Node Embedding with Adaptive Similarities for Scalable Learning over Graphs

Dimitris Berberidis, Student Member, IEEE, and Georgios B. Giannakis, Fellow, IEEE,

Abstract—Node embedding is the task of extracting informative and descriptive features over the nodes of a graph. The importance of node embedding for graph analytics as well as learning tasks, such as node classification, link prediction, and community detection, has led to a growing interest and a number of recent advances. Nonetheless, node embedding faces several major challenges. Practical embedding methods have to deal with real-world graphs that arise from different domains, with inherently diverse underlying processes as well as similarity structures and metrics. On the other hand, similar to principal component analysis in feature vector spaces, node embedding is an inherently unsupervised task. Lacking metadata for validation, practical schemes motivate standardization and limited use of tunable hyperparameters. Finally, node embedding methods must be scalable in order to cope with large-scale real-world graphs of networks with ever-increasing size. The present work puts forth an adaptive node embedding framework that adjusts the embedding process to a given underlying graph, in a fully unsupervised manner. This is achieved by leveraging the notion of a tunable node similarity matrix that assigns weights on multihop paths. The design of multihop similarities ensures that the resultant embeddings also inherit interpretable spectral properties. The proposed model is thoroughly investigated, interpreted, and numerically evaluated using stochastic block models. Moreover, an unsupervised algorithm is developed for training the model parameters efficiently. Extensive node classification, link prediction, and clustering experiments are carried out on many real-world graphs from various domains, along with comparisons with state-of-the-art scalable and unsupervised node embedding alternatives. The proposed method enjoys superior performance in many cases, while also yielding interpretable information on the underlying graph structure.

Index Terms—SVD, SVM, unsupervised, multiscale, random walks, spectral

1 INTRODUCTION

Unsupervised node embedding is an exciting field, in which a significant amount of progress has been made in recent years [15]. The task consists of mapping each node of a graph to a vector in a low-dimensional Euclidean space. The main goal is to extract features that can be utilized downstream in order to perform a variety of unsupervised or (semi-)supervised learning tasks, such as node classification, link prediction, or clustering [16]. Ideally, it is desired for the embedded nodal vectors to convey at least as much information as the original graph. Nevertheless, an appropriate embedding can boost the performance of certain learning tasks because they allow one to work with the more “friendly” and intuitive Euclidean representation, and deploy mature and widely implemented feature-based algorithms such as (kernel) support vector machines (SVMs), logistic regression, and K-means.

Early embedding works mostly focused on a structure-preserving dimensionality reduction of feature vectors (instead of nodes); see for instance [22], [23], [24], [25], [26]. In this context, graphs are constructed from pairwise feature vector relations and are treated as representations of the manifold that data lie on; embedded vectors are then generated so that they preserve the corresponding pair-wise proximities on the manifold. More recently, nodal vector embedding of a graph has attracted considerable attention in different fields, and is often posed as the

factorization of a properly defined node similarity matrix [27], [28], [29], [30], [31], [32], [33], [34]. Efforts in this direction mostly focus on designing meaningful similarity metrics to factorize. While some methods (e.g. [27], [29]) maintain scalability by factorizing similarity matrices in an implicit manner (without explicitly forming them), others such as [30], [31] form and/or factorize dense similarity matrices that scale poorly to large graphs. Another line of work opts to gradually fit pairs of embedded vectors to existing edges using stochastic optimization tools [35], [37]. Such approaches are naturally scalable and entail a high degree of locality. Recently, stochastic edge-fitting has been generalized to implicitly accommodate long-range node similarities [36]. Meanwhile, other works have approached node embeddings using random-walk-based tools and concepts originating from natural language processing [38], [39], [40]; see also related works on embedding of knowledge graphs [41], [42]. Methods that rely on graph convolutional neural networks and autoencoders have also been proposed for node embedding [45], [46], [47]. Moreover, a gamut of related embedding tasks are gaining traction, such as embedding based on structural roles of nodes [43], [44], supervised embeddings for classification [11], and inductive embedding methods that utilize multiple graphs [6].

We identify the following challenges that need to be addressed in order to design embedding methods that are applicable in practice:

• Diversity. Since graphs that arise from different domains are generally characterized by a diverse set of properties, there may not be a “one-size-fits-all”
node embedding approach.

- **No supervision.** At the same time, node embedding may need to be performed in a fully unsupervised manner, that is, without extra information (node attributes, labels, or groundtruth communities) to guide the parameter tuning process with cross-validation.

- **Scalability.** While some real-world networks are of moderate size, others may contain massive numbers of nodes and edges. Specifically, graphs encountered with social networks, transportation networks, knowledge graphs and others, typically scale to millions of nodes and tens of millions of edges. Thus, strict computational constraints must be accounted by the design of node embedding methods.

In response to these challenges, we propose a scalable node embedding framework that is based on factorizing an adaptive node similarity matrix. The first challenge is addressed by utilizing a large family of node similarity metrics, parametrized by placing different weights on node proximities of different orders; see also our precursor work [20]. Experiments indicate that the proposed model for similarity metrics is expressive enough to describe real-world graphs from diverse domains and with different structures. To address the second challenge (lack of supervision), we put forth a self-supervised parameter learning scheme based on predicting randomly removed edges. Finally, we accommodate scalability by constraining the parametrization of similarity matrices such that the proximity order parameters carry over to the embedded vectors in a smooth manner. This allows for learning proximity order parameters directly on the feature vectors. Consequently, dense similarity matrices do not need to be explicitly formed and factorized, thus endowing the proposed method with the desired level of scalability.

The rest of the paper is organized as follows. Section 1 introduces the problem and the proposed similarity model. Section 2, presents a numerical study on the properties of the model, while Section 3 deals with learning the model parameters in an unsupervised manner. Finally, Sections 4 contains experiments on real graphs, comparisons with competing alternatives, and interpretation of the results.

**Notation.** Bold lower-case letters denote column vectors (e.g., $v$); bold upper-case letters denote matrices (e.g., $Q$). Vectors $q_j$ and $q_i^T$ denote the $j^{th}$ column and the $i^{th}$ row of $Q$, respectively; whereas $Q_{ij}$ (or sometimes for clarity $Q_{j,i}$) denotes the $ij^{th}$ entry of $Q$. Vector $e_N$ denotes the $K^{th}$ canonical column vector; and $\|\|_\cdot$ denotes the Euclidean norm, unless stated otherwise. Calligraphic upper-case letters denote sets (e.g., $U$); and finally, symbol := is used in definition statements.

## 2 Problem Statement and Modeling

Given an undirected graph $G := \{V,E\}$, where $V$ is the set of $N$ nodes, and $E \subseteq V \times V$ is the set of edges, the task of node embedding boils down to determining $f(\cdot) : V \to \mathbb{R}^d$, where $d \ll N$. In other works, a function is sought to map every node of $G$ to a vector in the $d$-dimensional Euclidean space. Typically, the embedding is low dimensional with $d$ much smaller than the number of nodes. Given $f(\cdot)$, the low-dimensional vector representation of each node $v_i$ is $e_i \leftrightarrow f(v_i) \leftrightarrow v_i \in V$.

Since the number of nodes is finite, instead of finding a general $f(\cdot)$ (induction), one may pose the embedding task in its most general form as the following minimization problem over the embedded vectors

$$\{e_i^N\}_{i=1}^N = \arg\min_{\{e_i\}_{i=1}^N} \sum_{v_i,v_j \in V} \ell(s_G(v_i,v_j), s_E(e_i,e_j)) \quad (1)$$

where $\ell(\cdot,\cdot) : \mathbb{R} \to \mathbb{R}$ is a loss function; $s_G(\cdot,\cdot) : V \times V \to \mathbb{R}$ is a similarity metric over pairs of graph nodes; and $s_E(\cdot,\cdot) : \mathbb{R}^d \times \mathbb{R}^d \to \mathbb{R}$ a similarity metric over pairs of vectors in the $d$-dimensional Euclidean space.

In par with (1), node embedding can be viewed as the design of nodal vectors $\{e_i\}_{i=1}^N$ that successfully “encode” a certain notion of pairwise similarities among graph nodes.

### 2.1 Embedding as matrix factorization

Starting from the generalized framework in (1), one may arrive at concrete approaches by specifying choices of $s_G(\cdot,\cdot)$, $s_E(\cdot,\cdot)$, and $\ell(\cdot,\cdot)$. To start, suppose that the node similarity metric is symmetric; that is, $s_G(v_i,v_j) = s_G(v_j,v_i) \forall v_i,v_j \in V$. Furthermore, let the loss function be quadratic

$$\ell(x,x') = (x-x')^2$$

and the nodal vector similarity be the inner product

$$s_E(e_i,e_j) = e_i^T e_j.$$  

Using these specifications, (1) reduces to the following symmetric matrix factorization problem

$$E^* = \arg\min_{E \in \mathbb{R}^{N \times d}} \|S_G - EE^T\|_F^2 \quad (2)$$

where $S_G \in \mathbb{R}^{N \times N}$ is the symmetric similarity matrix with $[S_G]_{i,j} = s_G(v_i,v_j)$, and matrix $E := [e_1 \ldots e_N]^T$ concatenates all node embeddings as rows. A well-known analytical solution to (2) relies on the singular value decomposition (SVD) of the similarity matrix, that is $S_G = U \Sigma V^T$, where $U$ and $V$ are the $N \times N$ unitary matrices formed by the left and right singular vectors, and $\Sigma$ is diagonal with non-negative singular values sorted in decreasing order; in our case, $U = V$ since $S_G$ is symmetric. Given the SVD of $S_G$, the low-rank ($d \ll N$) solver in (2) is $E^* = U d \Sigma_d^{1/2}$, where $\Sigma_d$ contains the $d$ largest singular values, and $d \Sigma_d$ the corresponding singular vectors. $S_G = U \Sigma V^T$ can be obtained directly using the reduced-complexity scheme known as truncated SVD.

If in addition $S_G$ is sparse, (3) can be solved even more efficiently, with complexity that scales with the number of edges. One such example with sparse similarities is when $S_G = A$, where $A$ is the graph adjacency matrix. Embeddings generally gain scalability by avoiding the explicit construction of a dense $S_G$. In fact, simply storing $S_G$ in the working memory becomes prohibitive even for graphs of moderate sizes (say $N > 10^5$).

In the ensuing section, we will design a family of dense similarity matrices that (among other properties) can be decomposed implicitly, at the cost of input sparsity.
2.2 Multihop graph node similarities

Having reduced the node embedding problem to the one in \( \mathbb{R}^K \), it remains to specify the graph similarity metric that gives rise to \( S_G \). Towards this end, and in order to maintain expressibility, we will design a parametric model for \( S_G \), with each pairwise node similarity metric expressed as

\[
s_g(v_i, v_j; \theta) = \sum_{k=1}^{K} \theta_k s_k(v_i, v_j), \quad \text{s.t. } \theta \in S^K
\]

(3)

where \( S^K := \{ \theta \in \mathbb{R}^K : \theta \geq 0, \theta^T 1 = 1 \} \) is the \( K \)-dimensional probability simplex, and \( s_k(v_i, v_j) \) is a similarity metric that depends on all \( k \)-hop paths of possibly repeated nodes that start from \( v_i \) and end at \( v_j \) (or vice-versa). Thus, \( s_g(\cdot; \cdot; \theta) \) contains all \( k \)-hop interactions between two nodes, each weighted by a non-negative importance score \( \theta_k \) with \( k = 1, \ldots, K \).

Let \( S \) be any similarity matrix that is characterized by the same sparsity pattern as the adjacency matrix, that is

\[
S_{i,j} = \begin{cases} s_{i,j}, & (i, j) \in E \\ 0, & (i, j) \notin E \end{cases}
\]

(4)

where \( s_{i,j} \)s denote the generic non-negative values of entries that correspond to edges of \( G \). Maintaining the same sparsity pattern as \( A \) allows for the \( (i, j) \) entry of \( S^K \) to be interpreted as a measure of influence between \( v_i \) and \( v_j \) that depends on all \( k \)-hop paths that connect them; that is, \( \{S^K\}_{i,j} = s_k(v_i, v_j) \). For instance, selecting \( S = A \) is equivalent to using the \( k \)-step similarity \( s_k(v_i, v_j) = ||\{k \text{-length paths connecting } v_i \text{ to } v_j\}|| \).

2.3 Spectral multihop embeddings

While any symmetric \( S \) that obeys (3) can be used for constructing multihop similarities (cf. (5)), judicious designs of \( S \) can effect certain desirable properties. Bearing this in mind, consider the following identity

\[
S \in \mathbb{P}_N^+ \iff S = U \Sigma U^T = U \Lambda U^T \quad (9)
\]

where \( \mathbb{P}_N^+ \) denotes the space of \( N \times N \) symmetric positive definite (SPD) matrices, and \( \Lambda \) is the diagonal matrix that contains the eigenvalues of \( S \) sorted in decreasing order. For SPD matrices as in (9), the SVD is identical to the eigenvalue decomposition (EVD). Thus, if \( S \in \mathbb{P}_N^+ \), the solution to (2) is also given as (cf. (5))

\[
E^*(\theta) = U_d \sqrt{\Lambda_d(\theta)} \quad (10)
\]

where \( U_d \) are also the first \( d \) eigenvectors of \( S \), and \( \Lambda_d(\theta) = \sum_{k=1}^{K} \theta_k \Lambda_k^d \) is the \( K \)th order polynomial of its eigenvalues defined by \( \theta \).

Consider now specifying \( S \) as

\[
S = \frac{1}{2} \left( I + D^{-1/2} AD^{-1/2} \right) \quad (11)
\]

Recalling that \( \lambda_i \left( D^{-1/2} AD^{-1/2} \right) \in [-1,1] \forall i \), and after using the identity shifting and scaling, we deduce that \( \lambda_i(S) \in [0,1] \forall i \); hence, matrix \( S \) in (11) is SPD. It can also be readily verified that the first \( d \) eigenvectors of \( S \) coincide with the eigenvectors corresponding to the \( d \) smallest eigenvalues of the symmetric normalized Laplacian matrix

\[
L_{sym} := I - D^{-1/2} AD^{-1/2} \quad (12)
\]

These smallest eigenvalues are known to contain useful information on cluster structures of different resolution levels, a key property that has been successfully employed by spectral clustering (17). Intuitively, assigning weight \( \theta_k \) to \( k \)-hop paths in the node similarity of (5), is equivalent to shrinking the \( d \)-dimensional spectral node embeddings (rows of \( U_d \)) coordinates according to \( \Lambda_d(\theta) \). Interestingly, assigning large weights to longer paths (\( K \gg 1 \)) is equivalent to fast shrinking the coordinates that correspond to small eigenvalues and capture the fine-grained structures and local relations, what leads to a coarse, high-level cluster description of the graph.

2.4 Relation to random walks

Apart from the spectral embedding interpretation discussed in the last subsection, using powers of (11) to capture multihop similarities also admits an interesting random walk interpretation. We begin by expressing the \( k \)th power of \( S \) as

\[
S^k = \frac{1}{2^k} \left( I + D^{-1/2} AD^{-1/2} \right)^k = \sum_{\tau=0}^{k} \alpha_{\tau}(k) \left( D^{-1/2} AD^{-1/2} \right)^\tau \quad (13)
\]
where the sequence
\[
\alpha_r(k) := \begin{cases} 
\frac{1}{2^r} \binom{k}{r}, & 0 \leq r \leq k \\
0, & \text{else}
\end{cases}
\]
(14)
can be interpreted as nonzero weights that \( S^K \) assigns to all paths with the number of hops up to \( k \) (see Fig. 1). Using (13) and (14), the multipath similarity in (3) becomes
\[
S_G(\theta) = \sum_{r=0}^{K} c_r(\theta) \left( D^{-1/2} A D^{-1/2} \right)^r
\]
\[
= D^{-1/2} \left( \sum_{r=0}^{K} c_r(\theta) P^r \right) D^{1/2}
\]
(15)
where
\[
c_r(\theta) := \sum_{k=1}^{K} \theta_k \alpha_r(k)
\]
(16)
and \( P = AD^{-1} \) is the probability transition matrix of a simple random walk defined over \( G \); that is, \( P_{i,j} \) is the probability that a random walker positioned on node (state) \( j \) transitions to node \( i \) in one step. Thus, the \( k \)-hop similarity function defined in (3) is expressed as
\[
s_G(v_i, v_j, \theta) = \sqrt{\frac{d_j}{d_i} \sum_{r=0}^{K} c_r(\theta) \Pr\{X_r = v_i | X_0 = v_j\}}
\]
(17)
where \( \Pr\{X_r = v_i | X_0 = v_j\} := \left[ P^r \right]_{i,j} \) is the probability that a random walk starting from \( v_j \) lands on \( v_i \) after \( r \) steps.

Interestingly, \( S_G(\theta) \) does not weigh landing probabilities of different lengths independently. Instead, it accumulates the latter as weighted combinations (cf. (16)) in a basis of “wavelet”-type functions of different resolution (see Fig. 1).

Having established links to spectral clustering and random walks, our novel \( S_G(\theta) \) is well motivated as a family of node similarity matrices. Nevertheless, before devising an algorithm for learning \( \theta \) and testing it on real graphs, we will evaluate how well the basis \( \{ S^K \}_{K=1} \), on which \( S_G(\theta) \) is built, can capture underlying node similarities.

3 Model expressiveness

This section introduces a performance metric that quantifies how well a node similarity matrix derived from the graph itself matches the “true” underlying similarity structure between nodes. The discussion is followed by numerical evaluation of the performance of different similarity matrices (including the one in (15)) on graphs that are generated according to the stochastic block model [2].

To begin, suppose that for a given set of nodes, an adjacency matrix \( A \) is generated as
\[
A \sim f_A(A)
\]
where \( f_A(A) \) is a probability density function defined over the space of all possible adjacency matrices. Let the “true” underlying similarity between nodes \( v_i \) and \( v_j \) be
\[
s^*(v_i, v_j) := \Pr\{(i, j) \in E\} = E_{f_A}[A_{i,j}]
\]
which is the probability that the two nodes are connected. The “true” similarity matrix is thus given as the expected adjacency matrix
\[
S^* := E_{f_A}[A].
\]

We define the quality-of-match (QoM) between the underlying \( S^* \) and any similarity \( S = F(A) \) estimated from the adjacency matrix as
\[
\text{QoM} := E_{f_A}\left[ \text{PC}(S^*, F(A)) \right]
\]
(18)
where
\[
\text{PC}(X_1, X_2) := \frac{\| \text{vec}(X_1) - \text{vec}(X_2) \|_F}{\|X_1\|_F \|X_2\|_F}
\]
(19)
is the Pearson correlation between two matrices \( X_1 \) and \( X_2 \), with \( \text{vec}(X) \) denoting matrix vectorization. The latter is used for appropriate rescaling of the “true” similarity matrix in order for the comparison with \( S_G \) to be meaningful. Intuitively, (18) measures how well the estimated node similarities in \( S \) are expected to match the pattern of true underlying similarities in \( S^* \), when edges are generated according to the known \( f_A(\cdot) \).

3.1 Numerical experiments and observations

We numerically evaluate the QoM achieved by different similarity matrices, on a set of \( N \) nodes whose interconnections are generated according to a stochastic block model (SBM). For this set of experiments, we divided the nodes into three clusters of equal size
\[
C_l = \{ i : (l-1)N/3 \leq i \leq lN/3 \}, \ l \in \{1, 2, 3\}
\]
with inter- and intra-connection probabilities
\[
\Pr\{(i, j) \in E\} = \begin{cases} 
p & (i, j) \text{ in the same } C_l \\
q & (i, j) \text{ in } C_l \text{ and } j \in C_3 \\
c & \text{else}
\end{cases}
\]
(20)
where \( p \) is the probability of connection when two nodes belong to the same cluster, and \( c < 1 \) introduces asymmetry and a hierarchical clustering organization (see Fig. 2-top left), by making two of the clusters less likely to connect; we have
related Python scripts available\cite{github}

The SBM probability matrix \cite{sbm} is given as

\[
W_{\text{sbm}} = \begin{bmatrix}
p & q & cq \\
q & p & q \\
cq & q & p \\
\end{bmatrix} \tag{21}
\]

and the underlying similarity can be expressed as

\[
S^* = E[A] = W_{\text{sbm}} \otimes \left( \frac{1}{N/3} 1_{N/3}^T \right) - \text{diag}(p \mathbf{1}_N) \tag{22}
\]

where \( \otimes \) denotes the Kronecker product.

For each experiment, we set \( N = 150 \) and generated a graph according to \cite{sbm}. We then compared the QoM between \cite{sbm} and the \( k \)th power of the proposed \cite{proposed}, the \( k \)th power

\[\text{QoM} = \frac{\sum_{i,j} (S_{\text{true}}(i,j) - S_{\text{est}}(i,j))^2}{\sum_{i,j} S_{\text{true}}(i,j)^2}\]

Fig. 2: Depiction of groundtruth and estimated similarity matrices, as yielded from an instance of the numerical experiments described in Section 3.1.

Fig. 3: Quality of match between true SBM similarity and various estimates, as yielded from experiments of Section 3.1.

\[\text{QoM} = \frac{\sum_{i,j} (S_{\text{true}}(i,j) - S_{\text{est}}(i,j))^2}{\sum_{i,j} S_{\text{true}}(i,j)^2}\]

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of the adjacency \( (A^k) \), as well as each of the following well-known similarity metrics:

- \( \hat{S}_{PPR} := (1 - \alpha)(I - \alpha AD^{-1})^{-1} \): the steady state probability that a random walk restarting at \( v_i \) with probability \( 1 - \alpha \) at every step is located at \( v_j \). Essentially a personalized PageRank (PPR) computed for every node of the graph, inheriting the properties of the celebrated centrality measure \([7], [8], [9]\).
- \( \hat{S}_{KATZ} := (1 - \beta)(I - \beta A)^{-1}A \): the Katz index \([12]\), an exponentially weighted summation over paths of all possible hops between two nodes.
- \( \hat{S}_{NEIGH} := A^2 \): the number of common neighbors that every pair of nodes shares.
- \( \hat{S}_{AA} := AD^{-1}A \): Adamic-Adar: \([4]\) is a variant of common neighbors where each set of neighbors is weighted inversely proportional to its cardinality.

The resulting QoM was averaged over 200 experiments. Parameters \( \alpha \) in \( \hat{S}_{PPR} \) and \( \beta \) in \( \hat{S}_{KATZ} \) were tuned to maximize the performance of the metrics. Figure 3 depicts QoM as a function of \( k \), for three different scenarios.

In the first scenario (Fig. 3-a), with graphs being dense and clustered \((p = 0.3, q = 0.1)\), the proposed \( S^k \) improves sharply in the first few steps, reaching maximum QoM after 4 or 5 steps, and gradually decreases as \( k \) continues to increase. The \( k \)th order proximities that are given as entries of \( A^k \) follow a similar trend, however their QoM peaks shortly after 2 or 3 steps and declines fast for larger \( k \). The matrix plots of a randomly selected experiment depicted in Fig. 2 can aid in understanding the underlying mechanism that gives rise to this highly step-dependent behavior. Specifically, \( S^1 \) (bottom left) that has the same sparsity pattern as the adjacency is a poor similarity metric. Meanwhile, taking \( \beta = 0 \) yields embeddings with limited generalization capability. Simply put, regardless of the choice of \( \ell(\cdot) \), solving \( \ell(A, S_G(A; \theta)) \) amounts to predicting a set of edges by tuning a similarity metric that is generated by the same set of edges.

To mitigate overfitting but also promote generalization of the similarity metric and of the resulting embeddings, we explore the following idea. Suppose we are given a pair \( A_1, A_2 \) of adjacency matrices both drawn independently from \( f_A(\cdot) \). In this case, we would be able to use one as approximation of \( S^* \simeq A_1 \), and the other to form the multihop similarity matrix \( S_G(A_2; \theta) \); parameters \( \theta \) can then be learned by solving
\[
\min_{\theta \in S^K} \ell(A_1, S_G(A_2; \theta)).
\]

Separate samples are not available, we approximate the aforementioned process by randomly extracting part of \( A \) and approaching \([25]\) as
\[
\min_{\theta \in S^K} \ell_S(A, S_G(A \ast S^c; \theta))
\]
where \( S \in \{1, \ldots, N\}^2 \) is a subset of all possible pairs of nodes with \(|S| = N_s\), and \( S^c \) is an \( N \times N \) binary section matrix with \( S^c_{i,j} = 0 \), if \( \{i,j\} \in S \), and \( S^c_{i,j} = 1 \), otherwise. Furthermore, \( \ell_S(\cdot, \cdot) \) in \([26]\) denotes cost \( \ell(\cdot, \cdot) \) applied selectively only to entries of the matrix variables that belong to \( S \). Here, such that \( S = S^+ \cup S^- \), with \( S^+ \in \mathcal{E} \) being as subset of the edges and \( S^- \in \{1, \ldots, N\}^2 \setminus \mathcal{E} \) a subset of node index tuples that are not connected (non-edges). To balance the influence of existing and non-existing edges, we use subsets of equal cardinality, that is \(|S^+| = |S^-| = N_s/2\).

To arrive from the unsupervised similarity learning framework \([25]\) to a practical method, it remains to specify two modular sub-systems: one responsible for sampling edges, and one specifying \( \ell(\cdot, \cdot) \) to find \( \theta^* \) by solving \([26]\).
4.1 Edge sampling

The choice of the sampling scheme for $S$ plays an important role in the overall performance of the proposed adaptive embedding framework. Ideally, edge sampling should take into account the following criteria:

- Sample $S^+$ should be representative of the graph;
- Edge removal should inflict minimal perturbation;
- Edge removal should avoid isolating nodes; and
- Sampling scheme should be simple and scalable.

Aiming at a ‘sweet spot’ of these objectives, we populate $S^+$ by sampling edges according to the following procedure: first, a node $v_1$ is sampled uniformly at random from $V$; then, a second node $v_2$ is sampled uniformly from the neighborhood set $N_{G}(v_1)$ of $v_1$. The selected edge is removed only if both adjacent nodes have degree greater than one. Non-edges $S^-$ are obtained by uniform sampling without replacement over $\{1, \ldots, N\}^2 \setminus \mathcal{E}$. The overall procedure is summarized in Algorithm 2. For $N_s \ll N$, sampling probabilities remain approximately unchanged despite the removals, since the probability of selecting the same node is relatively small. Thus, one may approximate $Pr[e_t = (i, j)] \approx Pr[e_0 = (i, j)]$, and assuming for simplicity that $d_i > 1 \forall i$, it follows that

$$Pr\{e_0 = (i, j)\} = Pr\{v_1 = i, v_2 = j\} + Pr\{v_1 = j, v_2 = i\} = Pr\{v_2 = i|v_1 = j\} Pr\{v_1 = j\} + Pr\{v_2 = j|v_1 = i\} Pr\{v_1 = i\} = \frac{1}{d_i d_j N} \frac{1}{d_i d_j N} \propto \frac{d_i + d_j}{d_i d_j},$$

(27)

meaning that edge $e = (i, j)$ is removed with probability that is proportional to the harmonic mean of the degrees of the nodes that it connects. As shown in [14], the perturbation that the removal of edge $e = (i, j)$ inflicts on the spectrum of an undirected graph is proportional to $d_i d_j$; that is, removing edges that connect high-degree nodes leads to higher perturbation. Thus, Algorithm 2 tends to inflict minimal perturbation by sampling with probability that is inversely proportional to $d_i d_j$ for $d_i, d_j \gg 1$; this is because the denominator of (27) dominates its numerator for large degrees. On the other hand, for smaller $d_i$ and $d_j$, the numerator ensures relatively high probabilities for moderate-degree nodes. The combination of the two effects yields edge samples that are fairly representative of the graph, while inflicting low perturbation when removed.

4.2 Parameter training

Subsequently, for a given sample $S$, we can obtain the corresponding optimal parameters as (cf. (26))

$$\theta_S^* = \arg \min_{\theta \in \Theta^K} \sum_{i,j \in \mathcal{S}} \ell(A_{i,j}, s_{g^-}(v_i, v_j; \theta))$$

(28)

where $\mathcal{S}^+ = (\mathcal{V}, \mathcal{E} \setminus \mathcal{S}^+)$ is the original graph with the randomly sampled subset $\mathcal{S}^+$ of edges removed.

Interestingly, one way that (28) could be solved is by explicitly computing the entries of $S^k_{g}(\theta)$ that are in $S$. This would require performing $K$ sparse matrix-vector products to obtain every column of $S^k$ for $k \in \{1, \ldots, K\}$, for all the columns that contain sampled entries. In the worst case, if all nodes in the tuples of $S$ correspond to different columns of $S_{g}(\theta)$, two random walks are required for every tuple, for a total of $2N_s$ random walks. This requires $O(N_s K |E|)$ computations, and $O(N_s N)$ memory if they are to be performed concurrently or in matrix form. Since $K$ will typically be in the order of tens, these requirements will be affordable, if $N_s$ is relatively small. Nevertheless, they quickly become cumbersome for $N_s \gg K$, which may be necessary to estimate the $K$-dimensional $\theta$.

Algorithm 1 ADAPTIVE SIMILARITY EMBEDDING

Input: $G$ Output: $E$

// Training phase
$\Theta = \emptyset$

while $|\Theta| < T_s$ do
  $G^-, S^+, S^- \leftarrow$ SAMPLE EDGES($G$)
  $\theta_S^* \leftarrow$ TRAIN PARAMETERS($G^-, S^+, S^-$)
  $\Theta \leftarrow \Theta \cup \theta_S^*$
end while

$\theta^* = T_s^{-1} \sum_{\Theta} \Theta$

// Embedding phase
$S = \frac{1}{2} \left( I + D^{-1/2} AD^{-1/2} \right)$

$E = U_d \Sigma_d U_d^T$

$\Sigma_d(\theta^*) = \sum_{k=1}^{K} \theta_k \Sigma_d^k$

return $E = U_d \sqrt{\Sigma_d(\theta^*)}$

Algorithm 2 SAMPLE EDGES

Input: $G$ Output: $G^-, S^+, S^-$

// Sample edges
$S^+ = \emptyset$, $G^- = G$

while $|S^+| < N_s/2$ do
  Sample $v_1 \sim$ Unif ($\mathcal{V}$)
  if $|N_{G^-}(v_1)| > 1$ then
    Sample $v_2 \sim$ Unif ($N_{G^-}(v_1)$)
  end if
  if $|N_{G^-}(v_2)| > 1$ then
    $S^+ = S^+ \cup (v_1, v_2)$
    $G^- = G^- \setminus (v_1, v_2)$
  end if
end while

// Sample non-edges
$S^- = \emptyset$

while $|S^-| < N_s/2$ do
  Sample $(v_1, v_2) \sim$ Unif ($\mathcal{V} \times \mathcal{V}$)
  if $(v_1, v_2) \notin \mathcal{E}$ then
    $S^- = S^- \cup (v_1, v_2)$
  end if
end while

return $G^-, S^+, S^-$

Instead, we will rely on the fact that the proposed embeddings are smooth and differentiable wrt to $\theta$ (cf. [10]), to develop a solution that allows for selecting arbitrarily
We can then equivalently express (28) as

\[ \lambda \]

Algorithm 3 TRAIN PARAMETERS

Input: \( G, S^+, S^- \) Output: \( \theta^*_S \)

\[
S = \frac{1}{2} \left( I + D^{-1/2}AD^{-1/2} \right)
\]

\[
S = U_d \Sigma_d U_d^T
\]

\[
S = S^+ \cup S^-
\]

Form \( X_S = \{ x_{(i,j)} \}_{(i,j) \in S} \) as in (30)

return \( \theta^*_S = \text{SIMPLEXSVM}(X_S, S^+, S^-) \)

Algorithm 4 SIMPLEXSVM

Input: \( X, S^+, S^- \) Output: \( \theta^* \)

\[
\theta_0 = \frac{1}{N^2}, \quad t = 1
\]

while \( \| \theta_t - \theta_{t-1} \|_\infty \geq \text{tol} \) do

\[
t = t + 1, \quad \eta_t = a/\sqrt{t}
\]

\[
S^+_t = \{ e \in S^+ | x_e \theta_{t-1}^T \leq \epsilon \}
\]

\[
S^-_t = \{ e \in S^- | x_e \theta_{t-1}^T \geq -\epsilon \}
\]

\[
g_t = \sum_{e \in S^+_t} x_e - \sum_{e \in S^-_t} x_e
\]

\[
z_t = (1 - 2\eta_t) \theta_{t-1} - \frac{\eta_t}{\sqrt{t}} g_t
\]

\[
\theta_t = \text{SIMPLEXPROJ}(z_t)
\]

end while

return \( \theta_t \)

large \( N_s \), using the approximation

\[
s_{G-}(u_i, v_j; \theta) \approx s_{G-}(e_i^-(\theta), e_j^-(\theta))
\]

\[
= (e_i^-(\theta))^T e_j^-(\theta)
\]

\[
= \left( \Sigma_d(\theta) u_i \right)^T \sqrt{\Sigma_d(\theta)} u_j
\]

\[
= (u_i^T)^T \Sigma_d(\theta) u_j
\]

\[
= x_{i,j}^T \theta
\]

(29)

where

\[
x_{i,j} = \left( u_i^* \ast u_j^* \right)^T \Sigma_d^{K}
\]

(30)

and

\[
\Sigma_d^{K} = \begin{bmatrix}
\sigma_1 & \sigma_2 & \cdots & \sigma_d^K \\
\vdots & \ddots & \ddots & \vdots \\
\sigma_{d-1} & \sigma_d^2 & \cdots & \sigma_d^K \\
\sigma_d & \sigma_d^2 & \cdots & \sigma_d^K
\end{bmatrix}
\]

Conveniently, \( \{ x_{i,j} \} \)s act as features over every possible pair of nodes, which when linearly combined with weights \( \theta \) to produce similarities, allow us to approach (28) using well-understood learning and optimization tools. For instance, let \( \ell(\cdot) \) be the Hinge loss

\[
\ell(y, f) := \max(0, 1 - yf)
\]

and define targets \( y_{i,j} = 2A_{i,j} - 1 \) such that \( y_{i,j} \in \{-1, 1\} \). We can then equivalently express (28) as

\[
\theta^*_S = \arg \min_{\theta \in \mathbb{R}^d} \sum_{i,j \in S} \max(0, 1 - y_{i,j} x_{i,j}^T \theta) + \lambda \| \theta \|_2^2
\]

(32)

where \( \lambda \geq 0 \) is the regularization parameter of the \( \ell_2 \) regularization typically used to improve the generalization of SVMs [13]. To solve our variant of simplex-constrained SVMs (cf. (32)), we employ the projected-gradient descent approach [3] that we describe in Algorithm 4, where \( \text{SIMPLEXPROJ}(\cdot) \) is a subroutine that implements projections onto \( S^K; \) the latter can be performed with \( O(K \log K) \) complexity as described in [21]. The overall parameter learning procedure for a given sample is summarized in Algorithm 3.

In general, if runtime or computational resources allow, the sampling and training process described in the last two sections can be repeated \( T_s \) times to obtain different \( \{ \theta^*_S \}_s \), which can then be averaged in order to reduce their variance. In practice, this may not be necessary if \( N_s \) is large enough, which will yield a near-deterministic \( \theta \). The overall proposed adaptive-similarity embedding (ASE) framework is summarized in Algorithm 1.

4.3 Complexity

The computational complexity of ASE is dominated by the cost of performing the truncated SVD of \( S \) in the training as well as testing phases of Algorithm 1. Relying on the sparsity (\( |E| \ll N^2 \)) and symmetry of \( S \), the Lanczos algorithm followed by EVD of a tridiagonal matrix yield the truncated SVD in a very efficient manner. Provided that \( d \ll N \), the decomposition can be achieved in \( O(|E|d) \) time and using \( O(Nd) \) memory. Therefore, for the \( T_s \geq 1 \) training rounds and a single embedding round of Algorithm 1, the overall complexity is \( O((T_s + 1)|E|d) \).

5 RELATED WORK

Two recent embedding methods also pursue similarity matrices that combine walks of different lengths [12], [38]. Most relevant to the proposed ASE is the “Arbitrary-Order Proximity Preserved Network Embedding” [12] approach, where a method is proposed for obtaining the SVD of a polynomial of the adjacency matrix without having to recompute the singular vectors. Compared to [12], we put forth the following contributions. First, we introduce a family of multi-hop similarities whose decomposition leads to embeddings that inherit the rich information contained in the spectral embeddings (cf. Section 2.3). An equally important contribution in terms of modeling is that our embeddings can be differentiated with respect to (wrt) weights \( \theta \) (cf. (29)-(32)), whereas the embeddings in [12] are non-differentiable wrt the weights. Hence, [12] can only proceed in a “forward” fashion given some order proximity weights \( \theta \), whereas our approach allows for “navigating” the space of possible similarity functions \( s(u_i, v_j; \theta) \) in a smooth fashion, meaning that \( \theta \) can be learned with simple optimization on well-defined fitting models such as logistic regression or SVMs (cf. [32]). This leads to the third main contribution, which is a means of learning “personalized” \( \theta \) (cf. Section 4) in an unsupervised fashion, meaning without downstream information such as node or edge labels/attributes that can guide cross-validation in high-dimensional discretized parameter grids.

2. The SVM-based parameter learning presented here is by no means the only viable option. In our implementation, we also provide learning mechanisms based on least-squares, logistic regression, as well as finding the best single \( k \). However here, due to space constrains, we present and report results of the SVM-based approach.
The second related embedding method presented in [38] builds on the concept of graph attention mechanisms to place weights on lengths of truncated random walks. These mechanisms are used to build a similarity matrix containing co-occurrence probabilities. The matrix is jointly decomposed by maximizing a graph-likelihood function. The model in [38] is a generalization of the ones implicitly adopted by [39] and [40], building on similar tools and concepts that emerge from natural language processing. Different from [39], [40] and the proposed ASE, [38] explicitly constructs and factorizes a dense $N \times N$ similarity matrix. The detailed procedure incurs complexity that is cubic wrt $N$, and becomes at best quadratic after model approximations, meaning that [38] scales rather poorly beyond small graphs.

6 Experimental Evaluation

The present section reports extensive experimental results on a variety of real-world networks. The aim of the presented tests is twofold. First, to determine and quantify the quality of the proposed ASE embeddings for different downstream learning tasks. Second, to analyze and interpret the resulting embedding parameters for different networks.

Datasets. In our experiments, we used the following real-world networks (see also Table 1).

- **ca-AstroPh.** The Astro Physics collaboration network is from the e-print arXiv and covers scientific collaborations between co-authored papers submitted to Astro Physics category [51]. If an author $i$ co-authored a paper with author $j$, the graph contains a undirected edge from $i$ to $j$. If the paper is co-authored by $k$ authors, this generates a completely connected (sub)graph on $k$ nodes.
- **ca-CondMat.** Condense Matter Physics collaboration network from ArXiv [51].
- **CoCit.** A co-citation network of papers citing other papers extracted by [36]. labels represent conferences in which papers were published.
- **com-DBLP.** Computer science research bibliography collaboration network [51].
- **com-Amazon.** Network collected by crawling Amazon website [51]. It is based on “Customers Who Bought This Item Also Bought” feature of the Amazon website. If a product $i$ is frequently co-purchased with product $j$, the graph contains an undirected edge from $i$ to $j$.
- **vk2016-17.** VK is a Russian all-encompassing social network. In [36], two snapshots of the network were extracted in November 2016 and May 2017, to obtain information about link appearance.
- **email-Enron.** Enron email communication network covering all the email communication within a dataset of around half a million emails [51].
- **PPI (H. Sapiens).** Subgraph of the protein-protein interaction network for Homo Sapiens. The subgraph corresponds to the graph induced by nodes for which labels (representing biological states) were obtained from the hallmark gene sets [40].
- **Wikipedia.** This is a co-occurrence network of words appearing in the first million bytes of the Wikipedia dump. The labels represent the Part-of-Speech (POS) tags inferred using the Stanford POS-Tagger [40].

- **BlogCatalog.** A network of social relationships of the bloggers listed on the BlogCatalog website. The labels represent blogger interests inferred through the meta-data provided by the bloggers.

Methods. Experiments were run using the following unsupervised and scalable embedding methods.

- **ASE.** Our proposed adaptive similarity embedding. Based on observations made in Sections 3, and to retain optimization stability, we set the maximum number of steps to $K = 10$. We also use the default SVM regularizer ($\lambda = 1$). To have a single learning round with learned parameters having small enough variance, we sampled with $N_{c}/2 = 1,000$. We made our implementation of ASE freely available.
- **VERSE [36].** This is a scalable framework for generating node embeddings according to a similarity function by minimizing a KL-divergence-objective via stochastic optimization. We used the default version with similarity (PPR with $\alpha = 0.85$), as suggested and implemented by the authors.
- **Deepwalk [39].** This approach learns an embedding by sampling random walks from each node, and applying word2vec-based learning on those walks. We use the default parameters provided in [39], i.e., walk length $t = 80$, number of walks per node $s = 1,000$, and the scalable C++ implementation provided in [36].
- **HOPE [29].** This SVD-based approach approximates high-order proximities and leverages directed edges. We report the results obtained with the default parameters, i.e, Katz similarity as the similarity measure with $\beta$ inversely proportional to the spectral radius.
- **LINE [35].** This approach learns a $d$-dimensional embedding in two steps, both using adjacency similarity. First, it learns $d/2$ dimensions using first-order proximity; then, it learns another $d/2$ features using second-order proximity. Last, the two halves are normalized and concatenated. We obtained a copy of the code and run experiments with $T = 10^{10}$

### Table 1: Network Characteristics

| Graph      | $|V|$  | $|E|$  | $|Y|$  | Density |
|------------|------|------|------|---------|
| PPI (H. Sapiens) | 3,890 | 76,584 | 50 | $10^{-2}$ |
| Wikipedia  | 4,733 | 184,182 | 40 | $1.6 \times 10^{-2}$ |
| BlogCatalog | 10,312 | 333,983 | 39 | $6.2 \times 10^{-3}$ |
| ca-CondMat  | 23,133 | 93,497  | -  | $3.5 \times 10^{-4}$ |
| ca-AstroPh  | 18,772 | 198,110 | -  | $1.1 \times 10^{-3}$ |
| email-Enron | 36,692 | 183,831 | -  | $2.7 \times 10^{-4}$ |
| CoCit       | 44,312 | 195,362 | 15 | $2 \times 10^{-4}$ |
| vk2016-17   | 78,593 | 2,680,542 | -  | $8.7 \times 10^{-4}$ |
| com-Amazon  | 334,863 | 925,872  | -  | $1.7 \times 10^{-5}$ |
| com-DBLP    | 317,080 | 1,049,866 | -  | $2.1 \times 10^{-5}$ |

3. https://github.com/DimBer/ASE-project
4. https://github.com/xgfs/verse
5. https://github.com/xgfs/deepwalk-c
6. https://github.com/tangjianpku/LINE
TABLE 2: Inferred parameters and interpretation

| Graph          | $\theta_1$ | $\theta_2$ | $\theta_3$ | $\theta_4$ | $\theta_5$ | $\theta_6$ | $\theta_7$ | $\theta_8$ | $\theta_9$ | $\theta_{10}$ | range  | strength |
|----------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|-------------|---------|-----------|
| PPI (H. Sapiens) | 0.00       | 0.14       | 0.31       | 0.29       | 0.21       | 0.04       | 0.00       | 0.00       | 0.00       | 0.00        | medium  | medium    |
| Wikipedia      | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       | 0.01       | 0.37        | 0.62    | short     |
| BlogCatalog    | 1.00       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00        | short   | very strong |
| ca-CondMat     | 0.55       | 0.33       | 0.12       | short      | short      | short      | short      | short      | short      | short       | strong   | short     |
| ca-AstroPh     | 0.76       | 0.24       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00         | short   | short     |
| email-Enron    | 0.24       | 0.25       | 0.18       | 0.14       | 0.1        | 0.06       | 0.02       | 0.00       | 0.00       | 0.00         | medium   | weak      |
| CoCit          | 0.61       | 0.33       | 0.06       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00         | short   | strong    |
| vk2016-17      | 0.71       | 0.29       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       | 0.00         | short   | strong    |
| com-Amazon     | 0.10       | 0.10       | 0.10       | 0.10       | 0.10       | 0.09       | 0.09       | 0.09       | 0.09       | 0.09         | short   | very weak |
| com-DBLP       | 0.11       | 0.10       | 0.10       | 0.09       | 0.09       | 0.09       | 0.09       | 0.09       | 0.09       | 0.09         | short   | very weak |

Fig. 4: Micro and Macro $F_1$ scores for the four labeled graphs, when the “pure” $k$–order $S^k$ is used for embedding, given as a function of $k$. Red shade denotes the corresponding $k$’s where ASE assigned non-zero $\theta_k$’s; see also Table 2.

We excluded comparisons with Node2vec [40] and AROPE [12] because they use cross-validation for hyper-parameter selection. Thus comparing Node2vec and AROPE to methods such as LINE, Deepwalk, HOPE, VERSE, and EMB that all operate with fixed hyperparameters in a fully unsupervised manner would be unfair. We also excluded comparisons with GraRep [31] and M-NMF [30] due to their limited scalability ($O(N^2d)$ computational and $O(N^2)$ memory complexity).

Evaluation methodology. Our experiment setting follows the one in [36]. All methods are set to embed nodes to dimension $d = 100$. Using the resulting embeddings as feature vectors, we evaluated their performance in terms of node classification and link prediction accuracy, and clustering quality. All experiments were repeated 10 times and reported are the averaged results.

Interpretation of results. One interesting aspect of the proposed ASE method, is that the inferred parameters $\theta^*$ from the first phase of Algorithm 1 can be used to characterise the underlying similarity structure of the graph, and the way nodes “interact” over different path lengths (short, medium, and long range). The “strength” of interactions is inferred by how uniform the coefficients of $\theta^*$ are, and depend on the value of $\lambda$. Since the default value was $\lambda = 1$ for all graphs, the results can be interpreted as relative interaction strengths between them. The resulting $\{\theta^*\}$’s for all graphs are listed in Table 2.

It can be immediately observed that the type of node interactions varies significantly across different graphs, with similar behavior for graphs that belong to the same domain. Specifically, ca-CondMat, ca-AstroPh, and CoCit that belong to the citation/co-authorship domain all show relatively strong interactions of short range. BlogCatalog shows very strong short-range similarities of only one-hop neighborhood interactions among bloggers. On the other hand, the Wikipedia word co-occurrence network shows a strong tendency for long-range interactions; while other graphs, such as the PPI protein interaction network stay on the medium range.

Node classification. Graphs with labeled nodes are frequently used to measure the ability of embedding methods to produce features suitable for classification. For each experiment, nodes were randomly split to a training set and a test set. Similar to other works, and to cope with multi-label targets, we fed the training features and labels into the one-vs-the-rest configuration of logistic regression classifier provided by the sklearn Python library. In the testing phase, we sorted the predicted class probabilities
for each node in decreasing order, and extracted the top-$k_i$ ranking labels, were $k_i$ is the true number of labels of node $v_i$. We then computed the Micro- and Macro-averaged $F_1$ scores of the predicted labels.

Apart from comparisons with alternative embedding methods, node classification can reveal whether available node labels (metadata) are distributed in a manner that matches the node relations/interactions that are inferred by ASE. To reveal this information, we obtain embeddings for every $k \in \{1, \ldots, 10\}$ by ignoring the training phase and “forcing” $\theta^* = \theta_k$ in Algorithm 1 and then using each embedding for classification with 10% labeling rate. Figure 4 plots Micro and Macro $F_1$ for all labeled graphs as a function of $k$, while red shade is placed on the hops where the unsupervised ASE parameters $\theta^*$ are non-zero (cf. Table 1). As seen in Fig. 4, the accuracy on the four labeled graphs evolves with $k$ in a markedly different manner. Nevertheless, ASE identifies the trends and tends to assign non-zero weights to hops that yield a desirable trade-off between Micro and Macro $F_1$. Bearing in mind that ASE does not use labels for training or validation, this is rather remarkable considering the fact that $\theta^*$ depends only on the graph.

We also compared the classification accuracy of ASE embeddings with those of the alternative embedding approaches, with results plotted in Fig. 5. The plots for some method-graph pairs are not discernible when values are too low. While the relative performance of any given method varies from graph to graph, ASE adapts to each graph and yields consistently reliable embeddings, with accuracy that in most cases reaches or surpasses that of state-of-the-art methods, especially in terms of Macro $F_1$. The two exceptions are the Macro $F_1$ in CoCit, and Micro $F_1$ in Wikipedia, where VERSE and HOPE are correspondingly more accurate.

Interestingly, HOPE achieving high Micro $F_1$ and low Macro $F_1$ in Wikipedia is in agreement with the findings in Fig. 4, combined with the fact that HOPE focuses on longer paths.

### Link prediction

Link prediction is the task of estimating the probability that a link between two unconnected nodes will appear in the future. We repeat the experiment performed in [56] on the vk2016–17 social network. For every possible edge, we build a feature vector as the Hadamard product of the embedded vectors of its two adjacent nodes. Using the two time instances of vk2016–17, we predict whether a new friendship link appears between November 2016 and May 2017, using 50% of the new links for training and 50% for testing. To train the binary logistic regression classifier, we also randomly sample non-existing edges as negative examples. The link prediction accuracy for different embeddings is reported in Table 3. While for this experiment ASE does not reach the accuracy of VERSE, it provides the second most accurate link prediction, far surpassing the also SVD-based HOPE and spectral embeddings.

### Table 3: Link Prediction Accuracy on vk2016–17

|       | VERSE | ASE  | LINE | Deepwalk | HOPE | Spectral |
|-------|-------|------|------|----------|------|----------|
| Acc.  | 0.79  | 0.75 | 0.74 | 0.69     | 0.62 | 0.60     |

### Node clustering

Finally, the embedded vectors were used to cluster the nodes into different communities, using the sklearn library K-means with the default K-means++ initialization [18]. We evaluate the quality of node clustering with conductance, a well-known metric for measuring the goodness of a community [3]: conductance is minimized...
for large, well connected communities that are also well separated from the rest of the graph. Each plot in Fig. 6 gives the average conductance across communities, as a function of the total number of clusters. Results indicate
that the proposed ASE as well as the spectral clustering benchmark yield much lower conductance compared to other embeddings. Apparently, since ASE builds on the same basis of eigenvectors used by normalized spectral clustering, it inherits the property of the latter to approximately minimize the normalized-cut metric \( [17] \), which is very similar to conductance. A closer look at the resulting clusters, reveals that clustering based on VERSE, Deepwalk, LINE, and HOPE splits graphs into very large communities of roughly equal size, cutting a large number of edges in the process. This is an indication that these methods are subject to a resolution limit, which is the inability to detect well-separated communities that are below a certain size \( [1] \). On the other hand, Spectral and the proposed ASE separate the graph into a large-core component, and many smaller well-separated communities, a structure that many large-scale information networks have been observed to have \( [5] \). Indeed, the conductance gap is smaller for BlogCatalog, which is relatively small and with less pronounced communities.

**Parameter sensitivity.** We also present results after varying ASE parameters and measured classification Micro \( F_1 \) accuracy for PPI with 10% labeling rate. The aim is to assess the sensitivity of ASE wrt its basic parameters. The plot on the left shows how increasing \( \lambda \) (cf. (32)) may decrease accuracy by forcing the entries of \( \theta \) to be close to uniform, thus losing the benefits of graph-specific adaptation. Regarding the number of sampled edges \( N_s \), results (middle plot) indicate relative robustness of ASE embeddings, given a minimum number of samples. As expected, sampling a large number of edges may cause noticeable perturbation on the graph (even using the minimally-perturbing Algorithm 2); this may be causing a slight decrease in accuracy. Finally, the plot on the left depicts accuracy across a range of embedding dimensions \( d \).

**Runtime.** Finally, we compared different embedding methods in terms of runtime. Results for all graphs are reported in Fig. [5]. All experiments were run on a personal workstation with a quad-core i5 processor, and 16 GB of RAM. For our proposed ASE, we provide a light-weight yet highly portable implementation \( [7] \) that uses the SVMLIBC library \( [20] \) for sparse SVD. We also developed a more scalable implementation \( [8] \) that relies on (and requires installation of) the SLEPc package \( [49] \); this scalable version can perform large-scale sparse SVD on multiple processes and distributed memory environments using the message-passing interface (MPI) \( [48] \). We used the high-performance implementation for the five larger graphs, and the portable one for the five smaller ones. Evidently, ASE and HOPE that are SVD-based are orders of magnitudes faster than VERSE, Deepwalk, and LINE. The main factor that slows the latter down seems to be the large number of stochastic optimization iterations that these methods must perform to reach accurate embeddings. Nevertheless, it should be noted that sampling-based methods enjoy nearly-full parallelization and could thus benefit more from highly multi-threaded environments.

On the other hand, methods that rely on SVD (and EVD) can greatly benefit from decades of research on how to efficiently perform these decompositions, and a suite of stable and highly optimized software tools.

**7 Conclusions and Future work**

We presented a scalable node embedding framework that is based on factorizing an adaptive node similarity matrix. The model is carefully studied, interpreted, and numerically evaluated using stochastic block models, with an algorithmic scheme proposed for training the model parameters efficiently and without supervision.

The novel framework opens up several interesting future research directions. For instance, one can explore larger families of node similarity metrics that can be learned using the graph. Furthermore, it would be interesting to assess the performance of different randomized edge sampling methods, and generalize the notion of adaptive-similarity to heterogeneous and multi-layered graph embedding, as well as to edge embedding.

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