Abstract

Sparse coding is a crucial subroutine in algorithms for various signal processing, deep learning, and other machine learning applications. The central goal is to learn an overcomplete dictionary that can sparsely represent a given input dataset. However, a key challenge is that storage, transmission, and processing of the learned dictionary can be untenably high if the data dimension is high. In this paper, we consider the double-sparsity model introduced by Rubinstein et al. (2010b) where the dictionary itself is the product of a fixed, known basis and a data-adaptive sparse component. First, we introduce a simple algorithm for double-sparse coding that can be amenable to efficient implementation via neural architectures. Second, we theoretically analyze its performance and demonstrate asymptotic sample complexity and running time benefits over existing (provable) approaches for sparse coding. To our knowledge, our work introduces the first computationally efficient algorithm for double-sparse coding that enjoys rigorous statistical guarantees. Finally, we support our analysis via several numerical experiments on simulated data, confirming that our method can indeed be useful in problem sizes encountered in practical applications.

Keywords: Sparse coding, provable algorithms, unsupervised learning

1. Introduction

1.1 Motivation

Representing signals as sparse linear combinations of atoms from a dictionary is a popular approach in many domains. In this paper, we study the problem of dictionary learning (also known as sparse coding), where the goal is to learn an efficient basis (dictionary) that represents the underlying class of signals well. In the typical sparse coding setup, the dictionary is overcomplete (i.e., the cardinality of the dictionary exceeds the ambient signal dimension) while the representation is sparse (i.e., each signal is encoded by a combination of only very few dictionary atoms.)

Sparse coding has a rich history in diverse fields such as signal processing, machine learning, and computational neuroscience. Discovering optimal basis representations of data is a central focus of image analysis (Krim et al., 1999; Elad and Aharon, 2006; Rubinstein et al., 2010a), and dictionary learning has proven widely successful in imaging problems such as denoising, deconvolution, inpaint-
Sparse coding approaches have also been used as a core building block of deep learning systems for prediction (Gregor and LeCun, 2010; Boureau et al., 2010) and associative memory (Mazumdar and Rawat, 2017). Interestingly, the seminal work by Olshausen and Field (1997) has shown intimate connections between sparse coding and neuroscience: the dictionaries learned from image patches of natural scenes bear strikingly resemblance to spatial receptive fields observed in mammalian primary visual cortex.

From a mathematical standpoint, the sparse coding problem is formulated as follows. Given \( p \) data samples \( Y = [y^{(1)}, y^{(2)}, \ldots, y^{(p)}] \in \mathbb{R}^{n \times p} \), the goal is to find a dictionary \( D \in \mathbb{R}^{n \times m} \) \((m > n)\) and corresponding sparse code vectors \( X = [x^{(1)}, x^{(2)}, \ldots, x^{(p)}] \in \mathbb{R}^{m \times p} \) such that the representation \( DX \) fits the data samples as well as possible. Typically, one obtains the dictionary and the code vectors as the solution to the following optimization problem:

\[
\min_{D,X} L(D, X) = \frac{1}{2} \sum_{j=1}^{p} \|y^{(j)} - Dx^{(j)}\|_2^2,
\]

s.t. \( \sum_{j=1}^{p} S(x^{(j)}) \leq S \)

where \( S(\cdot) \) is some sparsity-inducing penalty function on the code vectors, such as the \( \ell_1 \)-norm. The objective function \( L \) controls the reconstruction error while the constraint enforces the sparsity of the representation.

However, even a cursory attempt at solving the optimization problem (1) reveals the following obstacles:

1. **Theoretical challenges.** The constrained optimization problem (1) involves a non-convex (in fact, bilinear) objective function, as well as potentially non-convex constraints depending on the choice of the sparsity-promoting function \( S \) (for example, the \( \ell_0 \) function.) Hence, obtaining provably correct algorithms for this problem can be challenging. Indeed, the vast majority of practical approaches for sparse coding have been heuristics (Engan et al., 1999; Aharon et al., 2006; Mairal et al., 2009); Recent works in the theoretical machine learning community have bucked this trend, providing provably accurate algorithms if certain assumptions are satisfied (Spielman et al., 2012; Agarwal et al., 2014; Arora et al., 2015; Sun et al., 2015; Blasiok and Nelson, 2016; law Adamczak, 2016; Chatterji and Bartlett, 2017). However, relatively few of these newer methods have been shown to provide good empirical performance in actual sparse coding problems.

2. **Practical challenges.** Even if theoretical correctness issues were to be set aside, and we are somehow able to efficiently learn sparse codes of the input data, we often find that applications using such learned sparse codes encounter memory and running-time issues. Indeed, in the overcomplete case, only the storage of the learned dictionary \( D \) incurs \( mn = \Omega(n^2) \) memory cost, which is prohibitive when \( n \) is large. Therefore, in practical applications (such as image analysis) one typically resorts to chop the data into smaller blocks (e.g., partitioning image data into patches) to make the problem manageable.

A related line of research has been devoted to learning dictionaries that obey some type of structure. Such structural information can be leveraged to incorporate prior knowledge of underlying
signals as well as to resolve computational challenges due to the data dimension. For instance, the dictionary is assumed to be separable, or obey a convolutional structure. One such variant is the double-sparse coding problem (Rubinstein et al., 2010b; Sulam et al., 2016) where the dictionary $D$ itself exhibits a sparse structure. To be specific, the dictionary is expressed as:

$$D = \Phi A,$$

i.e., it is composed of a known “base dictionary” $\Phi \in \mathbb{R}^{n \times n}$, and a learned “synthesis” matrix $A \in \mathbb{R}^{n \times m}$ whose columns are sparse. The base dictionary $\Phi$ is typically any fixed basis chosen according to domain knowledge, while the synthesis matrix $A$ is column-wise sparse and is to be learned from the data. The basis $\Phi$ is typically orthonormal (such as the canonical or wavelet basis); however, there are cases where the base dictionary $\Phi$ is overcomplete (Rubinstein et al., 2010b; Sulam et al., 2016).

There are several reasons why such the double-sparsity model can be useful. First, the double-sparsity assumption is rather appealing from a conceptual standpoint, since it lets us combine the knowledge of decades of modeling efforts in harmonic analysis with the flexibility of learning new representations tailored to specific data families. Moreover, such a double-sparsity model has computational benefits. If the columns of $A$ are (say) $r$-sparse (i.e., each column contains no more than $r \ll n$ non-zeroes) then the overall burden of storing, transmitting, and computing with $A$ is much lower than that for general unstructured dictionaries. Finally, such a model lends itself well to interpretable learned features if the atoms of the base dictionary are semantically meaningful.

All the above reasons have spurred researchers to develop a series of algorithms to learn doubly-sparse codes (Rubinstein et al., 2010b; Sulam et al., 2016). However, despite their empirical promise, no theoretical analysis of their performance have been reported in the literature and to date, we are unaware of a provably accurate, polynomial-time algorithm for the double-sparse coding problem. Our goal in this paper is precisely to fill this gap.

1.2 Our Contributions

In this paper, we provide a new framework for double-sparse coding. To the best of our knowledge, our approach is the first method that enjoys provable statistical and algorithmic guarantees for this problem. In addition, our approach enjoys three benefits: we demonstrate that the method is neurally plausible (i.e., its execution can plausibly be achieved using a neural network architecture), robust to noise, as well as practically useful.

Inspired by the aforementioned recent theoretical advances in sparse coding, we assume a learning-theoretic setup where the data samples arise from a ground-truth generative model. Informally, suppose there exists a true (but unknown) synthesis matrix $A^*$ that is column-wise $r$-sparse, and the $i$th data sample is generated as:

$$y^{(i)} = \Phi A^* x^{*(i)} + \text{noise}, \quad i = 1, 2, \ldots, p$$

where the code vector $x^{*(i)}$ is independently drawn from a distribution supported on the set of $k$-sparse vectors. We desire to learn the underlying matrix $A^*$. Informally, suppose that the synthesis matrix $A^*$ is incoherent (the columns of $A^*$ are sufficiently close to orthogonal) and has bounded spectral norm. Finally, suppose that the number of dictionary elements, $m$, is at most a constant multiple of $n$. All of these assumptions are standard\(^1\).

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\(^1\) We clarify both the data and the noise model more concretely in Section 2 below.
We will demonstrate that the true synthesis matrix $A^*$ can be recovered (with small error) in a tractable manner as sufficiently many samples are provided. Specifically, we make the following novel contributions:

1. We propose a new algorithm that produces a coarse estimate of the synthesis matrix that is sufficiently close to the ground truth $A^*$. In contrast with previous double-sparse coding methods (such as Sulam et al. (2016)), our algorithm is not based on alternating minimization. Rather, it builds upon spectral initialization-based ideas that have recently gained popularity in non-convex machine learning (Zhang et al., 2016; Wang et al., 2016).

2. Given the above coarse estimate of the synthesis matrix $A^*$, we propose a descent-style algorithm to refine the above estimate of $A^*$. This algorithm is simpler than previously studied double-sparse coding algorithms (such as the Trainlets approach of Sulam et al. (2016)), while still giving good statistical performance. Moreover, this algorithm can be realized in a manner amenable to neural implementations.

3. We provide a rigorous analysis of both algorithms. Put together, our analysis produces the first provably polynomial-time algorithm for double-sparse coding. We show that the algorithm provably returns a good estimate of the ground-truth; in particular, in the absence of noise we prove that $\Omega(mr \text{ polylog } n)$ samples are sufficient for a good enough initialization in the first algorithm, as well as guaranteed linear convergence of the descent phase up to a precise error parameter that can be interpreted as the radius of convergence.

   Indeed, our analysis shows that employing the double-sparsity model helps in this context, and leads to a strict improvement in sample complexity, as well as running time over previous rigorous methods for (regular) sparse coding such as Arora et al. (2015).

4. We also analyze our approach in a more realistic setting with the presence of additive noise and demonstrate its stability. We prove that $\Omega(mr \text{ polylog } n)$ samples are sufficient to obtain a good enough estimate in the initialization, and also to obtain guaranteed linear convergence during descent to provably recover $A^*$.

5. We underline the benefit of the double-sparse structure over the regular model by analyzing the algorithms in Arora et al. (2015) under the noisy setting. As a result, we obtain the sample complexity $O((mk + \sigma^2 \frac{2mn^2}{k})\text{polylog } n)$, which demonstrates a negative effect of noise on this approach.

6. We rigorously develop a hard thresholding initialization that extends the spectral scheme in Arora et al. (2015). Additionally, we provide more results for the case where $A$ is orthonormal, sparse dictionary to relax the condition on $r$, which may be of independent interest.

7. While our analysis mainly consists of sufficiency results and involves several (absolute) unspecified constants, in practice we have found that these constants are reasonable. We justify our observations by reporting a suite of numerical experiments on synthetic test datasets.

Overall, our approach results in strict improvement in sample complexity, as well as running time, over previous rigorously analyzed methods for (regular) sparse coding, such as Arora et al. (2015). See Table 1 for a detailed comparison.
Table 1: Comparison of various sparse coding techniques. Expt: whether numerical experiments have been conducted. ✓ in all other columns indicates no provable guarantees. Here, n is the signal dimension, and m is the number of atoms. The sparsity levels for A and x are r and k respectively, and p is the sample size.

| Setting            | Reference                      | Sample complexity (w/o noise) | Sample complexity (w/ noise) | Upper bound on running time | Expt |
|--------------------|--------------------------------|-------------------------------|------------------------------|-----------------------------|------|
| **Regular**        | MOD (Engan et al., 1999)       | ✗                            | ✗                            | ✗                           | ✓    |
|                    | K-SVD (Aharon et al., 2006)    | ✗                            | ✗                            | ✗                           | ✓    |
|                    | Spielman et al. (2012)         | O(n² log n)                   | ✗                            | Õ(n⁴)                       | ✓    |
|                    | Arora et al. (2014)            | Õ(m²/k²)                      | ✗                            | Õ(np²)                      | ✗    |
|                    | Gribonval et al. (2015a)       | O(nm³)                        | O(nm³)                       | ✗                           | ✗    |
|                    | Arora et al. (2015)            | Õ(mk)                         | ✗                            | Õ(mn²p)                     | ✗    |
| **Double Sparse**  | Double Sparsity (Rubinstein et al., 2010b) | ✗                            | ✗                            | ✗                           | ✓    |
|                    | Gribonval et al. (2015b)       | Õ(mr)                         | Õ(mr)                        | ✗                           | ✗    |
|                    | Trainlets (Sulam et al., 2016) | ✗                            | ✗                            | ✗                           | ✓    |
|                    | This paper                     | Õ(mr)                         | Õ(mr + σ² max)               | Õ(mnp)                      | ✓    |

1.3 Techniques

At a high level, our method is an adaptation of the seminal approach of Arora et al. (2015). As is common in the statistical learning literature, we assume a “ground-truth” generative model for the observed data samples, and attempt to estimate the parameters of the generative model given a sufficient number of samples. In our case, the parameters correspond to the synthesis matrix A*, which is column-wise r-sparse. The natural approach is to formulate a loss function in terms of A such as Equation (1), and perform gradient descent with respect to the surface of the loss function to learn A*.

The key challenge in sparse coding is that the gradient is inherently coupled with the codes of the training samples (i.e., the columns of X*), which are unknown a priori. However, the main insight of Arora et al. (2015) is that within a small enough neighborhood of A*, a noisy version of X* can be estimated, and therefore the overall method is similar to performing approximate gradient descent. Formulating the actual algorithm as a noisy variant of approximate gradient descent allows us to overcome the finite-sample variability of the loss, and obtain a descent property directly related to (the population parameter) A*.

The second stage of our approach (i.e., our descent-style algorithm) leverages this intuition. However, instead of standard gradient descent, we perform approximate projected gradient descent, such that the column-wise r-sparsity property is enforced in each new estimate of A*. Indeed, such an extra projection step is critical in showing a sample complexity improvement over the existing approach of Arora et al. (2015). The key novelty is in figuring out how to perform the projection in each gradient iteration. For this purpose, we develop a novel initialization algorithm that identifies the locations of the non-zeroes in A* even before commencing the descent phase. This is nontrivially
different from initialization schemes used in previous rigorous methods for sparse coding, and the analysis is somewhat more involved.

In Arora et al. (2015), (the principal eigenvector of) a weighted covariance matrix of \( y \) (estimated by the weighted average of outer products \( y_i y_i^T \)) is shown to provide a coarse estimate of a dictionary atom. We extend this idea and rigorously show that the diagonal of the weighted covariance matrix serves as a good indicator of the support of a column in \( A^* \). The success relies on the concentration of the diagonal vector with dimension \( n \), instead of the covariance matrix with dimensions \( n \times n \). With the support selected, our scheme only utilizes a reduced weighted covariance matrix with dimensions at most \( r \times r \). This initialization scheme enables us to effectively reduce the dimension of the problem, and therefore leads to significant improvement in sample complexity and running time over previous (provable) sparse coding methods when the data representation sparsity \( k \) is much smaller than \( m \).

Further, we rigorously analyze the proposed algorithms in the presence of noise with a bounded expected norm. Our analysis shows that our method is stable, and in the case of i.i.d. Gaussian noise with bounded expected \( \ell_2 \)-norms, is at least a polynomial factor better than previous polynomial time algorithms for sparse coding.

The empirical performance of our proposed method is demonstrated by a suite of numerical experiments on synthetic datasets. In particular, we show that our proposed methods are simple and practical, and improve upon previous provable algorithms for sparse coding.

1.4 Paper Organization

The remainder of this paper is organized as follows. Section 2 introduces notation, key model assumptions, and informal statements of our main theoretical results. Section 3 outlines our initialization algorithm (along with supporting theoretical results) while Section 4 presents our descent algorithm (along with supporting theoretical results). Section 5 provides a numerical study of the efficiency of our proposed algorithms, and compares it with previously proposed methods. Finally, Section 6 concludes with a short discussion. All technical proofs are relegated to the appendix.

2. Setup and Main Results

2.1 Notation

We define \( [m] \triangleq \{1, \ldots, m\} \) for any integer \( m > 1 \). For any vector \( x = [x_1, x_2, \ldots, x_m]^T \in \mathbb{R}^m \), we write \( \text{supp}(x) \triangleq \{i \in [m] : x_i \neq 0\} \) as the support set of \( x \). Given any subset \( S \subseteq [m], x_S \) corresponds to the sub-vector of \( x \) indexed by the elements of \( S \). For any matrix \( A \in \mathbb{R}^{n \times m} \), we use \( A_{\bullet i} \) and \( A^T_{\bullet} \) to represent the \( i \)-th column and the \( j \)-th row respectively. For some appropriate sets \( R \) and \( S \), let \( A_{R \bullet} \) (respectively, \( A_{\bullet S} \)) be the submatrix of \( A \) with rows (respectively columns) indexed by the elements in \( R \) (respectively \( S \)). In addition, for the \( i \)-th column \( A_{\bullet i} \), we use \( A_{R,i} \) to denote the sub-vector indexed by the elements of \( R \). For notational simplicity, we use \( A^T_{R \bullet} \) to indicate \( (A_{R \bullet})^T \), the transpose of \( A \) after a row selection. Besides, we use \( \circ \) and \( \text{sgn}(\cdot) \) to represent the element-wise Hadamard operator and the element-wise sign function respectively. Further, \( \text{threshold}_K(x) \) is a thresholding operator that replaces any elements of \( x \) with magnitude less than \( K \) by zero.

The \( \ell_2 \)-norm \( \|x\| \) for a vector \( x \) and the spectral norm \( \|A\| \) for a matrix \( A \) appear several times. In some cases, we also utilize the Frobenius norm \( \|A\|_F \) and the operator norm \( \|A\|_{1,2} \triangleq \max_{\|x\|_1 \leq 1} \|Ax\| \). The norm \( \|A\|_{1,2} \) is essentially the maximal Euclidean norm of any column of \( A \).
For clarity, we adopt asymptotic notations extensively. We write \( f(n) = O(g(n)) \) (or \( f(n) = \Omega(g(n)) \)) if \( f(n) \) is upper bounded (respectively, lower bounded) by \( g(n) \) up to some positive constant. Next, \( f(n) = \Theta(g(n)) \) if and only if \( f(n) = O(g(n)) \) and \( f(n) = \Omega(g(n)) \). Also \( \Omega \) and \( \Omega \) represent \( \Omega \) and \( \Omega \) up to a multiplicative poly-logarithmic factor respectively. Finally \( f(n) = o(g(n)) \) (or \( f(n) = \omega(g(n)) \)) if \( \lim_{n \to \infty} |f(n)/g(n)| = 0 \) (\( \lim_{n \to \infty} |f(n)/g(n)| = \infty \)). Throughout the paper, we use the phrase “with high probability” (abbreviated to w.h.p.) to describe an event with failure probability of order at most \( n^{-\omega(1)} \). In addition, \( g(n) = O^*(f(n)) \) means \( g(n) \leq Kf(n) \) for some small enough constant \( K \).

2.2 Model

Suppose that the observed samples are given by

\[
y^{(i)} = Dx^{(i)} + \varepsilon, \quad i = 1, \ldots, p,
\]

i.e., we are given \( p \) samples of \( y \) generated from a fixed (but unknown) dictionary \( D \) where the sparse code \( x^{*} \) and the error \( \varepsilon \) are drawn from a joint distribution \( \mathcal{D} \) specified below. In the double-sparse setting, the dictionary is assumed to follow a decomposition \( D = \Phi A^* \), where \( \Phi \in \mathbb{R}^{n \times n} \) is a known orthonormal basis matrix and \( A^* \) is an unknown, ground truth synthesis matrix. An alternative (and interesting) setting is an overcomplete \( \Phi \) with a square \( A^* \), which our analysis below does not cover; we defer this to future work. Our approach relies upon the following assumptions on the synthesis dictionary \( A^* \):

**A1** \( A^* \) is overcomplete (i.e., \( m \geq n \)) with \( m = O(n) \).

**A2** \( A^* \) is \( \mu \)-incoherent, i.e., for all \( i \neq j \), \( |\langle A^*_i, A^*_j \rangle| \leq \mu/\sqrt{n} \).

**A3** \( A^*_i \) has at most \( r \) non-zero elements, and is normalized such that \( \|A^*_i\| = 1 \) for all \( i \). Moreover, \( |A^*_{ij}| \geq \tau \) for \( A^*_{ij} \neq 0 \) and \( \tau = \Omega(1/\sqrt{r}) \).

**A4** \( A^* \) has bounded spectral norm such that \( \|A^*\| \leq O(\sqrt{m/n}) \).

All these assumptions are standard. In Assumption **A2**, the incoherence \( \mu \) is typically of order \( O(\log n) \) with high probability for a normal random matrix (Arora et al., 2014). Assumption **A3** is a common assumption in sparse signal recovery. The bounded spectral norm assumption is also standard (Arora et al., 2015). In addition to Assumptions **A1-A4**, we make the following distributional assumptions on \( \mathcal{D} \):

**B1** Support \( S = \text{supp}(x^*) \) is of size at most \( k \) and uniformly drawn without replacement from \([m] \) such that \( \mathbb{P}[i \in S] = \Theta(k/m) \) and \( \mathbb{P}[i, j \in S] = \Theta(k^2/m^2) \) for some \( i, j \in [m] \) and \( i \neq j \).

**B2** The nonzero entries \( x^*_S \) are pairwise independent and sub-Gaussian given the support \( S \) with \( \mathbb{E}[x^*_i | i \in S] = 0 \) and \( \mathbb{E}[x^*_i^2 | i \in S] = 1 \).

**B3** For \( i \in S \), \( |x^*_i| \geq C \) where \( 0 < C \leq 1 \).

**B4** The additive noise \( \varepsilon \) has i.i.d. Gaussian entries with variance \( \sigma^2 \) with \( \sigma = O(1/\sqrt{n}) \).
For the rest of the paper, we set $\Phi = I_n$, the identity matrix of size $n$. This only simplifies the arguments but does not change the problem because one can study an equivalent model:

$$y' = Ax^* + \varepsilon',$$

where $y' = \Phi^T y$ and $\varepsilon' = \Phi^T \varepsilon$, as $\Phi^T \Phi = I_n$. Due to the Gaussianity of $\varepsilon$, $\varepsilon'$ also has independent entries. Although this property is specific to Gaussian noise, all the analysis carried out below can be extended to sub-Gaussian noise with minor (but rather tedious) changes in concentration arguments.

Our goal is to devise an algorithm that produces a provably “good” estimate of $A^*$. For this, we need to define a suitable measure of “goodness”. We use the following notion of distance that measures the maximal column-wise difference in $\ell_2$-norm under some suitable transformation.

**Definition 1** ($(\delta, \kappa)$-nearness). A is said to be $\delta$-close to $A^*$ if there is a permutation $\pi : [m] \rightarrow [m]$ and a sign flip $\sigma : [m] : \{\pm 1\}$ such that $\|\sigma(i)A_{\pi(i)} - A^*_{\pi(i)}\| \leq \delta$ for every $i$. In addition, $A$ is said to be $(\delta, \kappa)$-near to $A^*$ if $\|A_{\pi} - A^*\| \leq \kappa \|A^*\|$ also holds.

For notational simplicity, in our theorems we simply replace $\pi$ and $\sigma$ in Definition 1 with the identity permutation $\pi(i) = i$ and the positive sign $\sigma(\cdot) = +1$ while keeping in mind that in reality we are referring to one element of the equivalence class of all permutations and sign flip transforms of $A^*$.

We will also need some technical tools from Arora et al. (2015) to analyze our gradient descent-style method. Consider any iterative algorithm that looks for a desired solution $z^* \in \mathbb{R}^n$ to optimize some function $f(z)$. Suppose that the algorithm produces a sequence of estimates $z^1, \ldots, z^s$ via the update rule:

$$z^{s+1} = z^s - \eta g^s,$$

for some vector $g^s$ and scalar step size $\eta$. The goal is to characterize “good” directions $g^s$ such that the sequence converges to $z^*$ under the Euclidean distance. The following gives one such sufficient condition for $g^s$.

**Definition 2.** A vector $g^s$ at the $s^{th}$ iteration is $(\alpha, \beta, \gamma_s)$-correlated with a desired solution $z^*$ if

$$\langle g^s, z^s - z^* \rangle \geq \alpha \|z^s - z^*\|^2 + \beta \|g^s\|^2 - \gamma_s.$$

We know from convex optimization that if $f$ is $2\alpha$-strongly convex and $1/2\beta$-smooth, and $g^s$ is chosen as the gradient $\nabla_z f(z)$, then $g^s$ is $(\alpha, \beta, 0)$-correlated with $z^*$. In our setting, the desired solution corresponds to $A^*$, the ground-truth synthesis matrix. In Arora et al. (2015), it is shown that $g^s = E_y[(A^*x - y)\text{sgn}(x)^T]$, where $x = \text{threshold}_{C/2}((A^*)^Ty)$ indeed satisfies Definition 2. This $g^s$ is a population quantity and not explicitly available, but one can estimate such $g^s$ using an empirical average. The corresponding estimator $\hat{g}^s$ is a random variable, so we also need a related correlated-with-high-probability condition:

**Definition 3.** A direction $\hat{g}^s$ at the $s^{th}$ iteration is $(\alpha, \beta, \gamma_s)$-correlated-w.h.p. with a desired solution $z^*$ if, w.h.p.,

$$\langle \hat{g}^s, z^s - z^* \rangle \geq \alpha \|z^s - z^*\|^2 + \beta \|\hat{g}^s\|^2 - \gamma_s.$$

From Definition 2, one can establish a form of descent property in each update step, as shown in Theorem 1.
Theorem 1. Suppose that $g^s$ satisfies the condition described in Definition 2 for $s = 1, 2, \ldots, T$. Moreover, $0 < \eta \leq 2\beta$ and $\gamma = \max_{s=1}^{T} \gamma_s$. Then, the following holds for all $s$:

$$\|z^{s+1} - z^s\|^2 \leq (1 - 2\alpha \eta)\|z^s - z^*\|^2 + 2\gamma \gamma_s.$$ 

In particular, the above update converges geometrically to $z^*$ with an error $\gamma/\alpha$. That is,

$$\|z^{s+1} - z^*\|^2 \leq (1 - 2\alpha \eta)^s\|z^0 - z^*\|^2 + 2\gamma/\alpha.$$ 

We can obtain a similar result for Definition 3 except that $\|z^{s+1} - z^*\|^2$ is replaced with its expectation.

Armed with the above tools, we now state some informal versions of our main results:

Theorem 2 (Provably correct initialization, informal). There exists a neurally plausible algorithm to produce an initial estimate $A^0$ that has the correct support and is $(\delta, 2)$-near to $A^*$ with high probability. Its running time and sample complexity are $\tilde{O}(mnp)$ and $\tilde{O}(mr)$ respectively. This algorithm works when the sparsity level satisfies $r = O^*(\log n)$.

Our algorithm can be regarded as an extension of Arora et al. (2015) to the double-sparse setting. It reconstructs the support of one single column and then estimates its direction in the subspace defined by the support. Our proposed algorithm enjoys neural plausibility by implementing a thresholding non-linearity and Oja’s update rule. We provide a neural implementation of our algorithm in Appendix G. The adaption to the sparse structure results in a strict improvement upon the original algorithm both in running time and sample complexity. However, our algorithm is limited to the sparsity level $r = O^*(\log n)$, which is rather small but plausible from the modeling standpoint. For comparison, we analyze a natural extension of the algorithm of Arora et al. (2015) with an extra hard-thresholding step for every learned atom. We obtain the same order restriction on $r$, but somewhat worse bounds on sample complexity and running time. The details are found in Appendix F.

We hypothesize that a stronger incoherence assumption can lead to provably correct initialization for a much wider range of $r$. For purposes of theoretical analysis, we consider the special case of a perfectly incoherent synthesis matrix $A^*$ such that $\mu = 0$ and $m = n$. In this case, we can indeed improve the sparsity parameter to $r = O^*(\min(\sqrt{n}/\log^2 n, n/k^2 \log^2 n))$, which is an exponential improvement. This analysis is given in Appendix E.

Theorem 3 (Provably correct descent, informal). There exists a neurally plausible algorithm for double-sparse coding that converges to $A^*$ with geometric rate when the initial estimate $A^0$ has the correct support and $(\delta, 2)$-near to $A^*$. The running time per iteration is $O(mkp + mrp)$ and the sample complexity is $\tilde{O}(m + \sigma^2 zmrrp/k)$.

Similar to Arora et al. (2015), our proposed algorithm enjoys neural plausibility. Moreover, we can achieve a better running time and sample complexity per iteration than previous methods, particularly in the noisy case. We show in Appendix F that in this regime the sample complexity of Arora et al. (2015) is $\tilde{O}(m + \sigma^2 zmrrp/k)$. For instance, when $\sigma \asymp n^{-1/2}$, the sample complexity bound is significantly worse than $O(m)$ in the noiseless case. In contrast, our proposed method leverages the sparse structure to overcome this problem and obtain improved results.

We are now ready to introduce our methods in detail. As discussed above, our approach consists of two stages: an initialization algorithm that produces a coarse estimate of $A^*$, and a descent-style algorithm that refines this estimate to accurately recover $A^*$. 

9
Algorithm 1 Truncated Pairwise Reweighting

- **Initialize**: \( L = \emptyset \)
- Randomly divide \( p \) samples into two disjoint sets \( \mathcal{P}_1 \) and \( \mathcal{P}_2 \) of sizes \( p_1 \) and \( p_2 \) respectively.
- **While** \( |L| < m \). Pick \( u \) and \( v \) from \( \mathcal{P}_1 \) at random.
  - For every \( l = 1, 2, \ldots, n \); compute
    \[
    \hat{e}_l = \frac{1}{p_2} \sum_{i=1}^{p_2} \langle y(i), u \rangle \langle y(i), v \rangle (y_l(i))^2
    \]
  - Sort \( (\hat{e}_1, \hat{e}_2, \ldots, \hat{e}_n) \) in descending order.
  - **If** \( r' \leq r \) s.t. \( \hat{e}_{(r')} \geq O(k/mr) \) and \( \hat{e}_{(r'+1)}/\hat{e}_{(r')} < O^*(r/\log^2 n) \)
    - Let \( \hat{R} \) be set of the \( r \) largest entries of \( \hat{e} \)
    - \( \hat{M}_{u,v} = \frac{1}{p_2} \sum_{i=1}^{p_2} \langle y(i), u \rangle \langle y(i), v \rangle y_{R}^i y_{R}^i \)
    - \( \delta_1, \delta_2 \leftarrow \) top singular values of \( \hat{M}_{u,v} \)
    - \( z_{R} \leftarrow \) top singular vector of \( \hat{M}_{u,v} \)
    - **If** \( \delta_1 \geq \Omega(k/m) \) and \( \delta_2 < O^*(k/m \log n) \)
      - **If** \( \text{dist}(\pm z, l) > 1/\log n \) for any \( l \in L \)
        - Update \( L = L \cup \{z\} \)
  - **Return** \( A^0 = (L_1, \ldots, L_m) \)

3. Stage 1: Initialization

In this section, we present a neurally plausible algorithm that can produce a coarse initial estimate of the ground truth \( A^* \). We give a neural implementation of the algorithm in Appendix G.

Our algorithm is an adaptation from the algorithm in Arora et al. (2015). The idea is to estimate dictionary atoms in a greedy fashion by iteratively re-weighting the given samples. The samples are re-scaled in a way that the weighted (sample) covariance matrix has the dominant first singular value, and its corresponding eigenvector is close to one particular atom with high probability. However, while this algorithm is conceptually very appealing, it incurs severe computational costs in practice. More precisely, the overall running time is \( \tilde{O}(mn^2p) \) in expectation, which is unrealistic for large-scale problems.

To overcome this burden, we leverage the double-sparsity assumption in our generative model to obtain a more efficient approach. The high-level idea is to first estimate the support of each column in the synthesis matrix \( A^* \), and then obtain a coarse estimate of the nonzero coefficients of each column based on knowledge of its support. The key ingredient of our method is a novel spectral procedure that gives us an estimate of the column supports purely from the observed samples. The full algorithm, that we call **Truncated Pairwise Reweighting**, is listed in pseudocode form below as Algorithm 1.

Let us provide some intuition of our algorithm. Fix a sample \( y = A^* x^* + \varepsilon \) from the available training set, and consider samples

\[
\begin{align*}
u = A^* \alpha + \varepsilon_u, & \quad v = A^* \alpha' + \varepsilon_v.
\end{align*}
\]
Now, consider the (very coarse) estimate for the sparse code of $u$ with respect to $A^*$:
\[
\beta = A^*T u = A^*T A^*\alpha + A^*T \varepsilon_u.
\]
As long as $A^*$ is incoherent enough and $\varepsilon_u$ is small, the estimate $\beta$ behaves just like $\alpha$, in the sense that for each sample $y$:
\[
\langle y, u \rangle \approx \langle x^*, \beta \rangle \approx \langle x^*, \alpha \rangle.
\]
Moreover, the above inner products are large only if $\alpha$ and $x^*$ share some elements in their supports; else, they are likely to be small. Likewise, the weight $\langle y, u \rangle \langle y, v \rangle$ depends on whether or not $x^*$ shares the support with both $\alpha$ and $\alpha'$.

Now, suppose that we have a mechanism to isolate pairs $u$ and $v$ who share exactly one atom among their sparse representations. Then by scaling each sample $y$ with an increasing function of $\langle y, u \rangle \langle y, v \rangle$ and linearly adding the samples, we magnify the importance of the samples that are aligned with that atom, and diminish the rest. The final direction can be obtained via the top principal component of the reweighted samples and hence can be used as a coarse estimate of the atom. This is exactly the approach adopted in Arora et al. (2015). However, in our double-sparse coding setting, we know that the estimated atom should be sparse as well. Therefore, we can naturally perform an extra “sparsification” step of the output. An extended algorithm and its correctness are provided in Appendix F. However, as we discussed above, the computational complexity of the re-weighting step still remains.

We overcome this obstacle by first identifying the locations of the nonzero entries in each atom. Specifically, define the matrix:
\[
M_{u,v} = \frac{1}{P_2} \sum_{i=1}^{P_2} \langle y^{(i)}, u \rangle \langle y^{(i)}, v \rangle y^{(i)} \odot y^{(i)}.
\]
Then, the diagonal entries of $M_{u,v}$ reveals the support of the atom of $A^*$ shared among $u$ and $v$: the $r$-largest entries of $M_{u,v}$ will correspond to the support we seek. Since the desired direction remains unchanged in the $r$-dimensional subspace of its nonzero elements, we can restrict our attention to this subspace, construct a reduced covariance matrix $\hat{M}_{u,v}$, and proceed as before. This truncation step alleviates the computational burden by a significant amount; the running time is now $\tilde{O}(mnp)$, which improves the original by a factor of $n$.

The success of the above procedure relies upon whether or not we can isolate pairs $u$ and $v$ that share exactly one dictionary atom. Fortunately, this can be done via checking the decay of the singular values of the (reduced) covariance matrix. Here too, we show via our analysis that the truncation step plays an important role. Overall, our proposed algorithm not only accelerates the initialization in terms of running time, but also improves the sample complexity over Arora et al. (2015). The performance of Algorithm 1 is described in the following theorem, whose formal proof is deferred to Appendix B.

**Theorem 4.** Suppose that Assumptions **B1-B4** hold and Assumptions **A1-A3** satisfy with $\mu = O^*(\frac{\sqrt{n}}{k \log^3 n})$ and $r = O^*(\log n)$. When $p_1 = \tilde{\Omega}(m)$ and $p_2 = \tilde{\Omega}(mr)$, then with high probability Algorithm 1 returns an initial estimate $A^0$ whose columns share the same support as $A^*$ and with $(\delta, 2)$-nearness to $A^*$ with $\delta = O^*(1/\log n)$.

The limit on $r$ arises from the minimum non-zero coefficient $\tau$ of $A^*$. Since the columns of $A^*$ are standardized, $\tau$ should degenerate as $r$ grows. In other words, it is getting harder to distinguish
the “signal” coefficients from zero as \( r \) grows with \( n \). However, this limitation can be relaxed when a better incoherence available, for example the orthonormal case. We study this in Appendix \( E \).

To provide some intuition about the working of the algorithm (and its proof), let us analyze it in the case where we have access to infinite number of samples. This setting, of course, is unrealistic. However, the analysis is much simpler and more transparent since we can focus on expected values rather than empirical averages. Moreover, the analysis reveals several key lemmas, which we will reuse extensively for proving Theorem \( 4 \). First, we give some intuition behind the definition of the “scores”, \( \epsilon_i \).

**Lemma 1.** Fix samples \( u \) and \( v \) and suppose that \( y = A^*x^* + \varepsilon \) is a random sample independent of \( u, v \). The expected value of the score for the \( i \)-th component of \( y \) is given by:

\[
e_i \triangleq E[(y, u)\langle y, v \rangle y_i^2] = \sum_{i \in U \cap V} q_i c_i \beta_i \beta_i^* A_i^2 + \text{perturbation terms}
\]

where \( q_i = P[i \in S], q_{ij} = P[i, j \in S] \) and \( c_i = E[x_i^* | i \in S] \). Moreover, the perturbation terms have absolute value at most \( O^*(k/m) \).

From Assumption \( B1 \), we know that \( q_i = \Theta(k/m) \), \( q_{ij} = \Theta(k^2/m^2) \) and \( c_i = \Theta(1) \). Besides, we will show later that \( |\beta_i| \approx |\alpha_i| = \Omega(1) \) for \( i \in U \), and \( |\beta_i| = o(1) \) for \( i \notin U \). Consider the first term \( E_0 = \sum_{i \in U \cap V} q_i c_i \beta_i \beta_i^* A_i^2 \). Clearly, \( E_0 = 0 \) if \( U \cap V = \emptyset \) or that \( l \) does not belong to support of any atom in \( U \cap V \). On the contrary, as \( E_0 \neq 0 \) and \( U \cap V = \{i\} \), then \( E_0 = |q_i c_i \beta_i \beta_i^* A_i^2| \geq \Omega(\tau^2 k/m) = \Omega(k/m) \) since \( |q_i c_i \beta_i \beta_i^* A_i^2| \geq \Omega(k/m) \) and \( |A_i| \geq \tau \).

Therefore, Lemma 1 suggests that if \( u \) and \( v \) share a unique atom among their sparse representations, and \( r \) is not too large, then we can indeed recover the correct support of the shared atom. When this is the case, the expected scores corresponding to the nonzero elements of the shared atom will dominate the remaining of the scores.

Now, given that we can isolate the support \( R \) of the corresponding atom, the remaining questions are how best we can estimate its non-zero coefficients, and when \( u \) and \( v \) share a unique elements in their supports. These issues are handled in the following lemmas.

**Lemma 2.** Suppose that \( u = A^*\alpha + \varepsilon_u \) and \( v = A^*\alpha' + \varepsilon_v \) are two random samples. Let \( U \) and \( V \) denote the supports of \( \alpha \) and \( \alpha' \) respectively. \( R \) is the support of some atom of interest. The truncated re-weighting matrix is formulated as

\[
M_{u,v} \triangleq E[\langle y, u \rangle \langle y, v \rangle y_R y_R^T] = \sum_{i \in U \cap V} q_i c_i \beta_i \beta_i^* A_{R,i}^* A_{R,i}^T + \text{perturbation terms}
\]

where the perturbation terms have norms at most \( O^*(k/m \log n) \).

Using the same argument for bounding \( E_0 \) in Lemma 1, we can see that \( M_0 = q_i c_i \beta_i \beta_i^* A_{R,i}^* A_{R,i}^T \) has norm at least \( \Omega(k/m) \) when \( u \) and \( v \) share a unique element \( i \) \( (\|A_{R,i}\| = 1) \). According to this lemma, the spectral norm of \( M_0 \) dominates those of the other perturbation terms. Thus, given \( R \) we can use the first singular vector of \( M_{u,v} \) as an estimate of \( A_{R,i}^* \).

**Lemma 3.** Under the setup of Theorem \( 4 \), suppose \( u = A^*\alpha + \varepsilon_u \) and \( v = A^*\alpha' + \varepsilon_v \) are two random samples with supports \( U \) and \( V \) respectively. \( R = \text{supp}(A_{R,i}^*) \). If \( u \) and \( v \) share the unique atom \( i \), the first \( r \) largest entries of \( e_i \) is at least \( O(k/mr) \) and belong to \( R \). Moreover, the top singular vector of \( M_{u,v} \) is \( \delta \)-close to \( A_{R,i}^* \) for \( O^*(1/\log n) \).
Proof. The recovery of $A^*_i$'s support directly follows Lemma 1. For the latter part, recall from Lemma 2 that

$$M_{u,v} = q_i c_i \beta_i^\prime A_{R,i}^* A_{R,i}^{*T} + \text{perturbation terms}$$

The perturbation terms have norms bounded by $O^*(k/m \log n)$. On the other hand, the first term is has norm at least $\Omega(k/m)$ since $\|A_{R,i}^*\| = 1$ for the correct support $R$ and $|q_i c_i \beta_i^\prime| \geq \Omega(k/m)$.

Then using Wedin’s Theorem to $M_{u,v}$, we can conclude that the top singular vector must be $O^*(k/m \log n)/\Omega(k/m) = O^*(1/\log n)$ -close to $A_{R,i}^*$.

\[\square\]

Lemma 4. Under the setup of Theorem 4, suppose $u = A^* \alpha + \varepsilon_u$ and $v = A^* \alpha' + \varepsilon_v$ are two random samples with supports $U$ and $V$ respectively. If the top singular value of $M_{u,v}$ is at least $\Omega(k/m)$ and the second largest one is at most $O^*(k/m \log n)$, then $u$ and $v$ share a unique dictionary element with high probability.

Proof. The proof follows from that of Lemma 37 in Arora et al. (2015). The main idea is to separate the possible cases of how $u$ and $v$ share support and to use Lemma 2 with the bounded perturbation terms to conclude when $u$ and $v$ share exactly one. We note that due to the condition where $\hat{e}_{(s)} \geq \Omega(k/mr)$ and $\hat{e}_{(s+1)}/\hat{e}_{(s)} \leq O^*(r/\log n)$, it must be the case that $u$ and $v$ share only one atom or share more than one atoms with the same support. When their supports overlap more than one, then the first singular value cannot dominate the second one, and hence it must not be the case.

Similar to (Arora et al., 2015), our initialization algorithm requires $\tilde{O}(m)$ iterations in expectation to estimate all the atoms, hence the expected running time is $\tilde{O}(mnp)$. All the proofs of Lemma 1 and 2 are deferred to Appendix B.

4. Stage 2: Descent

We now adapt the neural sparse coding approach of Arora et al. (2015) to obtain an improved estimate of $A^*$. As mentioned earlier, at a high level the algorithm is akin to performing approximate gradient descent. The insight is that within a small enough neighborhood (in the sense of $\delta$-closeness) of the true $A^*$, an estimate of the ground-truth code vectors, $X^*$, can be constructed using a neurally plausible algorithm.

The innovation, in our case, is the double-sparsity model since we know a priori that $A^*$ is itself sparse. Under sufficiently many samples, the support of $A^*$ can be deduced from the initialization stage; therefore we perform an extra projection step in each iteration of gradient descent. In this sense, our method is non-trivially different from Arora et al. (2015). The full algorithm is presented as Algorithm 2.

As discussed in Section 2, convergence of noisy approximate gradient descent can be achieved as long as $\hat{\nabla}^g$ is correlated-w.h.p. with the true solution. However, an analogous convergence result for projected gradient descent does not exist in the literature. We fill this gap via a careful analysis. Due to the projection, we only require the correlated-w.h.p. property for part of $\hat{\nabla}^g$ (i.e., when it is restricted to some support set) with $A^*$. The descent property is still achieved via Theorem 5. Due to various perturbation terms, $\hat{\nabla}$ is only a biased estimate of $\nabla_{A,L}(A,X)$; therefore, we can only refine the estimate of $A^*$ until the column-wise error is of order $O(\sqrt{k/n})$. The performance of Algorithm 2 can be characterized via the following theorem.
Algorithm 2 Double-Sparse Coding Descent Algorithm

\textbf{Initialize} \( A^0 \) is \((\delta, 2)\)-near to \( A^* \). \( H = (h_{ij})_{n \times m} \) where \( h_{ij} = 1 \) if \( i \in \text{supp}(A^0) \) and 0 otherwise.

\textbf{Repeat} for \( s = 0, 1, \ldots, T \)

- Encode: \( x^{(i)} = \text{threshold}_{C/2}((A^s)^Ty^{(i)}) \) for \( i = 1, 2, \ldots, p \)
- Update: \( A^{s+1} = P_H(A^s - \eta \tilde{g}^s) = A^s - \eta P_H(\tilde{g}^s) \)

where \( \tilde{g}^s = \frac{1}{p} \sum_{i=1}^p (A^s x^{(i)} - y^{(i)}) \text{sgn}(x^{(i)})^T \) and \( P_H(G) = H \circ G \)

\textbf{Theorem 5.} Suppose that the initial estimate \( A^0 \) has the correct column supports and is \((\delta, 2)\)-near to \( A^* \) with \( \delta = O^*(1/\log n) \). If Algorithm 2 is provided with \( p = \tilde{\Omega}(mr) \) fresh samples at each step and \( \eta = \Theta(m/k) \), then

\[ \mathbb{E}[\|A^s - A^*\|^2] \leq (1 - \rho)^s \|A^0 - A^*\|^2 + O(k/\sqrt{n}) \]

for some \( 0 < \rho < 1/2 \) and for \( s = 1, 2, \ldots, T \). Consequently, \( A^s \) converges to \( A^* \) geometrically until column-wise error \( O(\sqrt{k/n}) \).

We defer the full proof of Theorem 5 to Section D. In this section, we take a step towards understanding the algorithm by analyzing \( \tilde{g}^s \) in the infinite sample case, which is equivalent to its expectation \( g^s \triangleq \mathbb{E}[(A^s x - y) \text{sgn}(x)^T] \). We establish the \((\alpha, \beta, \gamma)\)-correlation of a truncated version of \( g^s \) with \( A^* \) to obtain the closed-form expression in Theorem 6 for the infinite sample case.

\textbf{Theorem 6.} Suppose that the initial estimate \( A^0 \) has the correct column supports and is \((\delta, 2)\)-near to \( A^* \). If Algorithm 2 is provided with infinite number of samples at each step and \( \eta = \Theta(m/k) \), then

\[ \|A^{s+1} - A^*\|^2 \leq (1 - \rho) \|A_s - A^*\|^2 + O(k^2/n^2) \]

for some \( 0 < \rho < 1/2 \) and for \( s = 1, 2, \ldots, T \). Consequently, it converges to \( A^* \) geometrically until column-wise error is \( O(k/n) \).

Note that the better error \( O(k^2/n^2) \) is due to the fact that infinitely many samples are given. The term \( O(\sqrt{k/n}) \) in Theorem 5 is a trade-off between the accuracy and the sample complexity of the algorithm. The proof of this theorem composes of two steps with two main results: 1) an explicit form of \( g^s \) (Lemma 6); 2) \((\alpha, \beta, \gamma)\)-correlation of column-wise \( g^s \) with \( A^* \) (Lemma 6). The proof of those lemmas are deferred to Appendix C. Since the correlation primarily relies on the \((\delta, 2)\)-nearness of \( A^s \) to \( A^* \) that is provided initially and maintained at each step, then we need to argue that the nearness is preserved after each step.

\textbf{Lemma 5.} Suppose that the initial estimate \( A^0 \) has the correct column supports and is \((\delta, 2)\)-near to \( A^* \). The column-wise update has the form \( g^s_{R,i} = p_i q_i (\lambda^s_i A^s_{R,i} - A^*_{R,i} + \xi^s_i \pm \zeta) \) where \( R = \text{supp}(A^s) \), \( \lambda^s_i = \langle A^s_i, A^*_{R,i} \rangle \) and \( \xi^s_i = A^s_{R,-i} \text{diag}(q_i) (A^s_{-i}-i)^T A^*_{R,i}/q_i \).

Moreover, \( \xi \) has norm bounded by \( O(k/n) \) for \( \delta = O^*(1/\log n) \) and \( \zeta \) is negligible.

We underline that the correct support of \( A^s \) allows us to obtain the closed-form expression of \( g^s_{R,i} \) in terms of \( A^s_{R,i} \) and \( A^*_{R,i} \). Likewise, the expression (8) suggests that \( g^s_{R,i} \) is almost equal to \( p_i q_i (A^s_{R,i} - A^*_{R,i}) \) (since \( \lambda^s \approx 1 \)), which directs to the desired solution \( A^*_{R,i} \). With Lemma 5, we will prove the \((\alpha, \beta, \gamma)\)-correlation of the approximate gradient to each column \( A^s_{R,i} \) and the nearness of each new update to the true solution \( A^*_{R,i} \).
4.1 \((\alpha, \beta, \gamma_s)\)-Correlation

**Lemma 6.** Suppose that \(A^s\) to be \((\delta, 2)\)-near to \(A^*\) and \(R = \text{supp}(A^*_{\bullet})\), then \(2g^s_{R,i}\) is \((\alpha, 1/2\alpha, \epsilon^2/\alpha)\)-correlated with \(A^*_{R,i}\); that is

\[
\langle 2g^s_{R,i}, A^*_{R,i} - A^*_{R,i} \rangle \geq \alpha\|A^*_{R,i} - A^*_{R,i}\|^2 + 1/(2\alpha)\|g^s_{R,i}\|^2 - \epsilon^2/\alpha
\]

Furthermore, the descent is achieved by

\[
\|A^s_{\bullet i} - A^*_{\bullet i}\|^2 \leq (1 - 2\alpha\eta)^s\|A^0_{\bullet i} - A^*_{\bullet i}\|^2 + \eta\epsilon^2/\alpha
\]

where \(\delta = O^*(1/\log n)\) and \(\epsilon = O\left(\frac{k^2}{mn}\right)\).

**Proof.** Throughout the proof, we omit the superscript \(s\) for simplicity and denote \(2\alpha = p_iq_i\). First, we rewrite \(g^s_{\bullet i}\) as a combination of the true direction \(A^*_{\bullet i} - A^*_{\bullet i}\) and a term with small norm:

\[
g_{R,i} = 2\alpha(A_{R,i} - A^*_{R,i}) + v, \tag{2}
\]

where \(v = 2\alpha[(\lambda_i - 1)A_{\bullet i} + \epsilon_i]\) with norm bounded. In fact, since \(A_{\bullet i}\) is \(\delta\)-close to \(A^*_{\bullet i}\), and both have unit norm, then \(\|2\alpha(\lambda_i - 1)A_{\bullet i}\| = \alpha\|A_{\bullet i} - A^*_{\bullet i}\|^2 \leq \alpha\|A_{\bullet i} - A^*_{\bullet i}\|\) and \(\|\xi_i\| \leq O(k/n)\) from the inequality (9). Therefore,

\[
\|v\| = \|2\alpha(\lambda_i - 1)A_{R,i} + 2\alpha\xi_i\| \leq \alpha\|A_{R,i} - A^*_{R,i}\| + \epsilon
\]

where \(\epsilon = O(k^2/mn)\). Now, we make use of (2) to show the first part of Lemma 6:

\[
\langle 2g_{R,i}, A_{R,i} - A^*_{R,i} \rangle = 4\alpha\|A_{R,i} - A^*_{R,i}\|^2 + \langle 2v, A_{R,i} - A^*_{R,i} \rangle. \tag{3}
\]

We want to lower bound the inner product term with respect to \(\|g_{R,i}\|^2\) and \(\|A_{R,i} - A^*_{R,i}\|^2\). Effectively, from (2)

\[
4\alpha\langle v, A_{\bullet i} - A^*_{\bullet i} \rangle = \|g_{R,i}\|^2 - 4\alpha^2\|A_{R,i} - A^*_{R,i}\|^2 \geq \|g_{R,i}\|^2 - 6\alpha^2\|A_{R,i} - A^*_{R,i}\|^2 - 2\epsilon^2, \tag{4}
\]

where the last step is due to Cauchy-Schwarz inequality: \(\|v\|^2 \leq 2(\alpha^2\|A_{R,i} - A^*_{R,i}\|^2 + \epsilon^2)\).

Substitute \(2\langle v, A_{\bullet i} - A^*_{\bullet i} \rangle\) in (3) for the right hand side of (4), we get the first result:

\[
\langle 2g_{R,i}, A_{R,i} - A^*_{R,i} \rangle \geq \alpha\|A_{R,i} - A^*_{R,i}\|^2 + \frac{1}{2\alpha}\|g_{R,i}\|^2 - \frac{\epsilon^2}{\alpha}.
\]

The second part is directly followed from Theorem 1. Moreover, we have \(p_i = \Theta(k/m)\) and \(q_i = \Theta(1)\), then \(\alpha = \Theta(k/m)\), \(\beta = \Theta(m/k)\) and \(\gamma_s = O(k^3/mn^2)\). Then \(g^s_{R,i}\) is \((\Omega(k/m), \Omega(m/k), O(k^3/mn^2))-\)correlated with the true solution \(A^*_{R,i}\).

**Proof of Theorem 6.** The descent in Theorem 6 directly follows from the above lemma. Next, we will establish the nearness for the update at step \(s\):

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Figure 1: (top) The performance of four methods on three metrics (recovery rate, reconstruction error and running time) in sample size in the noiseless case. (bottom) The same metrics are measured for the noisy case.

4.2 Nearness

**Lemma 7.** Suppose that \( A^s \) is \((\delta, 2)\)-near to \( A^* \), then \( \| A^{s+1} - A^* \| \leq 2 \| A^* \| \)

**Proof.** From Lemma 5 we have \( g^s_i = p_i^* q_i (\lambda_i A^s_i - A^*_{i}) + A_{-i} \text{diag}(q_{ij}) A^T_{-i} A^s_{ji} \pm \zeta \). Denote \( \bar{R} = [n] \setminus R \), then it is obvious that \( g^s_{\bar{R}, i} = A_{\bar{R}, -i} \text{diag}(q_{ij}) A^T_{-i} A^s_{ji} \pm \zeta \) is bounded by \( O(k^2/m^2) \). Then we follows the proof of Lemma 24 in (Arora et al., 2015) for the nearness with full \( g^s = g^s_{R, i} + g^s_{\bar{R}, i} \) to finish the proof for this lemma.

In sum, we have shown the descent property of Algorithm 2 in the infinite sample case. The study of the concentration of \( \hat{g}^s \) around its mean to the sample complexity is provided in Section D. In the next section, we corroborate our theory by some numerical results on synthetic data.

5. Empirical Study

We compare our method with three different methods for both standard sparse and double-sparse coding. For the standard approach, we implement the algorithm proposed in Arora et al. (2015), which currently is the best theoretically sound method for provable sparse coding. However, since their method does not explicitly leverage the double-sparsity model, we also implement a heuristic modification that performs a hard thresholding (HT)-based post-processing step in the initialization and learning procedures (which we dub \( \text{Arora + HT} \)). The final comparison is the \textit{Trainlets} approach of Sulam et al. (2016).
We generate a synthetic training dataset according to the model described in Section 2. The base dictionary $\Phi$ is the identity matrix of size $n = 64$ and the square synthesis matrix $A^*$ is a block diagonal matrix with 32 blocks. Each $2 \times 2$ block is of form $[1 1; 1 -1]$ (i.e., the column sparsity $r = 2$). The support of $x^*$ is drawn uniformly over all 6-dimensional subsets of $[m]$, and the nonzero coefficients are randomly set to $\pm 1$ with equal probability. In our simulations with noise, we add Gaussian noise $\varepsilon$ with entrywise variance $\sigma^2 = 0.01$ to each of those above samples. For all the approaches except Trainlets, we use $T = 2000$ iterations for the initialization procedure, and set the number of steps in the descent stage to 25. Since Trainlets does not have a specified initialization procedure, we initialize it with a random Gaussian matrix upon which column-wise sparse thresholding is then performed. The learning step of Trainlets is executed for 50 iterations, which tolerates its initialization deficiency. For each Monte Carlo trial, we uniformly draw $p$ samples, feed these samples to the four different algorithms, and observe their ability to reconstruct $A^*$. Matlab implementation of our algorithms is available online.

We evaluate these approaches on three metrics as a function of the number of available samples: (i) fraction of trials in which each algorithm successfully recovers the ground truth $A^*$; (ii) reconstruction error; and (iii) running time. The synthesis matrix is said to be “successfully recovered” if the Frobenius norm of the difference between the estimate $\hat{A}$ and the ground truth $A^*$ is smaller than a threshold which is set to $10^{-4}$ in the noiseless case, and to 0.5 in the other. All three metrics are averaged over 100 Monte Carlo simulations. As discussed above, the Frobenius norm is only meaningful under a suitable permutation and sign flip transformation linking $\hat{A}$ and $A^*$. We estimate this transformation using a simple maximum weight matching algorithm. Specifically, we construct a weighted bipartite graph with nodes representing columns of $A^*$ and $\hat{A}$ and adjacency matrix defined as $G = |A^T \hat{A}|$, where $|$ is taken element-wise. We compute the optimal matching using the Hungarian algorithm, and then estimate the sign flips by looking at the sign of the inner products between the matched columns.

The results of our experiments are shown in Figure 1 with the top and bottom rows respectively for the noiseless and noisy cases. The two leftmost figures suggest that all algorithms exhibit a “phase transitions” in sample complexity that occurs in the range of 500-2000 samples. In the noiseless case, our method achieves the phase transition with the fewest number of samples. In the noisy case, our method nearly matches the best sample complexity performance (next to Trainlets, which is a heuristic and computationally expensive). Our method achieves the best performance in terms of (wall-clock) running time in all cases.

6. Conclusion

In this paper, we have addressed an open theoretical question on learning sparse dictionaries under a special type of generative model. Our proposed algorithm consists of a novel initialization step followed by a descent-style step, both are able to take advantage of the sparse structure. We rigorously demonstrate its efficacy in both sample- and computation-complexity over existing heuristics as well as provable approaches for double-sparse and regular sparse coding. This results in the first known provable approach for double-sparse coding problem with statistical and algorithmic guarantees. Besides, we also show three benefits of our approach: neural plausibility, robustness to noise and practical usefulness via the numerical experiments.

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2. We utilize Trainlets’s implementation provided at http://jsulam.cswp.cs.technion.ac.il/home/software/.
3. https://github.com/thanh-isu/double-sparse-coding
Nevertheless, several fundamental questions regarding our approach remain. First, our initialization method (in the overcomplete case) achieves its theoretical guarantees under fairly stringent limitations on the sparsity level $r$. This arises due to our reweighted spectral initialization strategy, and it is an open question whether a better initialization strategy exists (or whether these types of initialization are required at all). Second, our analysis holds for complete (fixed) bases $\Phi$, and it remains open to study the setting where $\Phi$ is over-complete. Finally, understanding the reasons behind the very promising practical performance of methods based on heuristics, such as Trainlets, on real-world data remains a very challenging open problem.
Appendix A. Auxiliary Lemma

Claim 1 (Maximal row $\ell_1$-norm). Given that $\|A^*\|_F^2 = m$ and $\|A^*\| = O(\sqrt{m/n})$, then $\|A^T\|_{1,2} = \Theta(\sqrt{m/n})$.

Proof. Recall the definition of the operator norm:

$$\|A^T\|_{1,2} = \sup_{x \neq 0} \frac{\|A^T x\|}{\|x\|_1} \leq \sup_{x \neq 0} \frac{\|A^T x\|}{\|x\|} = \|A^*\| = O(\sqrt{m/n}).$$

Since $\|A^*\|_F^2 = m$, $\|A^T\|_{1,2} \geq \|A^*\|_F \sqrt{n} = \sqrt{m/n}$. Combining with the above, we have $\|A^T\|_{1,2} = \Theta(\sqrt{m/n})$.

Along with Assumptions A1 and A3, the above claim implies the number of nonzero entries in each row is $O(r)$. This Claim is an important ingredient in our analysis of our initialization algorithm shown in Section 3.

Appendix B. Analysis of Initialization Algorithm

B.1 Proof of Lemma 1

The proof of Lemma 1 can be divided into three steps: 1) we first establish useful properties of $\beta$ with respect to $\alpha$; 2) we then explicitly derive $e_i$ in terms of the generative model parameters and $\beta$; and 3) we finally bound the error terms in $E$ based on the first result and appropriate assumptions.

Claim 2. In the generative model, $\|x^*\| \leq \tilde{O}(\sqrt{k})$ and $\|\varepsilon\| \leq \tilde{O}(\sigma_{\varepsilon} \sqrt{n})$ with high probability.

Proof. The claim directly follows from the fact that $x^*$ is a $k$-sparse random vector whose nonzero entries are independent sub-Gaussian with variance 1. Meanwhile, $\varepsilon$ has $n$ independent Gaussian entries of variance $\sigma_{\varepsilon}^2$.

Despite its simplicity, this claim will be used in many proofs throughout the paper. Note also that in this section we will calculate the expectation over $y$ and often refer probabilistic bounds (w.h.p.) under the randomness of $u$ and $v$.

Claim 3. Suppose that $u = A^* \alpha + \varepsilon_u$ is a random sample and $U = \text{supp}(\alpha)$. Let $\beta = A^T u$, then, w.h.p., we have (a) $|\beta_i - \alpha_i| \leq \frac{\mu k \log n}{\sqrt{n}} + \sigma_{\varepsilon} \log n$ for each $i$ and (b) $\|\beta\| \leq \tilde{O}(\sqrt{k} + \sigma_{\varepsilon} \sqrt{n})$.

Proof. The proof mostly follows from Claim 36 of Arora et al. (2015), with an additional consideration of the error $\varepsilon_u$. Write $W = U \setminus \{i\}$ and observe that

$$|\beta_i - \alpha_i| = |A_i^T A_{iW}^* \alpha_W + A_i^T \varepsilon_u| \leq |\langle A_i^T A_{iW}^* , \alpha_W \rangle| + |\langle A_i^* , \varepsilon_u \rangle|$$

Since $A^*$ is $\mu$-incoherence, then $\|A_i^T A_{iW}^*\| \leq \mu \sqrt{k/n}$. Moreover, $\alpha_W$ has $k-1$ independent sub-Gaussian entries of variance 1, therefore $|\langle A_i^T A_{iW}^* , \alpha_W \rangle| \leq \frac{\mu k \log n}{\sqrt{n}}$ with high probability. Also recall that $\varepsilon_u$ has independent Gaussian entries of variance $\sigma_{\varepsilon}^2$, then $A_i^T \varepsilon_u$ is Gaussian with the same variance ($|\langle A_i^* , \varepsilon \rangle| = 1$). Hence $|A_i^T \varepsilon_u| \leq \sigma_{\varepsilon} \log n$ with high probability. Consequently, $|\beta_i - \alpha_i| \leq \frac{\mu k \log n}{\sqrt{n}} + \sigma_{\varepsilon} \log n$, which is the first part of the claim.

Next, in order to bound $\|\beta\|$, we express $\beta$ as

$$\|\beta\| = \|A^T A_{iU}^* \alpha_U + A^T \varepsilon_u\| \leq \|A^*\| \|A_{iU}^*\| \|\alpha_U\| + \|A^*\| \|\varepsilon_u\|$$
Because \( x \)

Claim 4. In the decomposition

We bound the remaining terms separately in the following claims. We decompose

We will use these results multiple times in the next few proofs.

Claim 3 suggests that the difference between

Using Claim 2 to get \( \|\alpha_U\| \leq \tilde{O}(\sqrt{k}) \) and \( \|\varepsilon_u\| \leq \tilde{O}(\sigma_e \sqrt{n}) \) w.h.p., and further noticing that \( \|A_{*U}\| \leq \|A^*\| \leq O(1) \), we complete the proof for the second part.

Proof of Lemma 1. We decompose \( d_l \) into small parts so that the stochastic model \( D \) is made use.

where the terms are

Because \( x^* \) and \( \varepsilon \) are independent and zero-mean, \( E_2 \) and \( E_4 \) are clearly zero. Moreover,

\[
E_6 = (\beta v^T + \beta^* u^T)\mathbb{E}[\varepsilon \varepsilon_l^2] = 0
\]
due to the fact that \( \mathbb{E}[\varepsilon_j \varepsilon_l^2] = 0 \), for \( j \neq l \), and \( \mathbb{E}[\varepsilon_l^3] = 0 \). Also,

\[
E_8 = A_{*l}^\top \mathbb{E}[x^*] \mathbb{E}[u^T \varepsilon \varepsilon_T v \varepsilon_l] = 0.
\]

We bound the remaining terms separately in the following claims.

Claim 4. In the decomposition (5), \( E_1 \) is of the form

where all those terms except \( \sum_{i \in U \cap V} q_i c_i \beta_i \beta_i' A_{li}^2 \) have magnitude at most \( O^*(k/m \log^2 n) \) w.h.p.
Proof. Using the generative model in Assumptions B1-B4, we have

$$E_1 = \mathbb{E}[(x^*, \beta^*)(x^*, \beta')^T(A_i^*, x^*)^2]$$
$$= \mathbb{E}_S[\mathbb{E}_{x^*|S} \left[ \sum_{i \in S} \beta_i x_i^* \left( \sum_{i \in S} A_i^* x_i^* \right)^2 \right]]$$
$$= \sum_{i \in [m]} q_i c_i \beta_i \beta_i' A_i^* + \sum_{i, j \in [m], j \neq i} q_{ij} (\beta_i \beta_i' A_i^2 + 2 \beta_i \beta_j' A_i^* A_j^*)$$
$$= \sum_{i \in U \cap V} q_i c_i \beta_i \beta_i' A_i^* + \sum_{i, j \in U \cap V} q_{ij} (\beta_i \beta_i' A_i^2)$$

where we have used the $q_i = \mathbb{P}[i \in S]$, $q_{ij} = \mathbb{P}[i, j \in S]$ and $c_i = \mathbb{E}[x_i^2 | i \in S]$ and Assumptions B1-B4. We now prove that the last three terms are upper bounded by $O^*(k/m \log n)$. The key observation is that all these terms typically involve a quadratic form of the $l$-th row $A_i^*$ whose norm is bounded by $O(1)$ (by Claim 1 and Assumption A4). Moreover, $|\beta_i \beta_i'|$ is relatively small for $i \notin U \cap V$ while $q_{ij} = \Theta(k^2/m^2)$. For the second term, we apply the Claim 3 for $i \in [m] \setminus (U \cap V)$ to bound $|\beta_i \beta_i'|$. Assume $\alpha_i = 0$ and $\alpha_i' \neq 0$, then with high probability

$$|\beta_i \beta_i'| \leq |(\beta_i - \alpha_i)(\beta_i' - \alpha_i')| + |\beta_i \alpha_i'| \leq O^*(1/\log n)$$

Using the bound $q_i c_i = \Theta(k/m)$, we have w.h.p.,

$$\sum_{i \in U \cap V} q_i c_i \beta_i \beta_i' A_i^2 \leq \max_i |\beta_i \beta_i'| \sum_{i \in U \cap V} A_i^2 \leq \max_i |\beta_i \beta_i'| \|A_i^*\|_2^2 \leq O^*(k/m \log n).$$

For the third term, we make the bounds on $\|\beta\|$ and $\|\beta'\|$ from the previous claim where $\|\beta\||\beta'| \leq \tilde{O}(k)$ w.h.p., and on $q_{ij} = \Theta(k^2/m^2)$. More precisely, w.h.p.,

$$\sum_{j \neq i} q_{ij} \beta_i \beta_i' A_i^2 \leq \left( \max_{i \neq j} q_{ij} \right) \sum_i |\beta_i \beta_i'| \left( \sum_j A_i^2 \right) \leq \left( \max_{i \neq j} q_{ij} \right) \|\beta\||\beta'| \|A_i^*\|_2^2 \leq \tilde{O}(k^3/m^2),$$

where the second last inequality follows from the Cauchy-Schwarz inequality. For the last term, we write it in a matrix form as $\sum_{j \neq i} q_{ij} \beta_i \beta_i' A_i^* A_j^* = A_i^* Q_\beta A_i^*$ where $(Q_\beta)_{ij} = q_{ij} \beta_i \beta_j'$ for $i \neq j$ and $(Q_\beta)_{ij} = 0$ for $i = j$. Then

$$\|A_i^* Q_\beta A_i^*\| \leq \|Q_\beta\| \|A_i^*\|_2^2 \leq \|Q_\beta\|_F \|A_i^*\|_2^2,$$

where $\|Q_\beta\|_F = \sum_{i \neq j} q_{ij}^2 \beta_i^2 (\beta_j')^2 \leq \left( \max_{i \neq j} q_{ij}^2 \right) \sum_i \beta_i^2 \sum_j (\beta_j')^2 \leq \left( \max_{i \neq j} q_{ij}^2 \right) \|\beta\|_2 \|\beta'\|_2^2$. Ultimately,

$$\sum_{j \neq i} q_{ij} \beta_i \beta_i' A_i^* A_j^* \leq \left( \max_{i \neq j} q_{ij} \right) \|\beta\||\beta'| \|A_i^*\|_2^2 \leq \tilde{O}(k^3/m^2).$$

Under Assumption $k = O^*(\sqrt{n})$, then $\tilde{O}(k^3/m^2) \leq O^*(k/m \log^2 n)$. As a result, the two terms above are bounded by the same amount $O^*(k/m \log n)$ w.h.p., so we complete the proof of the claim. \qed
Claim 5. In the decomposition (5), $|E_3|$, $|E_5|$, $|E_7|$ and $|E_9|$ is at most $O^*(k/m \log^2 n)$.

Proof. Recall that $\mathbb{E}[x_i^2 \mathbb{1}[S] = 1$ and $q_i = \mathbb{P}[i \in S] = \Theta(k/m)$ for $S = \text{supp}(x^*)$, then

$$E_3 = \mathbb{E}[(x^*, \beta)^T(x^*, \beta) \varepsilon_i^2] = \sigma^2_{\varepsilon} \mathbb{E}[\mathbb{1}[S] \sum_{i,j \in S} \beta_i \beta_j x_i^* x_j^*]$$

$$= \sigma^2_{\varepsilon} \mathbb{E}[\sum_{i \in S} \beta_i \beta_j] = \sum_i \sigma^2_{\varepsilon} q_i \beta_i \beta_i$$

Denote $Q = \text{diag}(q_1, q_2, \ldots, q_m)$, then $|E_3| = |\sigma^2_{\varepsilon}(Q, \beta, \beta')| \leq \sigma^2_{\varepsilon} ||Q|| \||\beta|| \||\beta'|| \leq \tilde{O}(\sigma^2_{\varepsilon} k^2/m) = \tilde{O}(k^3/mn)$ where we have used $||\beta|| \leq \tilde{O}(\sqrt{k})$ w.h.p. and $\sigma_{\varepsilon} \leq O(1/\sqrt{n})$. For convenience, we handle the seventh term before $E_5$:

$$E_7 = \mathbb{E}[u^T \varepsilon \varepsilon^T v] = \mathbb{E}[(A^*_i, x^*)^2] u^T \mathbb{E}[\varepsilon \varepsilon^T] v = \sum_i \sigma^2_{\varepsilon} (u, v) q_i A^2_{ii} = \sigma^2_{\varepsilon} (u, v) A^T_i Q A_i$$

To bound this term, we use Claim 9 in Appendix D to have $||u|| = ||A^* \alpha + \varepsilon_u|| \leq \tilde{O}(\sqrt{k})$ w.h.p. and $\langle u, v \rangle \leq \tilde{O}(\sqrt{k})$ w.h.p. Consequently, $|E_7| \leq \sigma^2_{\varepsilon} ||Q|| ||A^*_i||^2 (u, v) \leq \tilde{O}(k^2/mn)$ because $||A^*_i||^2 \leq O(m/n)$ and $\sigma_{\varepsilon} \leq O(1/\sqrt{n})$. Now, the first term $E_5$ is expressed as follows

$$E_5 = \mathbb{E}[(A^*_i, x^*) x^T (\beta u^T + \beta' u^T) \varepsilon_i]$$

$$= A^T_i \mathbb{E}[x^T \varepsilon_i] (\beta u^T + \beta' u^T) \mathbb{E}[\varepsilon_i]$$

$$= \sigma^2_{\varepsilon} A^T_i Q (v_1 \beta + u_1 \beta')$$

Observe that $|E_5| \leq \sigma^2_{\varepsilon} ||A^*_i|| \||Q|| \||v_1 \beta + u_1 \beta'|| \leq \sigma^2_{\varepsilon} ||A^*_i|| \||Q|| \||v_1 \beta + u_1 \beta'||$ and that $||v_1 \beta + u_1 \beta'|| \leq 2||v|| ||\beta|| \leq \tilde{O}(k)$ w.h.p. using the result $||v|| \leq \tilde{O}(k)$ and $||\beta|| \leq \tilde{O}(k)$ from Claim 3, then $E_5$ bounded by $\tilde{O}(k^2/mn)$.

The last term

$$E_9 = \mathbb{E}[u^T \varepsilon \varepsilon^T v^2] = u^T \mathbb{E}[\varepsilon \varepsilon^T] v = 9 \sigma^4_{\varepsilon} (u, v)$$

because the independent entries of $\varepsilon$ and $\mathbb{E}[\varepsilon_i^2] = 9 \sigma^2_{\varepsilon}$. Therefore, $|E_9| \leq 9 \sigma^4_{\varepsilon} ||u|| ||v|| \leq \tilde{O}(k^2/n^2)$. Since $m = O(n)$ and $k \leq O^*(\sqrt{\log n})$, we obtain the same bound $O^*(k/m \log^2 n)$ for $|E_3|$, $|E_5|$, $|E_7|$ and $|E_9|$, and conclude the proof of the claim.

Combining the bounds from Claim 4, 5 for every single term in (5), we finish the proof for Lemma 1.

B.2 Proof of Lemma 2

We prove this lemma by using the same strategy used to prove Lemma 1.

$$M_{u,v} \triangleq \mathbb{E}[(y, u) \langle y, v \rangle y R^T]$$

$$= \mathbb{E}[(A^* x^* + \varepsilon, u) \langle A^* x^* + \varepsilon, v \rangle (A^*_R x^* + \varepsilon_R)(A^*_R x^* + \varepsilon_R)^T]$$

$$= \mathbb{E}[(x^*, \beta) \langle x^*, \beta' \rangle + x^T (\beta u^T + \beta' u^T) \varepsilon + u^T \varepsilon \varepsilon^T] (A^*_R x^* x^T + A^*_R x^* \varepsilon_R + \varepsilon_R x^T A^*_R + \varepsilon_R \varepsilon_R^T)$$

$$= M_1 + \cdots + M_8,$$
in which only nontrivial terms are kept in place, including

\[
M_1 = \mathbb{E}[\langle x^*, \beta \rangle \langle x^*, \beta' \rangle A^*_{R, R} x^* x^{T} A^*_{R, R}]
\]

\[
M_2 = \mathbb{E}[\langle x^*, \beta \rangle \langle x^*, \beta' \rangle \varepsilon_{R, \varepsilon_{R}}]
\]

\[
M_3 = \mathbb{E}[x^* T (\beta v^{T} + \beta' u^{T}) \varepsilon A^*_{R, R} x^* e^{T}_{R}]
\]

\[
M_4 = \mathbb{E}[x^* T (\beta v^{T} + \beta' u^{T}) \varepsilon_{R, x^* T} A^*_{R, R}]
\]

\[
M_5 = \mathbb{E}[u^{T} \varepsilon_{R, v} A^*_{R, R} x^* x^{T} A^*_{R, R}]
\]

\[
M_6 = \mathbb{E}[u^{T} \varepsilon_{R, v} A^*_{R, R} x^* e^{T}_{R}]
\]

\[
M_7 = \mathbb{E}[u^{T} \varepsilon_{R, v} x^* T A^*_{R, R}]
\]

\[
M_8 = \mathbb{E}[u^{T} \varepsilon_{R, v} x^* e^{T}_{R}]
\]

(6)

By swapping inner product terms and taking advantage of the independence, we can show that

\[
M_6 = \mathbb{E}[A^*_{R, R} x^* u^{T} \varepsilon T v e^{T}_{R}] = 0
\]

and

\[
M_7 = \mathbb{E}[u^{T} \varepsilon_{R, v} x^* T A^*_{R, R}] = 0
\]

The remaining are bounded in the next claims.

**Claim 6. In the decomposition (6),**

\[
M_1 = \sum_{i \in U \cap V} q_{i} c_{i} \beta_{i} A^*_{R, i} A^*_{R, i} + E_{1} + E_{2} + E_{3}
\]

where \( E_{1} = \sum_{i \not\in U \cap V} q_{i} c_{i} \beta_{i} A^*_{R, i} A^*_{R, i} \), \( E_{2} = \sum_{i \neq j} q_{ij} \beta_{i} \beta_{j} A^*_{R, i} A^*_{R, j} \), and \( E_{3} = \sum_{i \neq j} q_{ij} (\beta_{i} A^*_{R, i} \beta_{j} A^*_{R, j} + \beta_{j} A^*_{R, i} \beta_{i} A^*_{R, j}) \) have norms bounded by \( O^{*}(k/m \log n) \).

**Proof.** The expression of \( M_1 \) is obtained in the same way as \( E_1 \) is derived in the proof of Lemma 1. To prove the claim, we bound all the terms with respect to the spectral norm of \( A^*_{R, R} \) and make use of Assumption A4 to find the exact upper bound.

For the first term \( E_{1} \), rewrite \( E_{1} = A^*_{R, S} D_{1} A^*_{R, S} \) where \( S = [m]\setminus(U \cap V) \) and \( D_{1} \) is a diagonal matrix whose entries are \( q_{i} c_{i} \beta_{i} \). Clearly, \( \| D_{1} \| \leq \max_{i \in S} |q_{i} c_{i} \beta_{i}| \leq O^{*}(k/m \log n) \) as shown in Claim 4. then

\[
\| E_{1} \| \leq \max_{i \in S} |q_{i} c_{i} \beta_{i}| \| A^*_{R, S} \|^2 \leq \max_{i \in S} |q_{i} c_{i} \beta_{i}| \| A^*_{R, R} \|^2 \leq O^{*}(k/m \log n)
\]

where \( \| A^*_{R, S} \| \leq \| A^*_{R, R} \| \leq O(1) \). The second term \( E_{2} \) is a sum of positive semidefinite matrices, and \( \| \beta \| \leq O(k \log n) \), then

\[
E_{2} = \sum_{i \neq j} q_{ij} \beta_{i} \beta_{j} A^*_{R, i} A^*_{R, j} \leq \max_{i \neq j} q_{ij} \left( \sum_{i} \beta_{i} \beta_{i}^{T} \right) \left( \sum_{j} A^*_{R, j} A^*_{R, j}^{T} \right) \leq (\max_{i \neq j} q_{ij}) \| \beta \| \| \beta' \| \| A^*_{R, R} \|^2
\]

which implies that \( \| E_{2} \| \leq (\max_{i \neq j} q_{ij}) \| \beta \| \| \beta' \| \| A^*_{R, R} \|^2 \leq O(k^3/m^2) \). Observe that \( E_{3} \) has the same form as the last term in Claim 4, which is \( E_{3} = A^*_{R, R} Q_{\beta} A^*_{R, R} \). Then

\[
\| E_{3} \| \leq \| Q_{\beta} \| \| A^*_{R, R} \|^2 \leq (\max_{i \neq j} q_{ij}) \| \beta \| \| \beta' \| \| A^*_{R, R} \|^2 \leq O(k^3/m^2)
\]

By Claim 3, we have \( \| \beta \| \) and \( \| \beta' \| \) are bounded by \( O(\sqrt{k \log n}) \), and note that \( k \leq O^{*}(\sqrt{n} / \log n) \), then we complete the proof for Lemma 6. \( \square \)
Lemma 8. We follow (Arora et al., 2015) to derive the closed form of $g$. We can see that 

$$R = \sum_i \sigma_i^2 q_{i} \beta_i \|\beta_i\|.$$ 

Then, $\|M_2\| \leq \sigma_i^2 \max_i \|\beta_i\| \|\beta_i\| \leq O(\sigma_i^2 k^2 \log^2 n/m)$. 

The next three terms all involve $A_{R*}^T$ whose norm is bounded according to Assumption A4. Specifically,

$$M_3 = \mathbb{E}[x^T (\beta v^T + \beta' u^T)e A_{R*}^T x^T e_{R}] = \mathbb{E}[A_{R*}^T x^T x^T (\beta v^T + \beta' u^T)e e_{R}]$$

$$= A_{R*}^T \mathbb{E}[x^T (\beta v^T + \beta' u^T)e e_{R}],$$

and

$$M_4 = \mathbb{E}[x^T (\beta v^T + \beta' u^T)e A_{R*}^T x^T A_{R*}^T e] = \mathbb{E}[A_{R*}^T e (\beta v^T + \beta' u^T)e e_{R}]$$

$$= \mathbb{E}[A_{R*}^T e (\beta v^T + \beta' u^T)e e_{R}] = \mathbb{E}[A_{R*}^T (\beta v^T + \beta' u^T)]A_{R*}^T,$$

and the fifth term $M_5 = \mathbb{E}[u^T \epsilon e_R x^T A_{R*}^T x^T A_{R*}^T e] = \sigma_i^2 u^T v A_{R*}^T \mathbb{E}[x^T x^T]A_{R*}^T = \sigma_i^2 u^T v A_{R*}^T Q A_{R*}^T$, 

We already have $\mathbb{E}[\mathbb{E}[\epsilon_R e_R]] = \sigma_i^2 \epsilon$, $\|Q\| \leq O(k/m)$ and $|u^T v| \leq O(k)$ (proof of Claim 9), then the remaining work is to bound $\|\beta v^T + \beta' u^T\|$, then the bound of $\|\beta v^T + \beta' u^T\|$ directly follows. We have $\|\beta v^T\| = \|A^* u^T v\| \leq \|A^*\| \|u\| \|v\| \leq \tilde{O}(k)$. Therefore, all three terms $M_3$, $M_4$ and $M_5$ are bounded in norm by $\tilde{O}(\sigma_i^2 k^3/m) \leq O(k^3/mn)$. 

The remaining term is

$$M_8 = \mathbb{E}[u^T \epsilon e_R x^T e_{R}] = \mathbb{E}[\sum_{i,j} u_{i} v_{j} e_{i} e_{j} e_{R}]$$

$$\leq \mathbb{E}[\sum_{i} u_{i} v_{i} e_{i} e_{R}] + \mathbb{E}[\sum_{i \neq j} u_{i} v_{j} e_{i} e_{j} e_{R}]$$

$$= \sigma_i^4 u R v R,$$

where $u_R = A_{R*}^T \alpha + (\epsilon_u) R$ and $v_R = A_{R*}^T \alpha' + (\epsilon_v) R$. We can see that $\|u_R\| \leq \|A_{R*}^T\| \|\alpha\| + \|\epsilon_u\| R \leq \tilde{O}(\sqrt{k})$. Therefore, $\|M_8\| \leq \tilde{O}(\sigma_i^4 k) = \tilde{O}(k^3/n^2)$. Since $m = O(n)$ and $k \leq O^*(\frac{\sqrt{n}}{\log n})$, then we can bound the above terms by $O^*(k/m \log n)$ and finish the proof of Claim 7. 

Combine the results of Claim 6 and 7, we complete the proof of Lemma 2.

Appendix C. Analysis of Main Algorithm

C.1 Simple Encoding

We can see that $(A^* x - y)\text{sgn}(x)^T$ is random over $y$ and $x$ that is obtained from the encoding step. We follow (Arora et al., 2015) to derive the closed form of $g^* = \mathbb{E}[(A^* x - y)\text{sgn}(x)^T]$ by proving that the encoding recovers the sign of $x^*$ with high probability as long as $A^*$ is close enough to $A^*$.

Lemma 8. Assume that $A^*$ is $\delta$-close to $A^*$ for $\delta = O(r/n \log n)$ and $\mu \leq \frac{\sqrt{n}}{2\kappa}$, and $k \geq \Omega(\log m)$ then with probability over random samples $y = A^* x^* + \varepsilon$

$$\text{sgn}(\text{threshold}_{C/2}(A^* y)) = \text{sgn}(x^*)$$ (7)
Proof of Lemma 8. We follow the same proof strategy from (Arora et al., 2015) (Lemmas 16 and 17) to prove a more general version in which the noise $\varepsilon$ is taken into account. Write $S = \text{supp}(x^*)$ and skip the superscript $s$ on $A^*$ for the readability. What we need is to show $S = \{i \in [m] : \langle A^*_i, y \rangle \geq C/2 \}$ and then $\text{sgn}(\langle A^*_i, y \rangle) = \text{sgn}(x^*_i)$ for each $i \in S$ with high probability. Following the same argument of (Arora et al., 2015), we prove in below a stronger statement that, even conditioned on the support $S$, $S = \{i \in [m] : \langle A^*_i, y \rangle \geq C/2 \}$ with high probability.

Rewrite

$$\langle A^*_i, y \rangle = \langle A^*_i, A^* x^* + \varepsilon \rangle = \langle A^*_i, A^* x^*_i \rangle + \sum_{j \neq i} \langle A^*_i, A^*_j \rangle x^*_j + \langle A^*_i, \varepsilon \rangle,$$

and observe that, due to the closeness of $A^*_i$ and $A^*_j$, the first term is either close to $x^*_i$ or equal to 0 depending on whether or not $i \in S$. Meanwhile, the rest are small due to the incoherence and the concentration in the weighted average of noise. We will show that both $Z_i = \sum_{S \setminus \{i\}} \langle A^*_i, A^*_j \rangle x^*_j$ and $\langle A^*_i, \varepsilon \rangle$ are bounded by $C/8$ with high probability.

The cross-term $Z_i = \sum_{S \setminus \{i\}} \langle A^*_i, A^*_j \rangle x^*_j$ is a sum of zero-mean independent sub-Gaussian random variables, which is another sub-Gaussian random variable with variance $\sigma^2_{Z_i} = \sum_{S \setminus \{i\}} \langle A^*_i, A^*_j \rangle^2$. Note that

$$\langle A^*_i, A^*_j \rangle^2 \leq 2(\langle A^*_i, A^*_j \rangle^2 + \langle A^*_i - A^*_j, A^*_j \rangle^2) \leq 2\mu^2/n + 2(\langle A^*_i - A^*_j, A^*_j \rangle)^2,$$

where we use Cauchy-Schwarz inequality and the $\mu$-incoherence of $A^*$. Therefore,

$$\sigma^2_{Z_i} \leq 2\mu^2k/n + 2\|A^*_{S^c}(A^*_i - A^*_j)\|_F^2 \leq 2\mu^2k/n + 2\|A^*_{S^c}\|_F^2 \|A^*_i - A^*_j\|_F^2 \leq O(1/\log n),$$

under $\mu \leq \frac{\sqrt{n}}{\log n}$, to conclude $2\mu^2k/n \leq O(1/\log n)$ we need $1/k = O(1/\log n)$, i.e. $k = \Omega(\log n)$. Applying Bernstein’s inequality, we get $|Z_i| \leq C/8$ with high probability. What remains is to bound the noise term $\langle A^*_i, \varepsilon \rangle$. In fact, $\langle A^*_i, \varepsilon \rangle$ is sum of $n$ Gaussian random variables, which is a sub-Gaussian with variance $\sigma^2_\varepsilon$. It is easy to see that $|\langle A^*_i, \varepsilon \rangle| \leq \sigma_\varepsilon \log n$ with high probability. Notice that $\sigma_\varepsilon = O(1/\sqrt{n})$.

Finally, we combine these bounds to have $|Z_i + \langle A^*_i, \varepsilon \rangle| \leq C/4$. Therefore, for $i \in S$, then $|\langle A^*_i, y \rangle| \geq C/2$ and negligible otherwise. Using union bound for every $i = 1, 2, \ldots, m$, we finish the proof of the Lemma.

Lemma 8 enables us to derive the expected update direction $g^s = \mathbb{E}[(A^* x - y)\text{sgn}(x) T]$ explicitly.

C.2 Approximate Gradient in Expectation

Proof of Lemma 5. Having the result from Lemma 8, we are now able to study the expected update direction $g^s = \mathbb{E}[(A^* x - y)\text{sgn}(x) T]$. Recall that $A^*$ is the update at the $s$-th iteration and $x \triangleq \text{threshold}_{C/2}(A^* T y)$. Based on the generative model, denote $p_i = \mathbb{E}[x^*_i \text{sgn}(x^*_i)|i \in S], q_i = \mathbb{P}[i \in S]$ and $q_{ij} = \mathbb{P}[i, j \in S]$. Throughout this section, we will use $\zeta$ to denote any vector whose norm is negligible although they can be different across their appearances. $A_{-i}$ denotes the sub-matrix of $A$ whose $i$-th column is removed. To avoid overwhelming appearance of the superscript $s$, we skip it from $A^*$ for neatness. Denote $F_{x^*}$ is the event under which the support of $x$ is the same as that of $x^*$, and $\overline{F}_{x^*}$ is its complement. In other words, $1_{F_{x^*}} = 1[\text{sgn}(x) = \text{sgn}(x^*)]$ and $1_{F_{x^*}} + 1_{\overline{F}_{x^*}} = 1$.

$$g^s_i = \mathbb{E}[(A x - y)\text{sgn}(x_i)] = \mathbb{E}[(A x - y)\text{sgn}(x_i) 1_{F_{x^*}}] \pm \zeta$$
Using the fact that $y = A^*x^* + \varepsilon$ and that under $F_x$ we have $Ax = A_Sx_S = A_SA_S^Ty = A_SA_S^TA^*x^* + A_SA_S^T\varepsilon$. Using the independence of $\varepsilon$ and $x^*$ to get rid of the noise term, we get

$$g_{\star}^s = \mathbb{E}[(A_SA_S^T - I_n)A^*x^*1_{F_x\star}] + \mathbb{E}[(A_SA_S^T - I_n)\varepsilon\text{sgn}(x_i)1_{F_x\star}] \pm \zeta$$

$$= \mathbb{E}[(A_SA_S^T - I_n)A^*x^*\text{sgn}(x_i)1_{F_x\star}] \pm \zeta \quad \text{(Independence of $\varepsilon$ and $x^*$'s)}$$

$$= \mathbb{E}[(A_SA_S^T - I_n)A^*x^*(x_i^*)^2 - 1_{F_x\star}] \pm \zeta \quad \text{(Under $F_x\star$ event)}$$

Recall from the generative model assumptions that $S = \text{supp}(x^*)$ is random and the entries of $x^*$ are pairwise independent given the support, so

$$g_{\star}^s = \mathbb{E}_S\mathbb{E}_{x^*\mid S}[(A_SA_S^T - I_n)A^*x^*\text{sgn}(x_i^*)] \pm \zeta$$

$$= p_i\mathbb{E}_{S,i\in S}[(A_SA_S^T - I_n)A_{\star}^i] \pm \zeta$$

$$= p_i\mathbb{E}_{S,i\in S}[(A_{\star}^i A_{\star}^T - I_n)A_{\star}^i] + p_i\mathbb{E}_{S,i\in S}[(\sum_{l\in S,l\neq i} A_{\star}^i A_{\star}^T A_{\star}^i)] \pm \zeta$$

$$= p_iq_i(A_{\star}^i A_{\star}^T - I_n)A_{\star}^i + p_i\sum_{l\in[m],l\neq i} q_{il} A_{\star}^l A_{\star}^T A_{\star}^i \pm \zeta$$

$$= p_iq_i(\lambda_i A_{\star}^i - A_{\star}^i) + p_iA_{\star,\cdot-i}\text{diag}(q_{ij})A_{\star,\cdot-i}^T A_{\star}^i \pm \zeta$$

where $\lambda_i^\star = (A_{\star}^i, A_{\star}^i)$. Let $\xi_{\star}^s = A_{R_{\star,\cdot-i}}\text{diag}(q_{ij})A_{\star,\cdot-i}^T A_{\star}^i / q_i$ for $j = 1, \ldots, m$, we now have the full expression of the expected approximate gradient at iteration $s$:

$$g_{R,\star}^s = p_iq_i(\lambda_i A_{R,\cdot-i}^s - A_{R,\cdot-i}^s + \xi_{\star}^s) \pm \zeta_R. \quad (8)$$

What remains is to bound norms of $\xi_s$ and $\zeta$. We have $\|A_{R_{\star,\cdot-i}}^s\| \leq \|A_{\star,\cdot-i}^s\| \leq O(\sqrt{m/n})$ w.h.p. Then, along with the fact that $\|A_{\star}^s\| = 1$, we can bound $\|\xi_{\star}^s\|$:

$$\|\xi_{\star}^s\| \leq \|A_{R_{\star,\cdot-i}}^s\| \max_{j \neq i} \frac{q_{ij}}{q_i} \|A_{\star,\cdot-i}^s\| \leq O(k/n). \quad (9)$$

Next, we show that norm of $\zeta$ is negligible. In fact, $F_{x^*}$ happens with very high probability, then it suffices to bound norm of $(Ax - y)\text{sgn}(x_i)$ which will be done using Lemma 12 and Lemma 11 in Section D. This concludes the proof for Lemma 5.

**Appendix D. Sample Complexity**

In previous sections, we rigorously analyzed both initialization and learning algorithms as if the expectations $g^s$, $e$ and $M_{u,v}$ were given. Here we show that corresponding estimates based on empirical means are sufficient for the algorithms to succeed, and identify how many samples are required. Technically, this requires the study of their concentrations around their expectations. Having had these concentrations, we are ready to prove Theorems 4 and 5.

The entire section involves a variety of concentration bounds. Here we make heavy use of Bernstein’s inequality for different types of random variables (including scalar, vector and matrix). The Bernstein’s inequality is stated as follows.

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Lemma 9 (Bernstein’s Inequality). Suppose that $Z^{(1)}, Z^{(2)}, \ldots, Z^{(p)}$ are $p$ i.i.d. samples from some distribution $\mathcal{D}$. If $\mathbb{E}[Z] = 0$, $\|Z^{(j)}\| \leq \mathcal{R}$ almost surely and $\|\mathbb{E}[Z^{(j)}](Z^{(j)})^T\| \leq \sigma^2$ for each $j$, then

$$
\frac{1}{p} \| \sum_{j=1}^{p} Z^{(j)} \| \leq \tilde{O}\left( \frac{\mathcal{R}}{p} + \sqrt{\frac{\sigma^2}{p}} \right)
$$

(10)

holds with probability $1 - n^{-\omega(1)}$.

Since all random variables (or their norms) are not bounded almost surely in our model setting, we make use of a technical lemma that is used in Arora et al. (2015) to handle the issue.

Lemma 10 (Arora et al. (2015)). Suppose a random variable $Z$ satisfies $\mathbb{P}[\|Z\| \geq \mathcal{R}(\log(1/\rho))^C] \leq \rho$ for some constant $C > 0$, then

(a) If $p = n^{O(1)}$, it holds that $\|Z^{(j)}\| \leq \tilde{O}(\mathcal{R})$ for each $j$ with probability $1 - n^{-\omega(1)}$.

(b) $\|\mathbb{E}[Z^1_{\|Z\| \geq \tilde{O}(\mathcal{R})}]\| = n^{-\omega(1)}$.

This lemma suggests that if $\frac{1}{p} \sum_{i=1}^{p} Z^{(j)}(1 - 1_{\|Z^{(j)}\| \geq \tilde{O}(\mathcal{R})})$ concentrates around its mean with high probability, then so does $\frac{1}{p} \sum_{i=1}^{p} Z^{(j)}$ because the part outside the truncation level can be ignored. Since all random variables of our interest are sub-Gaussian or a product of sub-Gaussian random variables that satisfy this lemma, we can apply Lemma 9 to the corresponding truncated random variables with carefully chosen truncation levels. Then the original random variables concentrate likewise.

In the next proofs, we define suitable random variables and identify good bounds of $\mathcal{R}$ and $\sigma^2$ for them. Note that in this section, the expectations are taken over $y$ by conditioning on $u$ and $v$. This aligns with the construction that the estimators of $e$ and $M_{u,v}$ are empirical averages over i.i.d. samples of $y$, while $u$ and $v$ are kept fixed. Due to the dependency on $u$ and $v$, these (conditional) expectations inherit randomness from $u$ and $v$, and we will formulate probabilistic bounds for them.

The application of Bernstein’s inequality requires a bound on $\|\mathbb{E}[ZZ^T(1 - 1_{\|Z\| \geq \tilde{O}(\mathcal{R})})]\|$. We achieve that by the following technical lemma, where $\tilde{Z}$ is a standardized version of $Z$.

Lemma 11. Suppose a random variable $\tilde{Z}Z^T = aT$ where $a \geq 0$ and $T$ is positive semi-definite. They are both random. Suppose $\mathbb{P}[a \geq A] = n^{-\omega(1)}$ and $B > 0$ is a constant. Then,

$$
\|\mathbb{E}[\tilde{Z}Z^T(1 - 1_{\|\tilde{Z}\| \geq B})]\| \leq A\|\mathbb{E}[T]\| + O(n^{-\omega(1)})
$$

Proof. To show this, we make use of the decomposition $\tilde{Z}Z^T = aT$ and a truncation for $a$. Specifically,

$$
\|\mathbb{E}[\tilde{Z}Z^T(1 - 1_{\|\tilde{Z}\| \geq B})]\| = \mathbb{E}[aT(1 - 1_{\|\tilde{Z}\| \geq B})]
$$

$$
\leq \|\mathbb{E}[a(1 - 1_{a \geq A})T(1 - 1_{\|\tilde{Z}\| \geq B})]\| + \|\mathbb{E}[a1_{a \geq A}T(1 - 1_{\|\tilde{Z}\| \geq B})]\|
$$

$$
\leq \|\mathbb{E}[a(1 - 1_{a \geq A})T]\| + \|\mathbb{E}[a1_{a \geq A}T]\|(1 - 1_{\|\tilde{Z}\| \geq B})]
$$

$$
\leq A\|\mathbb{E}[T]\| + (\mathbb{E}[\|aT\|^2(1 - 1_{\|\tilde{Z}\| \geq B})]\mathbb{E}[1_{a \geq A}])^{1/2}
$$

$$
\leq A\|\mathbb{E}[T]\| + (\mathbb{E}[\|\tilde{Z}\|^4(1 - 1_{\|\tilde{Z}\| \geq B})]\mathbb{P}[a \geq A])^{1/2}
$$

$$
\leq A\|\mathbb{E}[T]\| + B^2(\mathbb{P}[a \geq A])^{1/2}
$$

$$
\leq A\|\mathbb{E}[T]\| + O(n^{-\omega(1)}),
$$

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where at the third step we used $T(1 - 1_{\|\hat{Z}\| \geq B}) \leq T$ because of the fact that $T$ is the positive semi-definite and $1 - 1_{\|\hat{Z}\| \geq B} \in \{0,1\}$ . Then, we finish the proof of the lemma.

\section*{D.1 Sample Complexity of Algorithm 1}

In Algorithm 1, we empirically compute the “scores” $\hat{e}$ and the reduced weighted covariance matrix $\hat{M}_{u,v}$ to produce an estimate for each column of $A^\ast$. Since the construction of $\hat{M}_{u,v}$ depends upon the support estimate $\hat{R}$ given by ranking $\hat{e}$, we denote it by $\hat{M}_{u,v}^\ast$. We will show that we only need $p = \hat{O}(m)$ samples to be able to recover the support of one particular atom and up to some specified level of column-wise error with high probability.

Lemma 12. Consider Algorithm 1 in which $p$ is the given number of samples. For any pair $u$ and $v$, then with high probability a) $\|\hat{e} - e\| \leq O^\ast(k/m \log^2 n)$ when $p = \Omega(m)$ and b) $\|\hat{M}_{u,v} - M_{u,v}^R\| \leq O^\ast(k/m \log n)$ when $p = \Omega(mr)$ where $\hat{R}$ and $R$ are respectively the estimated and correct support sets of one particular atom.

D.1.1 Proof of Theorem 4

Using Lemma 12, we are ready to prove the Theorem 4. According to Lemma 1 when $U \cap V = \{i\}$, we can write $\hat{e}$ as

$$\hat{e} =qc_i \beta_i' A_{R,i}^\ast \circ A_{R,i}^* + \text{ perturbation terms} + (\hat{e} - e),$$

and consider $\hat{e} - e$ as an additional perturbation with the same magnitude $O^\ast(k/m \log^2 n)$ in the sense of $\|\cdot\|_\infty$ w.h.p. The first part of Lemma 3 suggests that when $u$ and $v$ share exactly one atom $i$, then the set $\hat{R}$ including $r$ largest elements of $\hat{e}$ is the same as supp($A^\ast$) with high probability.

Once we have $\hat{R}$, we again write $\hat{M}_{u,v}^\ast$ using Lemma 2 as

$$\hat{M}_{u,v}^\ast = qc_i \beta_i' A_{R,i}^\ast \circ A_{R,i}^* + \text{ perturbation terms} + (\hat{M}_{u,v} - M^R_{u,v}),$$

and consider $\hat{M}_{u,v} - M^R_{u,v}$ as an additional perturbation with the same magnitude $O^\ast(k/m \log n)$ in the sense of the spectral norm $\|\cdot\|$ w.h.p. Using the second part of Lemma 3, we have the top singular vectors of $\hat{M}_{u,v}^\ast$ is $O^\ast(1/\log n)$-close to $A_{R,i}^\ast$ with high probability.

Since every vector added to the list $L$ in Algorithm 1 is close to one of the dictionary, then $A^0$ must be $\delta$-close to $A^\ast$. In addition, the nearness of $A^0$ to $A^\ast$ is guaranteed via an appropriate projection onto the convex set $B = \{A|A \text{ close to } A^0 \text{ and } ||A|| \leq 2||A^\ast||\}$. Finally, we finish the proof of Theorem 4.

D.1.2 Proof of Lemma 12, Part a

For some fixed $l \in [n]$, consider $p$ i.i.d. realizations $Z^{(1)}, Z^{(2)}, \ldots, Z^{(p)}$ of the random variable $Z \triangleq \langle y, u \rangle \langle y, v \rangle y_i^2$, then $\hat{e}_l = \frac{1}{p} \sum_{i=1}^p Z^{(i)}$ and $e_l = E[Z]$. To show that $\|\hat{e} - e\|_\infty \leq O^\ast(k/m \log^2 n)$ holds with high probability, we first study the concentration for the $l$-th entry of $\hat{e} - e$ and then take the union bound over all $l = 1, 2, \ldots, n$. We derive upper bounds for $|Z|$ and its variance $E[Z^2]$ in order to apply Bernstein’s inequality in (12) to the truncated version of $Z$.

Claim 8. $|Z| \leq \hat{O}(k)$ and $E[Z^2] \leq \hat{O}(k^2/m)$ with high probability.

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Again, the expectation is taken over \( y \) by conditioning on \( u \) and \( v \), and therefore is still random due to the randomness of \( u \) and \( v \). To show Claim 8, we begin with proving the following auxiliary claim.

**Claim 9.** \( \|y\| \leq \tilde{O}(\sqrt{k}) \) and \( \|\langle y, u \rangle\| \leq \tilde{O}(\sqrt{k}) \) with high probability.

**Proof.** From the generative model, we have

\[
\|y\| = \|A_S^*x_S + \varepsilon\| \leq \|A_S^*x_S\| + \|\varepsilon\| \leq \|A_S^*\|\|x_S\| + \|\varepsilon\|,
\]

where \( S = \text{supp}(x^*) \). From Claim 2, \( \|x_S^*\| \leq \tilde{O}(\sqrt{k}) \) and \( \|\varepsilon\| \leq \tilde{O}(\sigma \sqrt{n}) \) w.h.p. In addition, \( A^* \) is overcomplete and has bounded spectral norm, then \( \|A_S^*\| \leq \|A^*\| \leq O(1) \). Therefore, \( \|y\| \leq \tilde{O}(\sqrt{k}) \) w.h.p., which is the first part of the proof. To bound the second term, we write it as

\[
|\langle y, u \rangle| = |\langle A_S^*x_S + \varepsilon, u \rangle| \leq |\langle x_S^*, A_S^*u \rangle| + |\langle \varepsilon, u \rangle|.
\]

Similar to \( y \), we have \( \|u\| \leq \tilde{O}(\sqrt{k}) \) w.h.p. and hence \( \|A_S^*u\| \leq \|A_S^*\|\|u\| \leq O(\sqrt{k}) \) with high probability. Since \( u \) and \( x^* \) are independent sub-Gaussian and \( \langle x_S^*, A_S^*u \rangle \) are sub-exponential with variance at most \( O(\sqrt{k}) \), \( |\langle x_S^*, A_S^*u \rangle| \leq \tilde{O}(k) \) w.h.p. Similarly, \( |\langle \varepsilon, u \rangle| \leq \tilde{O}(\sqrt{k}) \) w.h.p. Consequently, \( |\langle y, u \rangle| \leq \tilde{O}(\sqrt{k}) \) w.h.p., and we conclude the proof of the claim.

**Proof of Claim 8.** We have \( Z = \langle y, v \rangle y_i^2 = \langle y, u \rangle \langle y, v \rangle (\langle A_{1b}^*, x^* \rangle + \varepsilon_i)^2 \) with \( \langle y, u \rangle \langle y, v \rangle \leq \tilde{O}(k) \) w.h.p. according to Claim 9. What remains is to bound \( y_i^2 = (\langle A_{1b}^*, x^* \rangle + \varepsilon_i)^2 \). Because \( \langle A_{1b}^*, x^* \rangle \) is sub-Gaussian with variance \( \mathbb{E}_S(\sum_{i \in S} A_{i}^2) \leq \|A^*\|_{1,2}^2 = O(1) \), then \( |\langle A_{1b}^*, x^* \rangle| \leq O(\log n) \) w.h.p. Similarly for \( \varepsilon_i, |\varepsilon_i| \leq O(\sigma \log n) \) w.h.p. Ultimately, \( |\langle A_{1b}^*, x^* \rangle + \varepsilon_i| \leq O(\log n) \), and hence we obtain with high probability the bound \( |Z| \leq \tilde{O}(k) \).

To bound the variance term, we write \( Z^2 = \langle y, v \rangle^2 y_i^2 \langle y, u \rangle^2 y_i^2 \). Note that, from the first part, we get \( \langle y, v \rangle^2 y_i^2 \leq \tilde{O}(k) \) and \( |Z| \leq \tilde{O}(k) \) w.h.p.. We apply Lemma 11 with some appropriate scaling to both terms, then

\[
\mathbb{E}[Z^2(1 - 1_{|Z| \geq \tilde{O}(k)})] \leq \tilde{O}(k)\mathbb{E}[\langle y, u \rangle^2 y_i^2] + O(n^{-\omega(1)}),
\]

where \( \mathbb{E}[\langle y, u \rangle^2 y_i^2] \) is equal to \( e_i \) for pair \( u, v \) with \( v = u \). From Lemma 1 and its proof in Appendix Section “Analysis of Initialization Algorithm”,

\[
\mathbb{E}[\langle y, u \rangle^2 y_i^2] = \sum_{i=1}^{m} q_i c_i \beta_i^2 A_{ii}^2 + \text{perturbation terms},
\]

in which the perturbation terms are bounded by \( O^*(k/m \log^2 n) \) w.h.p. (following Claims 4 and 5). The dominant term \( \sum_i q_i c_i \beta_i^2 A_{ii}^2 \leq (\max q_i c_i \beta_i^2)\|A_{1b}^*\|^2 \leq \tilde{O}(k/m) \) w.h.p. because \( |\beta_i| \leq O(\log m) \) (Claim 3). Then we complete the proof of the second part.

**Proof of Lemma 12, Part a.** We are now ready to prove Part a of Lemma 12. We apply Bernstein’s inequality in Lemma 9 for the truncated random variable \( Z^{(i)}(1 - 1_{|Z^{(i)}| \geq \tilde{O}(R)}) \) with \( R = \tilde{O}(k) \) and variance \( \sigma^2 = \tilde{O}(k^2/m) \) from Claim 8, then

\[
\left\| \frac{1}{p} \sum_{i=1}^{p} Z^{(i)}(1 - 1_{|Z^{(i)}| \geq \tilde{O}(R)}) - \mathbb{E}[Z(1 - 1_{|Z| \geq \tilde{O}(R)})] \right\| \leq \frac{\tilde{O}(k)}{p} + \sqrt{\frac{\tilde{O}(k^2/m)}{p}} \leq O^*(k/m \log n), \quad (11)
\]
whereas \( \| R \)σ and variance \( Z \) variable. This implies to prove the concentration inequalities for the case when conditioned on the event that \( Z \).  

**Proof.** We take advantage of the bounds of \( Z \). Finally, the variance bound is \( \tilde{O}(kr) \). The second part is handled similarly as in the proof of Claim 8. We take advantage of the bounds of \( Z \). Specifically, using the first part \( \| Z \| \leq \tilde{O}(kr) \) and \( \langle y, v \rangle \| y \| R \)w.h.p., then applying Lemma 11, then \( \| E[Z^T(1 - 1_{\| Z \| \geq \tilde{O}(kr)})] \| \leq \tilde{O}(kr)\| E[(y, u) y R^T] \| + \tilde{O}(kr)O(n^{-\omega(1)}) \leq \tilde{O}(kr)\| M_{u,u} \| , \)

where \( M_{u,u} \) arises from the application of Lemma 2. Recall that

\[
M_{u,u} = \sum_i q_i c_i \beta_i^2 A_{R,i}^* A_{R,i}^T + \text{perturbation terms,}
\]

where the perturbation terms are all bounded by \( O^*(k/m \log n) \) w.h.p. by Claims 6 and 7. In addition,

\[
\| \sum_i q_i c_i \beta_i^2 A_{R,i}^* A_{R,i}^T \| \leq (\max_i q_i c_i \beta_i^2) \| A_{R,i}^* \| ^2 \leq \tilde{O}(k/m) \| A^* \| ^2 \leq \tilde{O}(k/m)
\]

w.h.p. Finally, the variance bound is \( \tilde{O}(k^2 r/m) \) w.h.p.

Then, applying Bernstein’s inequality in Lemma 9 to the truncated version of \( Z \) with \( R = \tilde{O}(kr) \) and variance \( \sigma^2 = \tilde{O}(k^2 r/m) \) and obtain the concentration for the full \( Z \) to get

\[
\| \tilde{M}_{u,v}^R - M_{u,v}^R \| \leq \frac{\tilde{O}(kr)}{p} + \sqrt{\frac{\tilde{O}(k^2 r/m)}{p}} \leq O^*(k/m \log n)
\]

w.h.p. when the number of samples is \( p = \tilde{O}(mr) \) under Assumption **A4.1**.

We have proved that \( \| \tilde{M}_{u,v}^R - M_{u,v}^R \| \leq O^*(k/m \log n) \) as conditioned on the support consistency event holds w.h.p. \( \| \tilde{M}_{u,v}^R - M_{u,v}^R \| \leq O^*(k/m \log n) \) is easily followed by the law of total probability through the tail bounds on the conditional and marginal probabilities (i.e. \( P[\| \tilde{M}_{u,v}^R - M_{u,v}^R \| \leq O^*(k/m \log n) | R = \tilde{R} R] \) and \( P[\tilde{R} \neq R] \). We finish the proof of Lemma 12, Part b for both cases of the spectral bounds. \( \square \)
D.2 Proof of Theorem 5 and Sample Complexity of Algorithm 2

In this section, we prove Theorem 5 and identify sample complexity per iteration of Algorithm 2. We divide the proof into two steps: 1) show that when $A^s$ is $(\delta_s, 2)$-near to $A^*$ for $\delta_s = O^*(1/\log n)$, the approximate gradient estimate $\hat{g}^s$ is $(\alpha, \beta, \gamma_s)$-correlated-whp with $A^*$ with $\gamma_s \leq O(k^2/mn) + o(\delta_s^2)$, and 2) show that the nearness is preserved at each iteration. These correspond to showing the following lemmas:

**Lemma 13.** At iteration $s$ of Algorithm 2, suppose that $A^s$ has each column correctly supported and is $(\delta_s, 2)$-near to $A^*$ and that $\eta = O(m/k)$. Denote $R = \text{supp}(A^s_{*,i})$, then the update $\hat{g}^s_{R,i}$ is $(\alpha, \beta, \gamma_s)$-correlated-whp with $A^*_{R,i}$ where $\alpha = \Omega(k/m)$, $\beta = \Omega(m/k)$ and $\gamma_s \leq O(k^2/mn) + o(\delta_s^2)$ for $\delta_s = O^*(1/\log n)$.

Note that this is a finite-sample version of Lemma 6.

**Lemma 14.** If $A^s$ is $(\delta_s, 2)$-near to $A^*$ and number of samples used in step $s$ is $p = \tilde{\Omega}(m)$, then with high probability $\|A^{s+1} - A^*\| \leq 2\|A^*\|$.

Proof of Theorem 5. The correlation of $\hat{g}_i$ with $A^*_i$, described in Lemma 13, implies the descent of column-wise error according to Theorem 1. Along with Lemma 14, the theorem follows directly.

D.2.1 Proof of Lemma 13

We prove Lemma 13 by obtaining a tail bound on the difference between $\hat{g}^s_{R,i}$ and $g^s_{R,i}$ using the Bernstein’s inequality in Lemma 9.

**Lemma 15.** At iteration $s$ of Algorithm 2, suppose that $A^s$ has each column correctly supported and is $(\delta_s, 2)$-near to $A^*$. For $R = \text{supp}(A^s_{*,i}) = \text{supp}(A^*_i)$, then $\|\hat{g}^s_{R,i} - g^s_{R,i}\| \leq O(k/m) \cdot (o(\delta_s) + O(\epsilon_s))$ with high probability for $\delta_s = O^*(1/\log n)$ and $\epsilon_s = O(\sqrt{k/n})$ when $p = \tilde{\Omega}(m + \sigma^2 x_{\text{max}}/k)$.

To prove this lemma, we study the concentration of $\hat{g}^s_{R,i}$, which is a sum of random vector of the form $(y - Ax)_{R\text{sgn}(x_i)}$. We consider random variable $Z \triangleq (y - Ax)_{R\text{sgn}(x_i)}|i \in S$, with $S = \text{supp}(x^*)$ and $x = \text{threshold}_{C/2}(A^Ty)$. Then, using the following technical lemma to bridge the gap in concentration of the two variables. We adopt this strategy from Arora et al. (2015) for our purpose.

**Claim 11.** Suppose that $Z^{(1)}, Z^{(2)}, \ldots, Z^{(N)}$ are i.i.d. samples of the random variable $Z = (y - Ax)_{R\text{sgn}(x_i)}|i \in S$. Then,

$$\left\| \frac{1}{N} \sum_{j=1}^{N} Z^{(j)} - E[Z] \right\| \leq o(\delta_s) + O(\epsilon_s)$$

(12)

holds with probability when $N = \tilde{\Omega}(k + \sigma^2 x_{\text{max}})$, $\delta_s = O^*(1/\log n)$ and $\epsilon_s = O(\sqrt{k/n})$.

Proof of Lemma 15. Once we have done the proof of Claim 11, we can easily prove Lemma 15. We recycle the proof of Lemma 43 in Arora et al. (2015).

Write $W = \{j : i \in \text{supp}(x^{(j)}_*)\}$ and $N = |W|$, then express $\hat{g}^s_{R,i}$ as

$$\hat{g}^s_{R,i} = \frac{N}{p} \frac{1}{N} \sum_{j} (y^{(j)}_i - Ax^{(j)}_{R\text{sgn}(x^{(j)}_i)})$$

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where \( \frac{1}{N} \sum_j (y^{(j)} - Ax^{(j)})R\text{sgn}(x^{(j)}) \) is distributed as \( \frac{1}{N} \sum_{j=1}^N Z^{(j)} \) with \( N = |W| \). Note that
\[
\mathbb{E}[(y - Ax)R\text{sgn}(x)] = \mathbb{E}[(y - Ax)R\text{sgn}(x)_i1_{i \in S}] = \mathbb{E}[Z]|_{i \in S} = q_i\mathbb{E}[Z] \text{ with } q_i = \Theta(k/m).
\]
Following Claim 11, we have
\[
\|g_{R,i}^* - g_{R,i}\| \leq O(k/m) \left\| \frac{1}{N} \sum_{j=1}^N Z^{(j)} - \mathbb{E}[Z] \right\| \leq O(k/m) \cdot (o(\delta) + O(\epsilon)),
\]
holds with high probability as \( p = \Omega(mN/k) \). Substituting \( N \) in Claim 11, we obtain the results in Lemma 15.

**Proof of Claim 11.** We are now ready to prove the claim. What we need are good bounds for \( \|Z\| \) and its variance, then we can apply Bernstein’s inequality in Lemma 9 for the truncated version of \( Z \), then \( Z \) is also concentrates likewise.

**Claim 12.** \( \|Z\| \leq \mathcal{R} \) holds with high probability for \( \mathcal{R} = \tilde{O}(\delta_s\sqrt{k} + \mu k/\sqrt{n} + \sigma \epsilon \sqrt{n}) \) with \( \delta_s = O^*(1/\log n) \).

**Proof.** From the generative model and the support consistency of the encoding step, we have
\[
y = A^*x^* + \epsilon = A^*_S x^*_S + \epsilon \text{ and } x_S = A^T_S y = A^*_S A^*_S x^*_S + A^*_S \epsilon. \]

Then,
\[
(y - Ax)_R = (A^*_R S x^*_S + \epsilon_R) - A_R S A^*_S A^*_S x^*_S - A_R S A^*_S \epsilon = (A^*_R - A_R S) x^*_S + A_R S (I_k - A^*_S A^*_S) x^*_S + (I_n - A^*_S A^*_S) R \epsilon.
\]

Using the fact that \( x^*_S \) and \( \epsilon \) are sub-Gaussian and that \( \|MW\| \leq \tilde{O}(\sigma_w \|M\|_F) \) holds with high probability for a fixed \( M \) and a sub-Gaussian \( w \) of variance \( \sigma^2_w \), we have
\[
\| (y - Ax) R \text{sgn}(x) \| \leq \tilde{O}(\|A^*_R S - A_R S\|_F + \|A_R S (I_k - A^*_S A^*_S)\|_F + \sigma \epsilon \| (I_n - A^*_S A^*_S) R \|_F).
\]

Now, we need to bound those Frobenius norms. The first quantity is easily bounded as
\[
\|A^*_R S - A_R S\|_F \leq \| A^*_S - A_S \|_F \leq \delta_s \sqrt{k},
\]

since \( A \) is \( \delta_s \)-close to \( A^* \). To handle the other two, we use the fact that \( \|UV\| \leq \|U\|\|V\|_F \). Using this fact for the second term, we have
\[
\|A_R S (I_k - A^*_S A^*_S)\|_F \leq \|A_R S\| \|(I_k - A^*_S A^*_S)\|_F,
\]

where \( \|A_R S\| \leq \|A_R \| \leq O(1) \) due to the nearness. The second part is rearranged to take advantage of the closeness and incoherence properties:
\[
\|I_k - A^T_S A^*_S\|_F \leq \|I_k - A^*_S A^*_S - (A_S - A^*_S) A^*_S\|_F
\leq \|I_k - A^T_S A^*_S\|_F + \|(A_S - A^*_S) A^*_S\|_F
\leq \|I_k - A^T_S A^*_S\|_F + \|A^*_S\| \|A_S - A^*_S\|_F
\leq \mu k/\sqrt{n} + O(\delta_s \sqrt{k}),
\]

where we have used \( \|I_k - A^T_S A^*_S\|_F \leq \mu k/\sqrt{n} \) because of the \( \mu \)-incoherence of \( A^* \), \( \|A_S - A^*_S\|_F \leq \delta_s \sqrt{k} \) in (13) and \( \|A^*_S\| \leq \|A^*\| \leq O(1) \). Accordingly, the second Frobenius norm is bounded by
\[
\|A_R S (I_k - A^T_S A^*_S)\|_F \leq O(\mu k/\sqrt{n} + \delta_s \sqrt{k}).
\]
The noise term is handled using the eigen-decomposition $UΛU^T$ of $A^*S_A^T S$, then with high probability
\[
\| (I_n - A^*S_A^T S)R \|_F = \| (UU^T - UΛU^T)R \|_F = \| UR(I_n - Λ) \|_F \leq \| I_n - Λ \| \| UR \|_F \leq O(\sqrt{r}),
\]
where the last inequality $\| I_n - Λ \| \leq O(1)$ follows by $\| A^*S \| \leq \| A \| \leq \| A - A^* \| + \| A^* \| \leq 3\| A^* \| \leq O(1)$ due to the nearness. Putting (13), (14) and (15) together, we obtain the bounds in Claim 12.

Next, we determine a bound for the variance of $Z$.

**Claim 13.** $E[\| Z \|_2^2] = E[\| (y - Ax)Rsgn(x_i) \|_2^2 | i \in S] \leq σ^2$ holds with high probability for $σ^2 = O(\delta^2 k + k^2/n + σ^2 r)$ with $δ_s = O^*(1/\log n)$.

**Proof.** We explicitly calculate the variance using the fact that $x^*_S$ is conditionally independent given $S$, and so is $ε$. $x^*_S$ and $ε$ are also independent and have zero mean. Then we can decompose the norm into three terms in which the dot product is zero in expectation and the others can be shortened using the fact that $E[x^*_S x^*_S^T] = I_k$, $E[εε^T] = σ^2 I_n$.

\[
E[\| (y - Ax)Rsgn(x_i) \|_2^2 | i \in S] = E[\| (A^*_{RS} - A_{RS}^*S_A^T S^*S) x^*_S + (I_n - A^*S_A^T S^*S) R_r 2 | i \in S] = E[\| A^*_{RS} - A_{RS}^*S_A^T S^*S \|_F^2 | i \in S] + σ^2 E[\| I_n - A^*S_A^T S^*S \|_F^2 | i \in S].
\]

Then, by re-writing $A^*_{RS} - A_{RS}^*S_A^T S^*S$ as before, we get the form $(A^*_{RS} - A_{RS}^*) + A_{RS}(I_k - A^*S_A^T S^*S)$ in which the first term has norm bounded by $δ_s \sqrt{k}$. The second is further decomposed as
\[
E[\| A_{RS}(I_k - A^*S_A^T S^*S) \|_F^2 | i \in S] \leq \text{sup}_S \| A_{RS} \| \| I_k - A^*S_A^T S^*S \|_F^2 | i \in S],
\]
where $\text{sup}_S \| A_{RS} \| \leq \| A_R \| \leq O(1)$. We will bound $E[\| I_k - A^*S_A^T S^*S \|_F^2 | i \in S] \leq O(k^2/\delta_s^2) + O(k^2/n)$ using the proof from Arora et al. (2015):

\[
E[\| I_k - A^*S_A^T S^*S \|_F^2 | i \in S] = E[\| (I_k - A^*S_A^T S^*S) \|_F^2 | i \in S] = E[\| (1 - A^*S_A^T S^*S) \|_F^2 | i \in S] = E[\sum_{j \in S} (1 - A^*_{ij} S^*_{ij})^2 + \sum_{j \in S} A^*_{ij} S^*_{ij} - A_{ij} S_{ij} | i \in S] = E[\| A_{ij} - A^*_{ij} | i \in S] + \sum_{j \in S} q_{ij} \| A^*_{ij} S^*_{ij} - A_{ij} S_{ij} | i \in S] + q_i \| A^*_{ij} S^*_{ij} - A_{ij} S_{ij} | i \in S] + q_i \| A^*_{ij} S^*_{ij} - A_{ij} S_{ij} | i \in S].
\]

where $A_{ij}$ is the matrix $A$ with the $i$-th column removed, $q_{ij} \leq O(k^2/m^2)$ and $q_i \leq O(k/m)$. For any $j = 1, 2, \ldots, m$,
\[
\| A^*_{ij} S^*_{ij} - A_{ij} S_{ij} | i \in S] + q_i \| A^*_{ij} S^*_{ij} - A_{ij} S_{ij} | i \in S] + q_i \| A^*_{ij} S^*_{ij} - A_{ij} S_{ij} | i \in S].
\]

The last inequality invokes the $μ$-incoherence, $δ$-closeness and the spectral norm of $A^*$. Similarly, we come up with the same bound for $\| A^*_{ij} S^*_{ij} - A_{ij} S_{ij} | i \in S] + q_i \| A^*_{ij} S^*_{ij} - A_{ij} S_{ij} | i \in S] + q_i \| A^*_{ij} S^*_{ij} - A_{ij} S_{ij} | i \in S]$.

\[
E[\| I_k - A^*S_A^T S^*S \|_F^2 | i \in S] \leq O(k^2/\delta_s^2) + O(k^2/n).
\]
Putting (16), (17) and (18) together and using \( \| A_{Ri} \| \leq 1 \), we obtain the variance bound of \( Z^s \):
\[
\sigma^2 = O(\delta_s^2 k + k^2/n + \sigma_z^2 r) \quad \text{with} \quad \delta_s = O(1/\log^2 n) .
\]
Finally, we complete the proof.

We now apply truncated Bernstein’s inequality to the random variable \( Z^{(j)}(1 - 1/\|Z^{(j)}\|_{\geq \Omega(R)}) \) with \( R \) and \( \sigma^2 \) in Claims 12 and 13, which are \( R = \tilde{O}(\delta_s \sqrt{k} + \mu k/\sqrt{n} + \sigma_z \sqrt{r}) \) and \( \sigma^2 = O(\delta_s^2 k + k^2/n + \sigma_z^2 r) \). Then, \( (1/N) \sum_j Z^{(j)} \) also concentrates:
\[
\left\| \frac{1}{N} \sum_{i=1}^N Z^{(j)} - E[Z] \right\| \leq \tilde{O}\left( \frac{R}{N} \right) + \tilde{O}\left( \sqrt{\frac{\sigma^2}{N}} \right) = o(\delta_s) + O(\sqrt{k/n})
\]
holds with high probability when \( N = \tilde{O}(k + \sigma_z^2 nr) \). Then, we finally finish the proof of Claim 11.

**Proof of Lemma 13.** With Claim 11, we study the concentration of \( \tilde{g}_{R_i}^s \) around its mean \( g_{R_i}^s \). Now, we consider this difference as an error term of the expectation \( g_{R_i}^s \) and using Lemma 6 to show the correlation of \( \tilde{g}_{R_i}^s \). Using the expression in Lemma 5 with high probability, we can write
\[
\tilde{g}_{R_i}^s = g_{R_i}^s + (g_{R_i}^s - \tilde{g}_{R_i}^s) = 2\alpha(A_{R,i}^* - A_{R,i}^s) + v,
\]
where \( \| v \| \leq \alpha \| A_{R,i}^* - A_{R,i}^s \| + O(k/m) \cdot (o(\delta_s) + O(\epsilon_s)) \). By Lemma 6, we have \( \tilde{g}_{R_i}^s \) is \((\alpha, \beta, \gamma_s)\)-correlated-whp with \( A_{R_i}^* \) where \( \alpha = \Omega(k/m) \), \( \beta = \Omega(m/k) \) and \( \gamma_s \leq O(k/m) \cdot (o(\delta_s) + O(\sqrt{k/n})) \), then we have done the proof Lemma 13.

**D.2.2 Proof of Lemma 14**

We have shown the correlation of \( \tilde{g}^s \) with \( A^* \) w.h.p. and established the descent property of Algorithm 2. The next step is to show that the nearness is preserved at each iteration. To prove \( \| A^{s+1} - A^* \| \leq 2 \| A^* \| \) holds with high probability, we recall the update rule
\[
A^{s+1} = A^s - \eta \mathcal{P}_H(\tilde{g}^s),
\]
where \( \mathcal{P}_H(\tilde{g}^s) = H \circ \tilde{g}^s \). Here \( H = (h_{ij}) \) where \( h_{ij} = 1 \) if \( i \in \text{supp}(A_{i,j}) \) and \( h_{ij} = 0 \) otherwise. Also, note that \( A^s \) is \((\delta_s, 2)\)-near to \( A^* \) for \( \delta_s = O^*(1/\log n) \). We already proved that this holds for the exact expectation \( g^s \) in Lemma 7. To prove for \( \tilde{g}^s \), we again apply matrix Bernstein’s inequality to bound \( \| \mathcal{P}_H(g^s) - \mathcal{P}_H(\tilde{g}^s) \| \) by \( O(k/m) \) because \( \eta = \Theta(m/k) \) and \( \| A^* \| = O(1) \).

Consider a matrix random variable \( Z \triangleq \mathcal{P}_H((y - Ax)\text{sgn}(x)^T) \). Our goal is to bound the spectral norm \( \| Z \| \) and, both \( \| \mathbb{E}[Z Z^T] \| \) and \( \| \mathbb{E}[Z^T Z] \| \) since \( Z \) is asymmetric. To simplify our notations, we denote by \( x_R \) the vector \( x \) by zeroing out the elements not in \( R \). Also, denote \( R_i = \text{supp}(h_{i,j}) \) and \( S = \text{supp}(x) \). Then \( Z \) can be written explicitly as
\[
Z = [(y - Ax)_{R_1, \text{sgn}(x_1)}, \ldots, (y - Ax)_{R_m, \text{sgn}(x_m)}],
\]
where many columns are zero since \( x \) is \( k \)-sparse. The following claims follow from the proof of Claim 42 in Arora et al. (2015). Here we state and detail some important steps.

**Claim 14.** \( \| Z \| \leq \tilde{O}(k) \) holds with high probability.
Proof. With high probability
\[ \|Z\| \leq \sqrt{\sum_{i \in S} \| (y - Ax)_{R_i} \|_2^2} \leq \sqrt{k} \| (y - Ax)_{R_i} \| \]
where we use Claim 12 with \( \| (y - Ax)_{R} \| \leq \tilde{O}(\delta \sqrt{k}) \) w.h.p., then \( \|Z\| \leq \tilde{O}(k) \) holds w.h.p.

**Claim 15.** \( \|E[Z^T Z]\| \leq O(k^2/n) \) and \( \|E[Z^T Z]\| \leq \tilde{O}(k^2/n) \) with high probability.

**Proof.** The first term is easily handled. Specifically, with high probability
\[ \|E[Z^T Z]\| \leq \|E[\sum_{i \in S} (y - Ax)_{R_i} \text{sgn}(x_i) \| (y - Ax)_{R_i} \|_2^2] \| = \|E[\sum_{i \in S} (y - Ax)_{R_i} (y - Ax)_{R_i}^T] \| \leq O(k^2/n), \]
where the last inequality follows from the proof of Claim 42 in Arora et al. (2015), which is tedious to be repeated.

To bound \( \|E[Z^T Z]\| \), we use bound of the full matrix \( (y - Ax)\text{sgn}(x)^T \). Note that \( \|y - Ax\| \leq \tilde{O}(\sqrt{k}) \) w.h.p. is similar to what derived in Claim 12. Then with high probability,
\[ \|E[Z^T Z]\| \leq \|E[\text{sgn}(x) (y - Ax)^T (y - Ax) \text{sgn}(x)^T] \| \leq \tilde{O}(k) \|E[\text{sgn}(x) \text{sgn}(x)^T] \| \leq \tilde{O}(k^2/m). \]
where \( E[\text{sgn}(x) \text{sgn}(x)^T] = \text{diag}(q_1, q_2, \ldots, q_m) \) has norm bounded by \( O(k/m) \). We now can apply Bernstein’s inequality for the truncated version of \( Z \) with \( \mathcal{R} = \tilde{O}(k) \) and \( \sigma^2 = \tilde{O}(k^2/m) \), then with \( p = \tilde{O}(m) \),
\[ \|P_H(g^*) - P_H(\mathcal{G}^*)\| \leq \frac{\tilde{O}(k)}{p} + \sqrt{\frac{\tilde{O}(k^2/m)}{p}} \leq O^*(k/m) \]
holds with high probability. Finally, we invoke the bound \( \eta = O(m/k) \) and complete the proof.

**Appendix E. A Special Case: Orthonormal \( A^* \)**

We extend our results for the special case where the dictionary is orthonormal. As such, the dictionary is perfectly incoherent and bounded (i.e., \( \mu = 0 \) and \( \|A^*\| = 1 \)).

**Theorem 7.** Suppose that \( A^* \) is orthonormal. When \( p_1 = \tilde{O}(n) \) and \( p_2 = \tilde{O}(nr) \), then with high probability Algorithm 1 returns an initial estimate \( A^0 \) whose columns share the same support as \( A^* \) and with \( (\delta, 2) \)-nearness to \( A^* \) with \( \delta = O^*(1/\log n) \). The sparsity of \( A^* \) can be achieved up to \( r = O^*(\min(\sqrt{n}/\log^2 n, n/k^2 \log^2 n)) \).

We use the same initialization procedure for this special case and achieve a better order of \( r \). The proof of Theorem 7 follows the analysis for the general case with following two results:

**Claim 16** (Special case of Claim 3). Suppose that \( u = A^* \alpha + \varepsilon_u \) is a random sample and \( U = \text{supp}(\alpha) \). Let \( \beta = A^T u \), then w.h.p., we have (a) \( |\beta_i - \alpha_i| \leq \sigma \log n \) for each \( i \) and (b) \( \|\beta\| \leq O(\sqrt{k} \log n + \sigma \varepsilon \sqrt{n} \log n) \).

**Proof.** We have \( \beta = A^T u = \alpha + A^T \varepsilon_u \), then \( \beta_i - \alpha_i = \langle A^* \alpha, \varepsilon_u \rangle \) and \( \|\beta - \alpha\| = \|\varepsilon_u\| \). Using probability bounds of \( \langle A^* \alpha, \varepsilon_u \rangle \), \( \|\varepsilon_u\| \) and \( \|\alpha\| \) in Claim 2, we have the claim proved.

We draw from the claim that for any \( i \notin U \cap V \), \( |\beta_i| \leq O(\sigma \varepsilon \log^2 n) \) and have the following result:

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Lemma 16. Fix samples $u$ and $v$ and suppose that $y = A^* x^* + \varepsilon$ is a random sample independent of $u,v$. The expected value of the score for the $i^{th}$ component of $y$ is given by:

$$e_i \triangleq \mathbb{E}[(y, u)(y, v)q_i^2] = \sum_{i \in \text{UnV}} q_i c_i \beta_i \beta_i^* A_i^2 + \text{perturbation terms}$$

where $q_i = \mathbb{P}[i \in S]$, $q_{ij} = \mathbb{P}[i, j \in S]$ and $c_i = \mathbb{E}[x_i^4|i \in S]$. Moreover, the perturbation terms have absolute value at most $O^*(k/n \log^2 n \max(1/\sqrt{n}, k^2/n))$.

Proof. Lemma follows Lemma 1 via Claim 3 except that the second term of $E_1$ is bounded by $O(k \log^2 n/n^{3/2})$.

Appendix F. Extensions of Arora et al. (2015)

F.1 Sample complexity in noisy case

In this section, we study the sample complexity of the algorithms in Arora et al. (2015) in the presence of noise. While noise with order $\sigma = O(1/\sqrt{n})$ does not change the sample complexity of the initialization algorithm, it affects that of the descent stage. The analysis involves producing a sharp bound for $\|g_{*,i}^* - g_{*,i}\|$.

Lemma 17. For a regular dictionary $A^*$, suppose $A^*$ is $(\delta, 2)$-near to $A^*$ with $\delta = O^*(1/\log n)$, then with high probability $\|g_{*,i}^* - g_{*,i}\| \leq O(k/m) \cdot (\sigma(\delta) + O(\sqrt{k/n}))$ when $p = \tilde{\Omega}(m + \sigma^2 k n^2)$.

Proof. This follows directly from Lemma 15 where $r = n$. \hfill \Box

We tighten the original analysis to obtain the complexity $\tilde{\Omega}(m)$ instead of $\tilde{\Omega}(mk)$ for the noiseless case. Putting together with $p = \tilde{\Omega}(mk)$ required by the initialization, we then have the overall sample complexity $\tilde{O}(mk + \sigma^2 mn^2)$ for the algorithms in Arora et al. (2015) in the noise regime.

F.2 Extension of Arora et al. (2015)'s initialization algorithm for sparse case

We study a simple and straightforward extension of the initialization algorithm of Arora et al. (2015) for the sparse case. This extension is produced by adding an extra projection, and is described in Figure 3. The recovery of the support of $A^*$ is guaranteed by the following terms Lemma:

Lemma 18. Suppose that $z^* \in \mathbb{R}^n$ is $r$-sparse whose nonzero entries are at least $\tau$ in magnitude. Provided $z$ is $\delta$-close to $z^*$ and $z^0 = H_r(z)$ with $\delta = O^*(1/\log n)$ and $r = O^*(\log^2 n)$, then $z^0$ and $z^*$ has the same support.

Proof. Since $z^0$ is $\delta$-close to $z^*$, then $\|z^0 - z^*\| \leq \delta$ and $|z_i - z_i^*| \leq \delta$ for every $i$. For $i \in \text{supp}(z^*)$,

$$|z_i| \geq |z_i^*| - |z_i - z_i^*| \geq \tau - \delta$$

and for $i \notin \text{supp}(z^*)$, $|z_i| \leq \delta$. Since $\tau > O(1/\sqrt{n}) \gg \delta$, then the $r$-largest entries of $z$ are in the support $z^*$, and hence $z^0$ and $z^*$ has the same support. \hfill \Box

Theorem 8. Suppose that Assumptions B1-B4 hold and Assumptions A1-A3 satify with $\mu = O^*(\sqrt{n}/k \log n)$ and $r = O^*(\log^2 n)$. When $p_1 = \tilde{\Omega}(m)$ and $p_2 = \tilde{\Omega}(mk)$, then with high probability Algorithm 3 returns an initial estimate $A^0$ whose columns share the same support as $A^*$ and with $(\delta, 2)$-nearness to $A^*$ with $\delta = O^*(1/\log n)$.  

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Algorithm 3 Pairwise Reweighting with Hard-Thresholding

Initialize $L = \emptyset$
Randomly divide $p$ samples into two disjoint sets $P_1$ and $P_2$ of sizes $p_1$ and $p_2$ respectively

While $|L| < m$. Pick $u$ and $v$ from $P_1$ at random
Reconstruct the re-weighted covariance matrix $\hat{M}_{u,v}$:

$$\hat{M}_{u,v} = \frac{1}{p_2} \sum_{i=1}^{p_2} \langle y^{(i)}, u \rangle \langle y^{(i)}, v \rangle y^{(i)} (y^{(i)})^T$$

Compute the top singular values $\delta_1, \delta_2$ and top singular vector $z$ of $\hat{M}_{u,v}$
If $\delta_1 \geq \Omega(k/m)$ and $\delta_2 < O^*(k/m \log n)$
    $z = H_r(z)$, where $H_r$ keeps $r$ largest entries of $z$
If $z$ is not within distance $1/\log n$ of any vector in $L$ even with sign flip
    $L = L \cup \{z\}$
Return $A^0 = (L_1, \ldots, L_m)$

This algorithm requires $r = O^*(\log^2 n)$, which is somewhat better than ours. However, the sample complexity and running time is inferior as compared with our novel algorithm.

Appendix G. Neural Implementation of Our Approach

We now briefly describe why our algorithm is “neurally plausible”. Basically, similar to the argument in Arora et al. (2015), we describe at a very high level how our algorithm can be implemented via a neural network architecture. One should note that although both our initialization and descent stages are non-trivial modifications of those in Arora et al. (2015), both still inherit the nice neural plausibility property.

G.1 Neural implementation of Stage 1: Initialization

Recall that the initialization stage includes two main steps: (i) estimate the support of each column of the synthesis matrix, and (ii) compute the top principal component(s) of a certain truncated weighted covariance matrix. Both steps involve simple vector and matrix-vector manipulations that can be implemented plausibly using basic neuronal manipulations.

For the support estimation step, we compute the product $\langle y, u \rangle \langle y, u \rangle y \circ y$, followed by a thresholding. The inner products, $\langle y, u \rangle$ and $\langle y, v \rangle$ can be computed using neurons via an online manner where the samples arrive in sequence; the thresholding can be implemented via a ReLU-type non-linearity.

For the second step, it is well known that the top principal components of a matrix can be computed in a neural (Hebbian) fashion using Oja’s Rule Oja (1992).

G.2 Neural implementation of Stage 2: Descent

Our neural implementation of the descent stage (Algorithm 2), shown in Figure 2, mimics the architecture of Arora et al. (2015), which describes a simple two-layer network architecture for computing a single gradient update of $A$. The only difference in our case is that most of the value
\[ x = \text{threshold}(A^T y) \]

in \( A \) are set to zero, or in other words, our network is sparse. The network takes values \( y \) from the input layer and produces \( x \) as the output; there is an intermediate layer in between connecting the middle layer with the output via synapses. The synaptic weights are stored on \( A \). The weights are updated by Hebbian learning. In our case, since \( A \) is sparse (with support given by \( R \), as estimated in the first stage), we enforce the condition the corresponding synapses are inactive. In the output layer, as in the initialization stage, the neurons can use a ReLU-type non-linear activation function to enforce the sparsity of \( x \).

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