

# Robust and Effective Factorization Machine

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## Abstract

Factorization Machine (FM) (Rendle 2010; 2012) is a generic framework which involves a weight matrix  $\mathbf{Z} \in \mathbb{R}^{d \times d}$  in the formulation to take into account the pairwise interactions between features. Due to its capability of efficiently modeling complex non-linear data, FM has achieved great success in various of classification and regression tasks. The key advantage of FM is that it learns the low-rank feature interaction matrix in a factorized form,  $\mathbf{Z} = \mathbf{V}\mathbf{V}^\top$ , where  $\mathbf{V} \in \mathbb{R}^{d \times k}$  and  $k \ll d$ . This could avoid overfitting, learn correlation among samples and allow to compute prediction efficiently. Although the factorized interaction allow us to reduce computation cost from  $O(d^2)$  to  $O(kd)$  and the computation of gradients is also easier, it can only find local optima because of its non-convex formulation. Moreover, the predictive accuracy of FM is sensitive to the rank parameter  $k$ , since a small deviation of  $k$  from optimal value may have enormous effect on the performance. But it is often difficult to choose or tune the best  $k$  from large range.

## Introduction

Factorization Machine (FM) (Rendle 2010; 2012) is a generic framework which involves a weight matrix  $\mathbf{Z} \in \mathbb{R}^{d \times d}$  in the formulation to take into account the pairwise interactions between features. Due to its capability of efficiently modeling complex non-linear data, FM has achieved great success in various of classification and regression tasks. The key advantage of FM is that it learns the low-rank feature interaction matrix in a factorized form,  $\mathbf{Z} = \mathbf{V}\mathbf{V}^\top$ , where  $\mathbf{V} \in \mathbb{R}^{d \times k}$  and  $k \ll d$ . This could avoid overfitting, learn correlation among samples and allow to compute prediction efficiently. Although the factorized interaction allow us to reduce computation cost from  $O(d^2)$  to  $O(kd)$  and the computation of gradients is also easier, it can only find local optima because of its non-convex formulation. Moreover, the predictive accuracy of FM is sensitive to the rank parameter  $k$ , since a small deviation of  $k$  from optimal value may have enormous effect on the performance. But it is often difficult to choose or tune the best  $k$  from large range.

To solve this problem, some authors (Blondel, Fujino, and Ueda 2015; Yamada et al. 2015) proposed convex variants of the original FM by relaxing the low-rank structure

of feature interaction matrix  $\mathbf{Z}$  with trace norm regularization  $\|\mathbf{Z}\|_*$ , which is defined as the sum of all singular values of  $\mathbf{Z}$ . Following the recent work about large scale optimization with trace norm constraint (Shalev-shwartz, Gonen, and Shamir 2011), Blondel et al. presented an efficient greedy coordinate descent algorithm which enjoys global convergence. Yamada et al. formulated the objective as a semidefinite programming problem and derived an efficient optimization procedure with Hazan’s algorithm (Hazan 2008).

Unfortunately, although the trace norm is capable of including low-rank and sparse structures (Tao and Yuan 2011) and learning potential correlations from sample, such convex formulation is based on a strong assumption which may not hold in real-world applications and the approximation error between rank minimization and trace norm constraint often can not be neglected (Sun, Xiang, and Ye 2013). For example, with the change of non-zero singular value, the trace norm value will change together but the rank value will remain the same.

Like most supervised learning methods, existing FM method train model with large amounts of labeled data, where outliers will be included unavoidably. These incorrectly labeled data is significantly different from normal data and could mislead the model training task, such that the learned model are not optimal and the prediction performance is reduced. Hence it is necessary to learn FM model resistant to outliers.

To address these challenging problems, we propose a novel robust and effective Factorization Machine model and derive an effective optimization algorithm with rigorous theoretical guarantees. To make FM model immune to the threat of outliers, we replace the hinge loss or squared loss in existing FM model with capped  $\ell_1$  norm based loss function  $\ell_{\epsilon_1} = \min\{|u|, \epsilon_1\}$ , where  $\epsilon_1$  is a threshold value. It is obvious that this loss make FM model robust to light and heavy outliers since it could eliminate outliers which often have large residual. To narrow the gap between rank minimization and trace norm, we develop a novel capped squared trace norm as low-rank regularization. It is defined as  $R_{\epsilon_2}(\mathbf{Z}) = \sum_s \min\{\lambda_s^2, \epsilon_2\}$  where  $\epsilon_2$  is a threshold value and  $\lambda_s$  is the eigenvalues of interaction matrix  $\mathbf{Z}$ . In this term, we can approximate the rank function by  $\text{rank}(\mathbf{Z}) \approx \sum_s \min\{1, \frac{\lambda_s^2}{\epsilon_2}\}$ . Noted that if all the squared singular values of  $\mathbf{Z}$  are greater than  $\epsilon_2$ , then the approxima-

tion will become equality which leads to a better approximation compared with traditional trace norm. Moreover, the capped squared trace norm penalizes the squared singular values that are less than  $\epsilon_2$ , which weakens the effect of non-relevant feature interaction, such that the FM model is more robust and stable in real world applications. The novel loss function  $\ell_{\epsilon_1}$  and regularization  $R_{\epsilon_2}(\mathbf{Z})$  involves the non-convexity and non-smoothness of the objective, which make it challenging to optimize. To tackle this issue, we introduce new efficient two-stage algorithm with rigorously proved local optimum convergence. Extensive experiments on both toy data and benchmark datasets show our proposed new robust FM models correctness and effectiveness.

## Problem Formulation

Factorization Machine (FM) is an increasingly popular method for efficiently utilize second-order feature interaction in classification or regression task. The prediction equation of a standard 2-order FMs mode is:

$$\hat{y}(\mathbf{x}|\mathbf{w}, \mathbf{V}) = \mathbf{w}^\top \mathbf{x} + \sum_{j=1}^d \sum_{j'=j+1}^d (\mathbf{V}\mathbf{V}^\top)_{jj'} x_j x_{j'},$$

where  $d$  is the dimensionality of feature vector  $\mathbf{x} \in \mathbb{R}^d$ ,  $k \ll p$  is a hyper-parameter that denotes the dimensionality of latent factors and  $\mathbf{V} \in \mathbb{R}^{d \times k}$ ,  $\mathbf{w} \in \mathbb{R}^d$  are the model parameters to be estimated. Here we consider a generalized prediction function:

$$\hat{y}(\mathbf{x}|\mathbf{w}, \mathbf{Z}) = \mathbf{w}^\top \mathbf{x} + \sum_{j=1}^d \sum_{j'=1}^d z_{jj'} x_j x_{j'} = \mathbf{w}^\top \mathbf{x} + \langle \mathbf{Z}, \mathbf{x}\mathbf{x}^\top \rangle,$$

where  $z_{jj'}$  is the elements of the low-rank symmetric positive semi-definite matrix  $\mathbf{Z} \in \mathbb{S}^{d \times d}$ , i.e.,  $\text{rank}(\mathbf{Z}) \ll d$ . Given a training set  $[\mathbf{x}_1, \dots, \mathbf{x}_n]^\top \in \mathbb{R}^{n \times d}$  and corresponding targets  $p[y_1, \dots, y_n]^\top \in \mathbb{R}^n$ , model parameters can be learned by using the principle of empirical risk minimization and solving the following non-convex problem:

$$\min_{\mathbf{w} \in \mathbb{R}^d, \mathbf{Z} \in \mathbb{S}_+^{d \times d}} \sum_{i=1}^n \ell(y_i, \hat{y}(\mathbf{x}_i|\mathbf{w}, \mathbf{Z})) + \frac{\alpha}{2} R(\mathbf{w}) + \frac{\beta}{2} R(\mathbf{Z}),$$

where  $R(\mathbf{w}), R(\mathbf{Z})$  are the regularization terms and  $\ell$  is a loss function incurred.

In the existing FM model, it usually apply  $\ell_2$ -norm loss for regression task,  $\ell_2$ -norm regularization for linear term and Frobenius norm regularization for quadratic term. To endow FM model with robustness capability, a natural way is to use  $\ell_1$ -norm loss function instead. However, if the extreme odd points incur very large residuals, they will still have significantly negative effects on the performance of FM model. To further better the performance of FM model, we propose to adopt the capped  $\ell_1$ -norm loss function  $\ell_{\epsilon_1}$  (Zhang 2009; Gao et al. 2015; Jiang, Nie, and Huang 2015) which was successfully used to approximate the  $\ell_0$  norm. The FM model with capped  $\ell_1$ -norm loss could be expressed as:

$$\ell_{\text{capped}}^{FM}(y_i, \hat{y}(\mathbf{x}_i|\mathbf{w}, \mathbf{Z})) = \min\{|y_i - \mathbf{w}^\top \mathbf{x}_i - \langle \mathbf{Z}, \mathbf{x}_i \mathbf{x}_i^\top \rangle|, \epsilon_1\}. \quad (1)$$

In this term, if the residual of a sample is larger than  $\epsilon_1$ , we consider this sample as extreme outlier and its residual is also capped as  $\epsilon_1$  such that its effect to the whole FM model is fixed. For other normal samples with smaller residual than

$\epsilon_1$  our objective will minimize  $|y_i - \mathbf{w}^\top \mathbf{x}_i - \langle \mathbf{Z}, \mathbf{x}_i \mathbf{x}_i^\top \rangle|$ , which is the standard  $\ell_1$ -norm loss and robust to outliers. Therefore, the proposed capped  $\ell_1$ -norm is a more robust loss function than traditional  $\ell_2$ -norm loss in FM model.

Recently, trace norm regularization has been utilized as the convex relaxation of the rank minimization so as to approximate the low-rank structure of feature interaction matrix in FM model (Blondel, Fujino, and Ueda 2015; Yamada et al. 2015). However, as we mention before, if the non-zero singular values of matrix  $\mathbf{Z}$  changes, the trace norm of  $\mathbf{Z}$  will change simultaneously, but the rank of  $\mathbf{Z}$  stays the same. Thus, there is still a gap between trace norm and rank minimization. To make much tighter approximation and more robust model, we propose a novel capped squared trace norm to uncover the low rank structure of feature interaction matrix  $\mathbf{Z}$ , which is defined as:

$$R(\mathbf{Z}) = \sum_s \min\{\lambda_s^2, \epsilon_2\}, \quad (2)$$

where  $\lambda_s$  is the eigenvalue of matrix  $\mathbf{Z}$  and  $\epsilon_2$  is a threshold value. We can approximate the rank function by  $\text{rank}(\mathbf{Z}) \approx \sum_s \min\{1, \frac{\lambda_s^2}{\epsilon_2}\}$ . The smaller  $\epsilon_2$ , the more accurate the approximation would be. Thus, by carefully choosing  $\epsilon_2$ , we can recovery matrix  $\mathbf{Z}$  more accurately than the trace norm.

Variational trace norms have been developed for better approximating the rank minimization in recent years. The authors in (Law, Thome, and Cord 2014; Huo et al. 2017) considered to minimize the  $k$ -smallest singular values. Although it can avoid the effect of large singular values and achieve a better approximation, this method suffers from the tedious best rank parameter selection process in the same way as the traditional trace norm. The authors in (Sun, Xiang, and Ye 2013; Huo, Nie, and Huang 2016) proposed to minimize the sum of singular values which are smaller than a threshold value. However, minimizing the sum of capped singular values would lead to a sparse solution, that is, some small singular value will become zero while others may get large values. Our novel capped squared trace norm could solve the above problems, since it avoids the cumbersome rank parameter selection process and minimizes the sum of capped squared singular values whose solution will be shrunk near to zero.

With the aforementioned capped norms, we propose to solve the following non-convex and non-smooth formulation:

$$\min_{\mathbf{w} \in \mathbb{R}^d, \mathbf{Z} \in \mathbb{S}_+^{d \times d}} \sum_{i=1}^n \min\{|y_i - \mathbf{w}^\top \mathbf{x}_i - \langle \mathbf{Z}, \mathbf{x}_i \mathbf{x}_i^\top \rangle|, \epsilon_1\} + \frac{\alpha}{2} \|\mathbf{w}\| + \sum_s \min\{\lambda_s^2, \epsilon_2\}, \quad (3)$$

where we use  $\ell_2$ -norm regularization for linear term to avoid overfitting. Clearly, the new objective function in problem (3) is not convex and not smooth due to the term (1) and term(2), which is difficult to solve. In next section, we will propose an efficient optimization algorithm to solve it.

## Optimization Algorithm

From the capped  $\ell_1$  loss in (1), we can observe that if  $\epsilon_1$  is set as  $\infty$  this loss is equivalent to the  $\ell_1$  loss. According to the multi-stage convex relaxation techniques (Zhang 2009;

2010; Nie et al. 2010; Nie, Yuan, and Huang 2014) and alternating minimization optimization procedure, we could transform the original objective to the following formulation:

$$\min_{\mathbf{w} \in \mathbb{R}^d, \mathbf{Z} \in \mathbb{S}_+^{d \times d}} \sum_{i=1}^n d_i (y_i - \mathbf{w}^\top \mathbf{x}_i - \langle \mathbf{Z}, \mathbf{x}_i \mathbf{x}_i^\top \rangle)^2 + \frac{\alpha}{2} \|\mathbf{w}\| + \sum_s \min\{\lambda_s^2, \epsilon_2\}, \quad (4)$$

$$d_i = \begin{cases} \frac{1}{\|y_i - \mathbf{w}^\top \mathbf{x}_i - \langle \mathbf{Z}, \mathbf{x}_i \mathbf{x}_i^\top \rangle\|_2}, & |y_i - \mathbf{w}^\top \mathbf{x}_i - \langle \mathbf{Z}, \mathbf{x}_i \mathbf{x}_i^\top \rangle| \leq \epsilon_1; \\ 0, & \text{otherwise,} \end{cases}$$

which can be solved via the iterative re-weighted optimization strategy. From the formulation (4), we can observe that it is similar with  $\ell_2$  loss in original FM model except the weights  $d_i$  for each sample. From the updating rule of weights  $d_i$ , we can find that the samples with lower residuals have higher weights, which is consistent with robustness of FM model. The subproblem (4) is similar with optimization problem of original FM model. We adopt the same strategy by using a two-block coordinate descent algorithm. That is, we alternate between minimizing with respect to  $\mathbf{w}$  and  $\mathbf{Z}$  until convergence. When the algorithm terminates, it returns  $\mathbf{w}$  and  $\mathbf{Z}$ . In the next section, we will prove that our objective function will converge.

With feature interaction matrix  $\mathbf{Z}$  fixed, we need to optimize

$$\min_{\mathbf{w} \in \mathbb{R}^d} \sum_{i=1}^n d_i (y_i - \mathbf{w}^\top \mathbf{x}_i - \langle \mathbf{Z}, \mathbf{x}_i \mathbf{x}_i^\top \rangle)^2 + \frac{\alpha}{2} \|\mathbf{w}\|_2^2, \quad (5)$$

which is a standard linear model objective except the constant bias term incurred by  $\mathbf{Z}$ . Therefore, we can solve objective (5) by standard methods, like gradient descent (Rendle 2010).

With linear term parameter  $\mathbf{x}$  fixed, we can reformulate the objective (4) as the following optimization problem:

$$\min_{\mathbf{Z} \in \mathbb{S}_+^{d \times d}} \sum_{i=1}^n d_i (y_i - \mathbf{w}^\top \mathbf{x}_i - \langle \mathbf{Z}, \mathbf{x}_i \mathbf{x}_i^\top \rangle)^2 + \frac{\beta}{2} \sum_s \min\{\lambda_s^2, \epsilon_2\}, \quad (6)$$

However, the capped trace norm is non-convex and non-smooth which make it difficult for direct optimization. Similarly, We follow the same multi-stage convex relaxation techniques strategy, and convert this objective (6) to a sub-problem.

Specifically, define an eigendecomposition of symmetric positive semi-definite matrix  $\mathbf{Z}$  as  $\mathbf{Z} = \mathbf{P}\mathbf{\Sigma}\mathbf{P}^\top = \sum_s \lambda_s \mathbf{p}_s \mathbf{p}_s^\top$ , where  $\mathbf{P}$  is an orthogonal matrix with columns  $\mathbf{p}_s \in \mathbb{R}^d$  and  $\mathbf{\Sigma} = \text{diag}(\boldsymbol{\lambda})$  is diagonal singular matrix with eigenvalues  $\lambda_s$  in ascending order. Denote the set of index whose singular value is smaller than  $\epsilon_2$  as  $M = \{s | \lambda_s \leq \epsilon_2\}$ , and their corresponding eigenvectors as  $\mathbf{P}_M$ . It is easy to have  $\text{Tr}(\mathbf{P}_M^\top \mathbf{Z} \mathbf{Z}^\top \mathbf{P}_M) = \sum_{s \in M} \lambda_s^2$ . The sub-problem of the objective (6) is formulated as:

$$\min_{\mathbf{Z} \in \mathbb{S}_+^{d \times d}} \sum_{i=1}^n d_i (y_i - \mathbf{w}^\top \mathbf{x}_i - \langle \mathbf{Z}, \mathbf{x}_i \mathbf{x}_i^\top \rangle)^2 + \frac{\beta}{2} \sum_s \text{Tr}(\mathbf{P}_M^\top \mathbf{Z} \mathbf{Z}^\top \mathbf{P}_M). \quad (7)$$

With matrix parameter  $\mathbf{P}_M$  fixed, this sub-problem is convex. We could use proximal gradient to optimize it iteratively. At each round, the subgradient with respect to  $\mathbf{Z}$  is:

$$\nabla_{\mathbf{Z}} = - \sum_{i=1}^n d_i (y_i - \mathbf{w}^\top \mathbf{x}_i - \langle \mathbf{Z}, \mathbf{x}_i \mathbf{x}_i^\top \rangle) \mathbf{x}_i \mathbf{x}_i^\top + \beta \mathbf{P}_M \mathbf{P}_M^\top \mathbf{Z}. \quad (8)$$

After each step,  $\mathbf{Z}$  is projected onto the positive semidefinite cone with  $\mathbf{Z} = \Pi_{\mathbb{S}_+^{d \times d}}(\mathbf{Z} - \eta \nabla_{\mathbf{Z}})$ . We find that we only need to compute  $\mathbf{P}_M \mathbf{P}_M^\top$  instead of  $\mathbf{P}_M$  and  $\mathbf{P}_M^\top$ . Suppose  $\mathbf{P} = [\mathbf{P}_M, \mathbf{P}_{\bar{M}}]$ , where  $\bar{M} = \{s | \lambda_s > \epsilon_2\}$  and  $\mathbf{P}_{\bar{M}}$  are singular values whose corresponding singular vector larger than  $\epsilon_2$ . It is easy to see that  $\mathbf{P}_M \mathbf{P}_M^\top = \mathbf{I} - \mathbf{P}_{\bar{M}} \mathbf{P}_{\bar{M}}^\top$ . Since  $\mathbf{Z}$  is a low-rank matrix, if we set  $\epsilon_2$  appropriately, the set  $\bar{M}$  could be quite small. Thus it could be much more efficient to compute  $\mathbf{P}_M \mathbf{P}_M^\top$  with truncated SVD algorithm than compute  $\mathbf{P}_M$  and  $\mathbf{P}_M^\top$  independently. Our optimization algorithm is summarized in 1.

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**Algorithm 1** Optimization Algorithm for Robust and Effective Factorization Machine Model

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**Input:** Training data  $\{(x_n, y_n)\}_{n=1}^N$ , parameters  $\alpha, \beta, \epsilon_1, \epsilon_2$   
**Initialization:**  $d_i = 1$  for  $i = 1, 2, \dots, n$   
**while** not converge **do**  
    Update  $\mathbf{w}$  according to (5)  
    Update  $\mathbf{Z}$  and  $\mathbf{P}_M \mathbf{P}_M^\top$  according to (7)  
    Compute  $d_i = 1$  for  $i = 1, 2, \dots, n$  according to (4)  
**end while**  
**Output:** model parameter  $\mathbf{w}, \mathbf{Z}$

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## Computational complexity

### Convergence Analysis

**Lemma 1.** According to (Theobald 1975), any two hermitian matrices  $\mathbf{A}, \mathbf{B} \in \mathbb{R}^{n \times n}$  satisfy the inequality  $(\lambda_i(\mathbf{A}), \lambda_i(\mathbf{B}))$  are singular values sorted in the same order

$$\sum_{i=1}^n \lambda_i(\mathbf{A}) \lambda_{n-i+1}(\mathbf{B}) \leq \text{Tr}(\mathbf{A}^\top \mathbf{B}) \leq \sum_{i=1}^n \lambda_i(\mathbf{A}) \lambda_i(\mathbf{B})$$

**Lemma 2.** Let  $\mathbf{Z} = \mathbf{P}\mathbf{\Sigma}\mathbf{P}^\top$ ,  $\mathbf{\Sigma} = \text{diag}(\boldsymbol{\lambda})$  is diagonal singular matrix with eigenvalues  $\lambda_s$  and  $M = \{s | \lambda_s \leq \epsilon_2\}$  is the set of index whose singular value is smaller than  $\epsilon_2$  in ascending order.  $\hat{\mathbf{Z}} = \hat{\mathbf{P}}\hat{\mathbf{\Sigma}}\hat{\mathbf{P}}^\top$  is the updated matrix after  $\mathbf{Z}$ ,  $\hat{\mathbf{\Sigma}} = \text{diag}(\hat{\boldsymbol{\lambda}})$  is diagonal singular matrix with eigenvalues  $\hat{\lambda}_s$  and  $\hat{M} = \{s | \hat{\lambda}_s \leq \epsilon_2\}$  is the set of index whose singular value is smaller than  $\epsilon_2$  in ascending order. Then we have

$$\begin{aligned} & \sum_s \min\{\hat{\lambda}_s^2, \epsilon_2\} - \text{Tr}(\mathbf{P}_M^\top \hat{\mathbf{Z}} \hat{\mathbf{Z}}^\top \mathbf{P}_M) \\ & \leq \sum_s \min\{\lambda_s^2, \epsilon_2\} - \text{Tr}(\mathbf{P}_M^\top \mathbf{Z} \mathbf{Z}^\top \mathbf{P}_M) \end{aligned} \quad (9)$$

*Proof.* According to the definition of  $\mathbf{P}_M \mathbf{Z}$ , it is apparent that  $\text{Tr}(\mathbf{P}_M^\top \mathbf{Z} \mathbf{Z}^\top \mathbf{P}_M) = \text{Tr}(\mathbf{P}_M \mathbf{P}_M^\top \mathbf{P} \mathbf{\Sigma}^2 \mathbf{P}^\top) = \sum_{s \in M} \lambda_s^2$ . The RHS of inequality (9) is equivalent to

$$\sum_{s \in M} \lambda_s^2 + \sum_{s \notin M} \epsilon_2 - \sum_{s \in M} \lambda_s^2 = \sum_{s \notin M} \epsilon_2. \quad (10)$$

Similarly, with the definition of  $\hat{P}$ ,  $\hat{M}$  and Lemma 1, we know that  $Tr(\mathbf{P}_M^\top \hat{\mathbf{Z}} \hat{\mathbf{Z}}^\top \mathbf{P}_M) = Tr(\mathbf{P}_M \mathbf{P}_M^\top \hat{\mathbf{P}} \hat{\Sigma}^2 \hat{\mathbf{P}}^\top) \geq \sum_{s \in M} \hat{\lambda}_s^2$ . Since  $\hat{M}$  denotes the total eigenvalues of  $\hat{\mathbf{Z}}$  that are smaller than  $\epsilon_2$ , no matter how the index set  $\hat{M}$  varies from  $M$ , we could obtain that  $\sum_{s \in \hat{M}} \hat{\lambda}_s^2 + \sum_{s \notin \hat{M}} \epsilon_2 \leq \sum_{s \in M} \hat{\lambda}_s^2 + \sum_{s \notin M} \epsilon_2$ . Therefore, from the LHS of inequality (9), we have

$$\begin{aligned} & \sum_{s \in \hat{M}} \hat{\lambda}_s^2 + \sum_{s \notin \hat{M}} \epsilon_2 - Tr(\mathbf{P}_M^\top \hat{\mathbf{Z}} \hat{\mathbf{Z}}^\top \mathbf{P}_M) \\ & \leq \sum_{s \in M} \hat{\lambda}_s^2 + \sum_{s \notin M} \epsilon_2 - \sum_{s \in M} \hat{\lambda}_s^2 = \sum_{s \notin M} \epsilon_2 \end{aligned} \quad (11)$$

Combining inequality (10) and (11) completes the proof.  $\square$

## Experimental Results

### References

- Blondel, M.; Fujino, A.; and Ueda, N. 2015. Convex factorization machines. In *Joint European Conference on Machine Learning and Knowledge Discovery in Databases*, 19–35. Springer.
- Gao, H.; Nie, F.; Cai, W.; and Huang, H. 2015. Robust capped norm nonnegative matrix factorization: Capped norm nmf. In *Proceedings of the 24th ACM International Conference on Information and Knowledge Management*, 871–880. ACM.
- Hazan, E. 2008. Sparse approximate solutions to semidefinite programs. In *Latin American Symposium on Theoretical Informatics*, 306–316. Springer.
- Huo, Z.; Gao, S.; Cai, W.; and Huang, H. 2017. Video recovery via learning variation and consistency of images. In *AAAI*, 4082–4088.
- Huo, Z.; Nie, F.; and Huang, H. 2016. Robust and effective metric learning using capped trace norm: Metric learning via capped trace norm. In *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, 1605–1614. ACM.
- Jiang, W.; Nie, F.; and Huang, H. 2015. Robust dictionary learning with capped l1-norm. In *IJCAI*, 3590–3596.
- Law, M. T.; Thome, N.; and Cord, M. 2014. Fantope regularization in metric learning. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, 1051–1058.
- Nie, F.; Huang, H.; Cai, X.; and Ding, C. H. 2010. Efficient and robust feature selection via joint 2, 1-norms minimization. In *Advances in neural information processing systems*, 1813–1821.
- Nie, F.; Yuan, J.; and Huang, H. 2014. Optimal mean robust principal component analysis. In *Proceedings of the 31st international conference on machine learning (ICML-14)*, 1062–1070.
- Rendle, S. 2010. Factorization machines. *Proceedings - IEEE International Conference on Data Mining, ICDM* 995–1000.
- Rendle, S. 2012. Factorization machines with libfm. *ACM Transactions on Intelligent Systems and Technology (TIST)* 3(3):57.
- Shalev-shwartz, S.; Gonen, A.; and Shamir, O. 2011. Large-scale convex minimization with a low-rank constraint. In *Proceedings of the 28th International Conference on Machine Learning (ICML-11)*, 329–336.
- Sun, Q.; Xiang, S.; and Ye, J. 2013. Robust principal component analysis via capped norms. In *Proceedings of the 19th ACM SIGKDD international conference on Knowledge discovery and data mining*, 311–319. ACM.
- Tao, M., and Yuan, X. 2011. Recovering low-rank and sparse components of matrices from incomplete and noisy observations. *SIAM Journal on Optimization* 21(1):57–81.
- Theobald, C. 1975. An inequality for the trace of the product of two symmetric matrices. In *Mathematical Proceedings of the Cambridge Philosophical Society*, volume 77, 265–267. Cambridge Univ Press.
- Yamada, M.; Lian, W.; Goyal, A.; Chen, J.; Wimalawarne, K.; Khan, S. A.; Kaski, S.; Mamitsuka, H.; and Chang, Y. 2015. Convex factorization machine for regression. *arXiv preprint arXiv:1507.01073*.
- Zhang, T. 2009. Multi-stage convex relaxation for learning with sparse regularization. In *Advances in Neural Information Processing Systems*, 1929–1936.
- Zhang, T. 2010. Analysis of multi-stage convex relaxation for sparse regularization. *Journal of Machine Learning Research* 11(Mar):1081–1107.