c}$. One concludes the proof by using relation (32) and the fact that the conditional variance of a spin given its neighbors is bounded from below:

$$\begin{aligned} \operatorname{Var} [\sigma_i \mid \underline{\sigma}_{A^c}] &= 1 - \tanh^2 \left(\sum_{j \in \partial i} \theta_{ij}^* \sigma_j \right) \\ &\geq \exp(-2\beta d). \end{aligned} \quad (34)$$

□

Lemma 8. Consider an Ising model with p spins, with maximum degree d and maximum coupling intensity β . For all $\epsilon_4 > 0$ and $R > 0$, when $n \geq 2^{11} d^2 (d+1)^2 e^{4\beta d} \ln \frac{p^2}{\epsilon_4}$ the ISO satisfies, with probability at least $1 - \epsilon_4$, the restricted strong convexity condition

$$\delta \mathcal{S}_n(\Delta_u, \theta_u^*) \geq \frac{e^{-3\beta d}}{4(d+1)(1+2\sqrt{d}R)} \|\Delta_u\|_2^2, \quad (35)$$

for all $\Delta_u \in \mathbb{R}^{p-1}$ such that $\|\Delta_u\|_1 \leq 4\sqrt{d} \|\Delta_u\|_2$ and $\|\Delta_u\|_2 \leq R$.

Proof. First we apply Lemma 5 to get the quadratic bound

$$\begin{aligned} \delta \mathcal{S}_n(\Delta_u, \theta^*) &\geq \frac{e^{-\beta d}}{2 + \|\Delta_u\|_1} \Delta_u^\top H^n \Delta_u \\ &\geq \frac{e^{-\beta d}}{2(1+2\sqrt{d}R)} \Delta_u^\top H^n \Delta_u. \end{aligned} \quad (36)$$

Second we use Lemma 7 to bound the quadratic form

$$\begin{aligned} \Delta_u^\top H^n \Delta_u &= \Delta_u^\top H \Delta_u + \Delta_u^\top (H^n - H) \Delta_u \\ &\geq \frac{e^{-2\beta d}}{d+1} \|\Delta_u\|_2^2 + \Delta_u^\top (H^n - H) \Delta_u. \end{aligned} \quad (37)$$

Third we conclude with Lemma 6, controlling randomness independently of Δ_u . Choosing $\delta = \frac{e^{-2\beta d}}{32d(d+1)}$, we get with probability at least $1 - \epsilon_4$ that

$$\begin{aligned} \Delta_u^\top (H^n - H) \Delta_u &\geq -\frac{e^{-2\beta d}}{32d(d+1)} \|\Delta_u\|_1^2 \\ &\geq -\frac{e^{-2\beta d}}{2(d+1)} \|\Delta_u\|_2^2, \end{aligned} \quad (38)$$

whenever $n \geq \frac{2}{\delta^2} \ln \frac{p^2}{\epsilon_4} = 2^{11} d^2 (d+1)^2 e^{4\beta d} \ln \frac{p^2}{\epsilon_4}$. □

References

- [1] A. Montanari, “Computational implications of reducing data to sufficient statistics,” *Electron. J. Statist.*, vol. 9, no. 2, pp. 2370–2390, 2015.