HYPEREDGE2VEC: DISTRIBUTED REPRESENTATIONS FOR HYPEREDGES

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ABSTRACT

Data structured in form of overlapping or non-overlapping sets is found in a variety of domains, sometimes explicitly but often subtly. For example, teams, which are of prime importance in social science studies are "sets of individuals"; "item sets" in pattern mining are sets; and for various types of analysis in language studies a sentence can be considered as a "set or bag of words". Although building models and inference algorithms for structured data has been an important task in the fields of machine learning and statistics, research on "set-like" data still remains less explored. Relationships between pairs of elements can be modeled as edges in a graph. However, modeling relationships that involve all members of a set, a hyperedge is a more natural representation for the set. In this work, we focus on the problem of embedding hyperedges in a hypergraph (a network of overlapping sets) to a low dimensional vector space. We propose a probabilistic deep-learning based method as well as a tensor-based algebraic model, both of which capture the hypergraph structure in a principled manner without loosing set-level information. Our central focus is to highlight the connection between hypergraphs (topology), tensors (algebra) and probabilistic models. We present a number of interesting baselines, some of which adapt existing node-level embedding models to the hyperedge-level, as well as sequence based language techniques which are adapted for set structured hypergraph topology. The performance is evaluated with a network of social groups and a network of word phrases. Our experiments show that accuracy wise our methods perform similar to those of baselines which are not designed for hypergraphs. Moreover, our tensor based method is quiet efficient as compared to deep-learning based auto-encoder method. We therefore, argue that we have proposed more general methods which are suited for hypergraphs (and therefore also for graphs) while maintaining accuracy and efficiency.

1 INTRODUCTION

In group structured data we have multiple entities related by some form of group relationships. In fact, such data is more abundantly found in the real world than has been usually studied (Estrada & Rodriguez-Velazquez, 2005). There are increasing number of fields where such data is being found more than ever before. In social networks domain: team data from massive online multi-player games (Ahmed et al., 2011) such as World of Warcraft, group communication tools such as Skype and Google Docs and research collaborations (Subbian et al., 2013; pub). There are other fields in which structural relationships between entities is important as well, and large datasets capturing them exist. Examples include Natural Language Processing (Bengio & Bengio, 2000), Biology (Hwang et al., 2008; Klamt et al., 2009), e-commerce (Deshpande & Karypis, 2004; Christakopoulou & Karypis, 2014) and Chemistry (Bartholomay, 1960). Figure 1 shows such examples for networks of groups, sentences, and item sets.

Hypergraph (Berge, 1984), which is a generalization of graphs, is a popular model to naturally capture higher-order relationships between sets of objects (Figure 2) (Estrada & Rodriguez-Velazquez, 2005). Within machine learning, algorithms guided by the structure of such higher order networks (Zhou et al., 2006) have found applications in a variety of domains (Tian et al., 2009; Gao et al., 2013; Li & Li, 2013; Sharma et al., 2015; 2017).

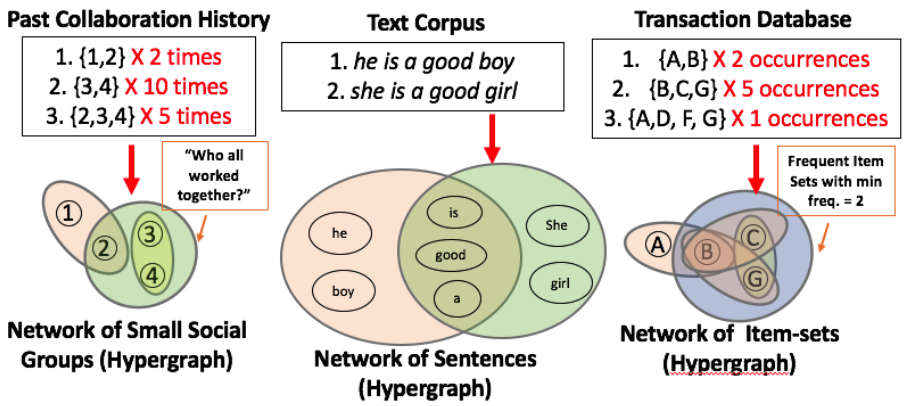

Figure 1: Example illustrating "set-like" structures from various domains.

More recently, the interest of representation learning in NLP (Mikolov et al., 2013a) has stimulated its application in graph embedding (learning low dimensional representation for graph nodes) (Perozzi et al., 2014; Tang et al., 2015b; Grover & Leskovec, 2016; Cai et al., 2017). However, this new line of research is limited to simple graphs and we are unaware of any work that considers hyperedge embeddings (learning representations for hyperedges). In this paper we aim to develop methods which (1) learn hypergraph embeddings directly, (2) leverage the hypergraph topology and (3) not loose the hyperedge-level joint information. These learned embeddings can then be employed by a supervised or semi-supervised algorithm to perform various predictive tasks pertaining to hyperedges. For example performance prediction of a team (set of individuals) engaged in a collaborative task or sentiment analysis of a sentence (set of words).

Although, there have been a variety of attempts to learn *node* embeddings for hypergraphs by extending traditional graph embedding methods for hypergraph setting. These approaches differ in the extent they address the aims (2) and (3) as pointed previously. In first category, there are a number of methods that incorporate the hypergraph topology using proxy graphs (Zhou et al., 2006; Hwang et al., 2008), therefore, incur loss of information. Also, Agarwal et al. (2006) squarely criticize that such representations can be learned by constructing graphs, which are proxies for the hypergraph structure. Second, are methods which actually, take into account the hyperedge-level information, like the classical Neural Language Model which maintains the higher order sequence information (Bengio & Bengio, 2000). But their model is designed for sequences and also simply ignores the topology (sequences are linked by common words forming a network of sequences). However recently, there has been interest in modeling "set-like" structures within deep-learning community (Vinyals et al., 2016; Rezatofighi et al., 2016). But they do not consider the hypergraph structure between the sets and therefore, not model hypergraphs in a principled manner. Third category are those methods that do not ignore the topology completely and also retain the hyperedge-level information. Among this are k-way tensor based methods that explicitly do not work on hypergraph (Shashua et al., 2006; Bulò & Pelillo, 2009), but the connection exists in the form that k-way tensor represents a k-uniform hypergraph (Qi, 2005). But they are restricted to uniform hypergraphs.

We therefore, propose two methods, both of which directly learn hyperedge embeddings for general hypergraphs and capture the hypergraph structure in a principled manner. First, is an auto-encoder based deep-learning method and second, is a tensor-based algebraic method. We also highlight the connection between hypergraphs (topology), tensors (algebra) and probabilistic models. A number of interesting baselines are also developed, some of which adapt existing node-level embedding models to hypergraph setting and also sequence based NLP techniques are adapted for set structured hypergraphs. We have experimented with social group dataset (network of teams as a hypergraph) from an online game for team (hyperedge) performance prediction as well as language networks (sentence/phrase hypergraphs) for phrase-level sentiment analysis. Our experiments show that accuracy wise our methods perform similar to those of baselines which are not designed for hypergraphs. Moreover, our tensor based method is quiet efficient as compared to deep-learning based auto-encoder method. We therefore, argue that we have proposed more general methods which are suited for hypergraphs (and therefore also for graphs) while maintaining accuracy and efficiency. In summary the main contributions of our paper are:

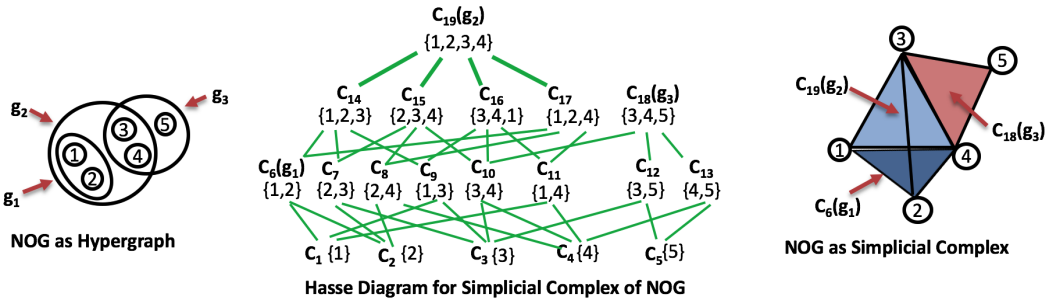

Figure 2: Example illustrating *network of groups (NOG)* which is the *hypergraph (HG)* (top left), the corresponding *simplicial complex (SC)* (top right) and the *hasse diagram (HD)* (bottom) corresponding to the simplicial complex, for a scenario where the actors {1,2,3,4,5} have collaborated in past as groups: $g_1 = \{1, 2\}$, $g_2 = \{1, 2, 3, 4\}$ and $g_3 = \{3, 4, 5\}$.

- We propose the novel concept of a *dual tensor* corresponding to the hypergraph dual and allows us to get hyperedge embedding directly.
- We propose a general *hypergraph tensor decomposition* method designed for general hypergraphs (containing different cardinality hyperedges) unlike simple uniform hypergraph tensor decomposition which is restricted to fixed cardinality hyperedges (i.e. uniform hypergraph). We are unaware of any such works or applications employing this approach.
- We propose the novel idea to use of de-noising auto-encoder in a hypergraph setting. Moreover, we also develop techniques of creating noise using random-walks over hasse diagram topology, which is original and unique.
- We highlight and argue that embeddings from tensor based methods have a natural hypergraph theoretic interpretation unlike the deep learning based black-box approaches.
- Our proposed methods learn hypergraph embeddings based on the unique approach of leveraging the *existing structure* present in network data as context, in contrast to context generation based existing graph embedding techniques.

Following is the outline for the rest of the paper. In section 2 we describe the problem definition and statement followed by Section 3 where we describe in detail the various methods proposed in this paper. Section 4 describes the datasets, experimental tasks & settings for the models. Section 5 provides an overview of the related literature followed by conclusion and appendix.

2 PRELIMINARIES

In this paper we consider the scenario where we have a collection of *elements*. These elements can represent individual actors in case of social groups or words in sentences or items in item-sets within a transaction database. In other words a social group or a sentence or an item-set are *sets* which contain these *elements*. Let $V = \{v_1, v_2, ..., v_n\}$ represents n elements and we have m sets defined over these elements, denoted by $G = \{g_1, g_2, ..., g_m\}$, where $g_i \subseteq V$ represents the ith set. The cardinality $|g_i|$ represents the number of elements in the set. Also each set $g_i \in G$ has an occurrence number $R(g_i)$, which denotes the number of times it has occurred. Such overlapping or non-overlapping sets can be modeled as a hypergraph Berge (1984), where the nodes and hyperedges, represent the elements and sets, respectively. This hypergraph is represented as $N_g = (V, G)$ with G as the collection of hyperedges over the nodes V. The incidence matrix $\mathbf{H} \in \{0, 1\}^{|G|\times|V|}$ for N_g represents the presence of nodes in different hyperedges with $\mathbf{H}(g_i, v) = 1$ if $v \in g_i$ else 0. A specialization of hypergraph model is the Simplicial complex (Munkres, 1984) (Figure 2), in which additionally each hyperedge has the subset closure property, i.e., each subset of hyperedge is also a valid hyperedge.

Problem Statement: Given this setting, our goal is to learn the mapping $\phi : G \rightarrow \mathbb{R}^d$ from hyperedges to feature representations (i.e., embeddings) that can be used to build predictive models involving sets. Here d is a parameter specifying the number of dimensions of the embedding vector.

Equivalently, ϕ can be thought of as a look-up matrix of size $|G| \times d$, where $|G|$ is the total number of sets or hyperedges.

3 METHODOLOGY

As we had mentioned before there are several methods to learn representation of nodes in a graph. Given that a hyperedge is a set of nodes, a natural question arises is that, can we combine the node level embeddings (learned using existing methods) within a given hyperedge to find a suitable representation of that hyperedge? However, there are large number of possible ways one can combine the node embeddings. Therefore, in the following two subsections, we develop two methods that learn the embeddings for hyperedges directly in a more principled manner. Our tensor based method is focused on retaining the set-level information intact while harnessing the hypergraph network structure. Where the auto-encoder based method harnesses the non-linearity of representation offered by deep learning to generate crisp and powerful embeddings. Tensor based method has a natural *hasse diagram* based topological interpretation and can generate both node and hyperedge embeddings. Whereas deep learning model is more black-box based approach and can only generate hyperedge embeddings.

3.1 HYPEREDGE2VEC USING HYPERGRAPH TENSOR DECOMPOSITION

In this section, we develop tensor (higher-order matrices) based linear algebraic methods that learn node as well as hyperedge embedding by taking into account the joint probability over a hyperedge. The idea behind using tensors is that they retain the set-level information contained in a hypergraph, unlike the proxy graphs (corresponding to hypergraphs) based techniques (used as baselines in our experiments), which approximate hyperedge or set-level information with dyadic edge-level information. Therefore, we design an algorithm which is principally suited for hypergraph structured data. For a given hypergraph we can extract a sub-hypergraph that only consists of the hyperedges with cardinality k. This sub-hypergraph is a k-uniform hypergraph or k-graph Cooper & Dutle (2012). Corresponding to this k-uniform hypergraph, we can define a kth order n-dimensional symmetric tensor Qi (2005) $\mathcal{A}^{\mathbf{k}}_{\mathbf{hyp}} = (a_{p_1,p_2,..,p_k}) \in \mathbb{R}^{[k,n]}$ whose elements are initialized as follows:

$$a_{p_1,p_2,..,p_k} = R(g_i) \tag{1}$$

where $\{v_{p_1}, v_{p_2}, ..., v_{p_k}\} \in g_i$ and $|g_i| = k, \forall i \in \{1, ..., m\}$. Note that symmetry here implies that value of element $a_{p_1,p_2,..,p_k}$ is invariable under any permutation of its indices $(p_1, p_2, .., p_k)$. Rest all the elements in the tensor are zeros.

In a similar manner we can also define a *dual tensor*, corresponding to *hypergraph dual* where the roles of nodes and hyperedges are interchanged. We consider all the hyperedges in the hypergraph dual that are of cardinality k. This basically corresponds to all the vertices in the original hypergraph which have a degree of k, i.e., they are part of exactly k hyperedges in the original hypergraph. Corresponding to this k-uniform hypergraph dual, we can define a kth order m-dimensional symmetric dual tensor $\mathcal{A}^{\mathbf{k}}_{\mathbf{dual}} = (a_{q_1,q_2,..,q_k}) \in \mathbb{R}^{[k,m]}$ whose elements are initialized as follows:

$$a_{q_1,q_2,..,q_k} = 1 \tag{2}$$

where $\{g_{q_1}, g_{q_2}, ..., g_{q_k}\} \ni v_j$ and $|\{r|\mathbf{H}(r,j) = 1\}| = k, \forall j \in \{1, ..., n\}$. Note that this tensor is also symmetric and rest all the elements in the tensor are zeros.

To realize our aim of learning node and hyperedge embeddings we perform joint CP Tensor Decomposition Kolda & Bader (2009) (of the tensors we just described) across different cardinality hyperedges simultaneously. Specifically, for the node embeddings we solve the following optimization problem:

$$\min_{\mathbf{Z}} \sum_{k=c_{min}}^{c_{max}} \|\mathcal{A}^{\mathbf{k}}_{\mathbf{hyp}} - \widehat{\mathcal{A}^{\mathbf{k}}_{\mathbf{hyp}}}\| \tag{3}$$

where,

$$\widehat{\mathcal{A}^{\mathbf{k}}_{\mathbf{hyp}}} = \sum_{r=1}^{d} \lambda_r \underbrace{\mathbf{z}_r \circ \mathbf{z}_r ... \circ \mathbf{z}_r}_{k \text{ times}} \equiv \langle \lambda | \underbrace{\mathbf{Z}, \mathbf{Z}, ..., \mathbf{Z}}_{k \text{ times}} \rangle \tag{4}$$

with $\mathbf{z}_r \in \mathbb{R}^n$, $\lambda_r \in \mathbb{R}_+$, $\mathbf{Z} \in \mathbb{R}^{n \times d}$ and $\mathbf{Z}(:, r) = \mathbf{z}_r$. Notice, that equation 4 is the standard *symmetric* CP decomposition but equation 3 is summation of reconstruction errors in different tensor decompositions for different cardinality hyperedges. Each error term learns a common latent factor matrix $\mathbf{Z}$ using the empirical observed k-uniform sub-hypergraph stored in $\mathcal{A}^{\mathbf{k}}_{\mathbf{hyp}}$ tensor. We perform this joint decomposition by augmenting the standard CP Decomposition into the **Hypergraph-CP-ALS** algorithm 1. Lines (4-8) is the standard (*non-symmetric*) CP Decomposition (see reference (Kolda & Bader, 2009) for details), which solves the following optimization:

$$\widehat{\mathcal{A}^{\mathbf{k}}_{\mathbf{hyp}}} = \sum_{r=1}^{d} \lambda_r {}_k\mathbf{u}_r^{(1)} \circ {}_k\mathbf{u}_r^{(2)} ... \circ {}_k\mathbf{u}_r^{(k)} \equiv \langle \lambda | {}_k\mathbf{U}^{(\mathbf{1})}, {}_k\mathbf{U}^{(\mathbf{2})}, ..., {}_k\mathbf{U}^{(\mathbf{k})} \rangle \tag{5}$$

with ${}_k\mathbf{u}_r^{(j)} \in \mathbb{R}^n$, $\lambda_r \in \mathbb{R}_+$, ${}_k\mathbf{U}^{(\mathbf{j})} \in \mathbb{R}^{n \times d}$, ${}_k\mathbf{U}^{(\mathbf{j})}(:, r) = {}_k\mathbf{u}_r^{(j)}$ and $j \in \{1, .., k\}$. As we want to learn common representations ($\mathbf{Z}$) for all the nodes, we add additional constraint that enforce that ${}_k\mathbf{U}^{(\mathbf{j})}$ are same for all $j \in \{1, .., k\}$ and for all $k \in [c_{min}, c_{max}]$. Lines (9-15) is where we force all representations for all cardinalities to be average of the ${}_k\mathbf{U}^{(\mathbf{j})}$ achieved by the last decomposition iteration that occurred in lines (4-8). Averaging can be interpreted as equal contribution from the latent factors learned from different cardinality (uniform) sub-hypergraphs. We make repeated pass through the entire hypergraph (by learning via different k-uniform sub-hypergraph (line 3)) until the objective (equation 3) converges. In our implementation we empirically observe that using the above mentioned unbiased averaging heuristic, our algorithm converges successfully. The same algorithm 1 is used to get the hyperedge embeddings, by just passing $\mathcal{A}_{\mathbf{dual}}$ instead of $\mathcal{A}_{\mathbf{hyp}}$. We shall jointly refer to the embeddings achieved for nodes and hyperedges via the above tensor decomposition techniques as **t2v**.

Algorithm 1 Hypergraph-CP-ALS $(\mathcal{A}_{\mathbf{hyp}}, c_{min}, c_{max})$

1: randomly initialize ${}_k\mathbf{U}^{(\mathbf{j})}, \forall k \in [c_{min}, c_{max}], \forall j \in \{1, ..., k\}$
2: **repeat**
3: **for** $k = c_{min}$ to c_{max} **do**
4: **for** $j = 1$ to k **do**
5: $\mathbf{V} \leftarrow {}_k\mathbf{U}^{(\mathbf{1})^\intercal} {}_k\mathbf{U}^{(\mathbf{1})} * ... * {}_k\mathbf{U}^{(\mathbf{j-1})^\intercal} {}_k\mathbf{U}^{(\mathbf{j-1})} * {}_k\mathbf{U}^{(\mathbf{j+1})^\intercal} {}_k\mathbf{U}^{(\mathbf{j+1})} * ... * {}_k\mathbf{U}^{(\mathbf{j})^\intercal} {}_k\mathbf{U}^{(\mathbf{j})}$
6: ${}_k\mathbf{U}^{(\mathbf{j})} \leftarrow (\mathcal{A}^{\mathbf{k}}_{\mathbf{hyp}})^{(j)} ({}_k\mathbf{U}^{(\mathbf{k})} \odot ... \odot {}_k\mathbf{U}^{(\mathbf{j+1})} \odot {}_k\mathbf{U}^{(\mathbf{j-1})} \odot ... \odot {}_k\mathbf{U}^{(\mathbf{1})}) \mathbf{V}^\dagger$
7: normalize columns of ${}_k\mathbf{U}^{(\mathbf{j})}$ (and store norms as λ)
8: **end for**
9: $\mathbf{Z} \leftarrow \frac{1}{k} \sum_{j=1}^{k} {}_k\mathbf{U}^{(\mathbf{j})}$
10: **for** $p = c_{min}$ to c_{max} **do**
11: **for** $j = 1$ to p **do**
12: ${}_p\mathbf{U}^{(\mathbf{j})} \leftarrow \mathbf{Z}$
13: **end for**
14: **end for**
15: **end for**
16: **until** fit criteria achieved or maximum number of iterations exceeded
17: **return** $\mathbf{Z}$

We would like to highlight a few points regarding the tensor methods. The tensors that we have employed are super-symmetric and hence able to capture distribution over sets rather than sequence. But in general we can employ a k-way tensor which is not symmetric to even capture sequence. In this sense tensors are more general purpose. Another point one can observe that when we initialize the hypergraph tensor $\mathcal{A}^{\mathbf{k}}_{\mathbf{hyp}}$, we have initialized all the permutations of vertices corresponding to a given hyperedge (Eq. 1). Moreover, we initialize it by the repetition counts.

3.2 HYPEREDGE2VEC USING HASSE DE-NOISING AUTOENCODER

An autoencoder (Bengio et al., 2009), takes an input vector $\mathbf{x} \in [0, 1]^n$ and maps it to a latent representation $\mathbf{y} \in [0, 1]^d$. This is typically done using an affine mapping followed by a non-linearity (more so when the input, like in our case, is binary (Vincent et al., 2010)): $f_{en}(\mathbf{x}) = s(\mathbf{W}\mathbf{x} + \mathbf{b})$, with parameters $\theta = \{\mathbf{W}, \mathbf{b}\}$. Here, $\mathbf{W}$ is a $n \times d$ weight matrix and $\mathbf{b}$ is the offset.

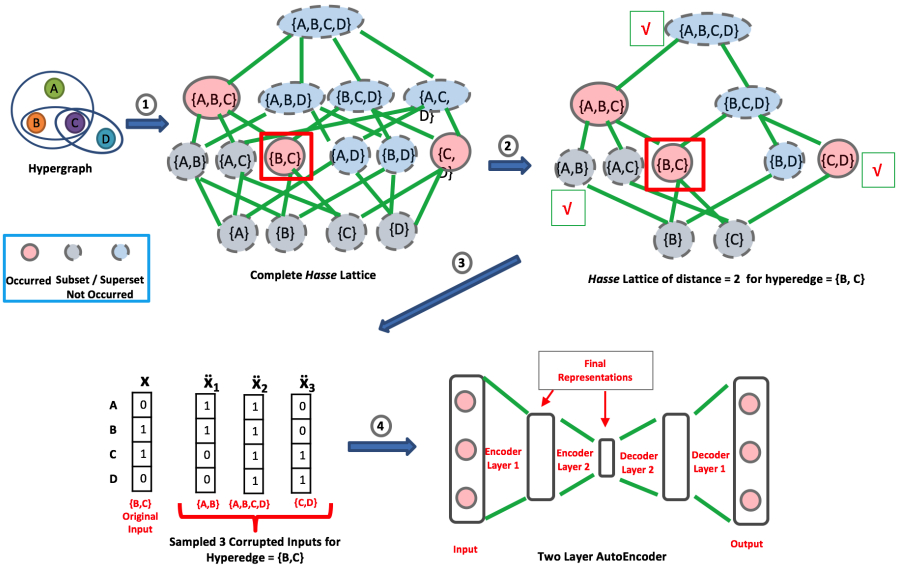

Figure 3: For the given hypergraph between four nodes (A,B,C,D) we consider the complete *hasse* lattice. For a given hyperedge {B,C} (square box) we then construct the sub-lattice made of hyperedges with distance $h = 2$ from {B,C}. We perform random walk (with $\tau = 0.2$) starting from the node corresponding to hyperedge {B,C} and sample $p = 3$ hyperedges (nodes visited by the random walk; shown with a check-mark ✓). Finally, we train the autoencoder to reconstruct the original hyperedge from these p noisy hyperedges.

This latent representation is reconstructed into a vector $\mathbf{z} = f_{de}(\mathbf{y}) = s(\mathbf{W}'\mathbf{y} + \mathbf{b}')$, in the input space, $\mathbf{z} \in [0,1]^n$ and parameters $\theta' = \{\mathbf{W}', \mathbf{b}'\}$. The mappings f_{en} and f_{de} are referred as the **encoder** and **decoder**, respectively. The representation $\mathbf{y}$ is learned by minimizing the following reconstruction error:

$$\theta^*, \theta'^* = \underset{\theta^*,\theta'^*}{\arg\min} \frac{1}{m} \sum_{i=1}^{m} L(\mathbf{x}_i, \mathbf{z}_i) = \underset{\theta^*,\theta'^*}{\arg\min} \frac{1}{m} \sum_{i=1}^{m} L(\mathbf{x}_i, g_{\theta'}(f_\theta(\mathbf{x}_i)) \tag{6}$$

where L is a loss function, which in case of binary or bit probabilities is often chosen as the *cross-entropy loss*:

$$L(\mathbf{x}, \mathbf{z}) = \sum_{j=1}^{n} [\mathbf{x}(j) \log \mathbf{z}(j) + (1 - \mathbf{x}(j)) \log(1 - \mathbf{z}(j))] \tag{7}$$

In their paper, Vincent et al. (2010) have shown that minimizing reconstruction amounts to maximizing the lower bound on the mutual information between input (x) and the representation $\mathbf{y}$. However, they have further argued (Vincent et al. (2008)) that $\mathbf{y}$ retaining information about input $\mathbf{x}$ is insufficient. They further, propose the idea that the learned representation should be able to recover (*denoising*) the original input even after being trained with corrupted input (*adding noise*). They generate the corrupted input $(\tilde{\mathbf{x}})$, using a stochastic mapping $q(\tilde{\mathbf{x}}|\mathbf{x})$. Choice of noise is usually either *Gaussian* for real inputs and *Salt-and-pepper noise* for discrete inputs. The *denoising autoencoder* then learns the representation for each input, $\mathbf{x}$, same as Equation 6, but with the following modified loss function: $L(\mathbf{x}(i), g_{\theta'}(f_\theta(\tilde{\mathbf{x}}(i))))$.

We leverage the denoising autoencoder for learning representation for j^{th} hyperedge, by treating each hyperedge as an input, $\mathbf{x} = \mathbf{H}(j,:)$. The size of this input vector for each hyperedge is n, which is the number of vertices in the hypergraph. In most natural hypergraphs, specially social networks, n can be quiet high ranging from thousands to millions or even billions (like Facebook for example). Therefore, randomly using a discrete noise like *salt-and-pepper*, might not be reasonable, as there are large number of possible permutations (as size n is large) and not all of them are related. Random addition of 1s or deletion of existing 1s from $\mathbf{x}$, amounts to randomly adding or deleting vertices to the hyperedge corresponding to $\mathbf{x}$. This might end up in new hyperedges that are completely unrelated to the given hyperedge $(\mathbf{x})$. For example, users (nodes) in a social network

from completely different regions of the network suddenly form a group (hyperedge). Such anomalous scenarios rarely happen in practice and social groups evolve in a gradual fashion via simple processes (Sharma et al., 2017; 2015).

Rather, we take advantage of the hypergraph structure to systematically guide us in generating this noise. A hypergraph can be defined by its corresponding *hasse lattice* (Sharma et al., 2017). For a given hyperedge ($\mathbf{x}$), we consider the sub-lattice consisting of only those hyperedges that are a distance h from it in the complete lattice. On this sub-lattice we sample p hyperedges (nodes in sub-lattice) by performing random walk starting at the given hyperedge's node (see Figure 3). We assume that all the nodes in the sub-lattice which correspond to previously occurred hyperedge g_i have weight $R(g_i)$ and rest all nodes have a constant weight τ. During random walk from a given node we choose a neighboring node (as the next node) in proportion to this neighboring node's weight as compared to the other neighboring nodes. Our stochastic mapping $q(\tilde{\mathbf{x}}|\mathbf{x})$ is therefore, a random walk on the sub-lattice of hyperdge ($\mathbf{x}$) containing hyperedges at distance h from it. Intuitively, the hyperedges coming within a reasonable distance will affect each others representations and will have more similar representations. We will refer to the hyperedge representations learned by the above autoencoder technique, as **h2v-auto**.

4 EXPERIMENTS

4.1 DATASET DESCRIPTION

As the first dataset, we use group interaction log-data of the Sony's Online multi-player game EverQuest II (**EQ II**) (www.everquest2.com) for a time period of nine months. In this game, several players work together as a team to perform various tasks. Each team earn points after completion of each task, and as the teams progress by earning points, they are escalated to different levels of game play. The interestingness of the game increases with each level. The points earned by the teams are treated as a measure of group performance. Each set of players who played together is treated as a hyperedge. We treat the number of times same set of players play together again as hyperedge occurrence number ($R(g_i)$). Players can participate in several teams over time, therefore, resulting in a hypergraph with overlapping hyperedges. We consider hyperedges of cardinality $\in [2, 6]$ as almost 90% of our hyperedges lie within this range. The resulting dataset contains a total of 5964 hyperedges (teams) among 6536 nodes (players).

Second dataset, is the fully labeled and publicly available sentiment analysis corpus of *Stanford Sentiment Treebank* (**LangNet**) (Socher et al., 2013). This dataset is based on the reviews from a movie review website (www.rottentomatoes.com) and contains 215,154 unique phrases. Each of the phrases are labeled with a sentiment score (a real number $\in [0, 1]$, larger value indicates positive sentiment) by human annotators. Each phrase is a set or hyperedge of words. As there is no occurrence information for a phrase hyperedge we consider $R(g_i) = 1, \forall i \in \{1, ..., m\}$. Given that words are shared across various phrases, these common words connect the phrase hyperedges, resulting in a phrase hypergraph with overlapping phrase hyperedges. Again, we only consider hyperedges of cardinality $\in [2, 6]$. After applying this cardinality filter we are left with 141,410 hyperedges (phrases) and 21,122 nodes (words).

4.2 EVALUATION METHODOLOGY AND EXPERIMENTAL SETUP

4.2.1 METHODS COMPARED

As mentioned before we refer to our proposed methods: tensor and auto-encoder methods, as **t2v** and **h2v-auto**, respectively. We compare our proposed methods against six baselines which we have developed by adapting various language models as well as dyadic graph embedding techniques, for hypergraph setting. These are as follows:

1. **h2v-DM:** Hyperedge and node embeddings obtained using sentence embedding using distributed memory (DM) model (refer section A.1)
2. **h2v-DBOW:** Hyperedge and node embeddings obtained using sentence embedding using distributed memory (DBOW) model (refer section A.1)

3. **h2v-inv:** Hyperedge and node embeddings obtained using node2vec on inverted hypergraph (refer section A.2)
4. **h2v-dual:** Hyperedge and node embeddings obtained using node2vec on hypergraph dual (refer section A.2)
5. **e2v:** Hyperedge and node spectral embeddings obtained using eigen decomposition of inverted hypergraph laplacian and graph laplacian, respectively (refer section A.3)
6. **e2v-hyp:** Hyperedge and node spectral embeddings obtained using eigen decomposition of dual laplacian and hypergraph laplacian, respectively (refer section A.3)

Note that methods (1-2) are adapted from sequence based language models for set structured data. Methods (3-6) are various kind of dyadic graph based embedding methods. The details of these baseline can be found in Appendix A. Except for **h2v-auto**, each of these methods result in node as well as hyperedge embeddings of dimension $d = 128$. We further combine the node and hyperedge embedding using five different strategies: i) node embedding summation (dimension $d = 128$), ii) node embedding summation and concatenation with hyperedge embedding (dimension $2 \times d = 256$), iii) node embedding averaging (dimension $d = 128$), iv) node embedding averaging and concatenation with hyperedge embedding (dimension $2 \times d = 256$), and v) only hyperedge embedding (dimension $d = 128$). **h2v-auto** only produces hyperedge embeddings of dimension $d = 128$. But it builds the embeddings using three different scenarios as mentioned in next section. Therefore, in total we have 38 ($= 35 + 3$) different scenarios each resulting in a different hyperedge embedding.

4.2.2 Evaluation Tasks and Setup

We perform two regression based tasks for the two datasets. In **EQII** dataset each team (hyperedge) has a team performance score associated with it. This team performance score is a real number, equal to the number of points earned by the team while performing one or more tasks within a gaming session. We treat the embedding learned for a given team (hyperedge) as its feature vector which is associated with a real number (team performance). We therefore, perform on regression over all the hyperedges (teams) with team performance as the dependent variable.

Similarly, in **LangNet** dataset each phrase (hyperedge) has a sentiment score associated with it, which again is a real number. Similar to the team dataset above, we treat the embedding learned for a given phrase (hyperedge) as its feature vector which is associated with a real number (sentiment score). We therefore, treat this as a regression task with sentiment score as the dependent variable and perform regression using the feature matrix containing embeddings of all the phrases.

For both the tasks we just described, we perform several evaluation runs. In each run we randomly choose 30% of hyperedges (teams or phrases) as the test set and learn ridge regression parameters using the remaining 70% training hyperedges for each of the 38 different embedding scenarios. Root mean squared error (RMSE) was chosen as the evaluation metric (the lower, the better). RMSE was calculated for each of the 38 scenarios and for each run. Final RMSE score was taken as the average RMSE score across five runs. Ridge regression's hyper-parameter was chosen by 5-fold cross-validation.

For the autoencoder method (**h2v-auto**) we consider three scenarios: (1) single hidden layer ($L1$) of $d = 128$; (2) two hidden layers ($L1$ & $L2$) with size of $L1 : d = 96$ and of $L2 : d = 32$. We concatenate these embedding to get a single $d = 128$ size embedding; and (3) two hidden layers ($L1$ & $L2$) with size of $L1 : d = 512$ and of $L2 : d = 128$. We use the output of $L2$, which is of dimension $d = 128$, as the embedding. For sampling, we use the distance parameter $h = 2$ for generating the sub-lattice and $\tau = 0.2$ for both datasets. Also, $p = 10$ & $p = 5$ number of hyperedges are sampled (corresponding to each hyperedge) from **EQII** and **LangNet**, respectively.

4.3 Results and Discussion

Tables 1 &2 show the RMSE scores for the tasks of team performance prediction and sentiment score prediction, respectively. These tables contain scores for all the 35 different scenarios: columns represent 7 (6 baselines and the proposed **t2v**) different models while rows represent combination strategies. The scores for *Hypergraph Auto-encoder* are shown in the separate Table 3 as auto-encoder only generates hyperedge embeddings.

Table 1: RMSE Scores for **EQ II** team performance

	Embedding Methods						
	Sentence Embed based		Node2Vec based		Spectral methods		Tensor method
Embed Combination	**h2v-DM**	**h2v-DBOW**	**h2v-inv**	**h2v-dual**	**e2v**	**e2v-hyp**	**t2v**
Node Embed Sum	0.79308	0.79567	0.80418	0.79956	0.81183	0.81405	0.81341
Node Embed Sum + Hyperedge Embed	0.79651	0.80241	0.81362	0.80636	0.8113	0.81652	0.81299
Node Embed Average	0.81584	0.81733	0.82407	0.82281	0.81234	0.81369	0.81303
Node Embed Avg + Hyperedge Embed	0.8182	0.82077	0.83378	0.82896	0.81223	0.81608	0.8127
Only Hyperedge Embed	0.81203	0.81522	0.82189	0.81984	0.81233	0.81608	0.81341

Table 2: RMSE Scores for **LangNet** Sentiment Analysis

	Embedding Methods						
	Sentence Embed based		Node2Vec based		Spectral methods		Tensor method
Embed Combination	**h2v-DM**	**h2v-DBOW**	**h2v-inv**	**h2v-dual**	**e2v**	**e2v-hyp**	**t2v**
Node Embed Sum	0.14081	0.14029	N/A	N/A	0.14633	0.14854	0.14194
Node Embed Sum + Hyperedge Embed	0.14028	0.13883	N/A	N/A	0.14627	0.14845	0.14144
Node Embed Average	0.14245	0.14115	N/A	N/A	0.14665	0.14852	0.14381
Node Embed Avg + Hyperedge Embed	0.14178	0.14007	N/A	N/A	0.14661	0.14845	0.14333
Only Hyperedge Embed	0.14194	0.14147	N/A	N/A	0.14744	0.14844	0.1482

Table 3: *Hypergraph AutoEncoder* (**h2v-auto**) RMSE Scores & Run-times for **LangNet** (Sentiment Analysis) & **EQ II** (Team Performance)

	EQ II			LangNet		
Layer Sizes	**L1:128**	**L1:96/L2:32**	**L1:512/L2:128**	**L1:128**	**L1:96/L2:32**	**L1:512/L2:128**
RMSE	0.81104	0.81512	0.81635	0.14568	0.14529	0.14784
Run Time	52 min	40 min	1 hr 20 min	2 hr 10 min	3 hr 20 min	6 hr

Table 4: Average Runtime (seconds) of various methods across datasets

	Embedding Methods						
	Sentence Embed based		Node2Vec based		Spectral methods		Tensor method
Dataset	**h2v-DM**	**h2v-DBOW**	**h2v-inv**	**h2v-dual**	**e2v**	**e2v-hyp**	**t2v**
EQ2	455.84	103.47	90.05	93.41	128.03	12.01	213.37
LangNet	80.61	62.31	211.97*	207.86*	221.46	47.12	483.81

***** these are average time taken for learning vertex embeddings only

As we can observe that for our datasets and for both the regression tasks, almost all the embeddings are performing very similarly in terms of accuracy. However, we can observer in Table 4 that tensor based method (**t2v**) have significant less time than the expensive auto-encoder technique (**h2v-auto**) (Table 3). This makes tensor based well understood and interpretable decomposition techniques more attractive than the black-box type deep learning based auto-encoder method.

Over all, we observe that **e2v**, **e2v-hgraph** and **t2v**, all of which are matrix or tensor based algebraic techniques, perform comparable to state of the art embedding techniques from NLP. Therefore, it provides motivation to further explore algebraic techniques, which are easily interpretable in graph theoretic terms, as a reasonable alternative for learning representations.

Another thing we notice, is that in case of **LangNet** dataset, that Node2Vec based **h2v-inv** and **h2v-dual** methods are simply unable to run, as the $\mathbf{A_{inv}}$ and $\mathbf{A_{dual}}$ are quiet large (see N/A in Table 2). It seems that in **LangNet** and possibly in text data in general the hypergraph dual, which contain phrase to phrase edges turns out be containing significantly more edges than the number of node to node edges in $\mathbf{A_{hyp}}$. Performing context generation over $\mathbf{A_{inv}}$ and $\mathbf{A_{dual}}$ graphs turns out be very

costly and we were unable to get hyperedge embeddings for **h2v-inv** and **h2v-dual** methods. Note, we however do get vertex embedding (as mentioned with a * mark below Table 4). But as you can see that even the time time taken for vertex embedding is similar or more than the total time taken by spectral methods for learning both hyperedge as well as vertex embedding, together. This indicates the robustness of the Spectral methods, specially the **e2v-hyp** for different kinds of hypergraph data and edge densities (sparsity).

Scalability Main scalability in the tensor approach arises with the increase in range of cardinality k. For a hyperedge of cardinality k there are $k!$ entries to be filled in the tensor $\mathcal{A}^{\mathbf{k}}_{\mathbf{hyp}}$. Per iteration complexity of the algorithm is $O(\sum_{k=c_{min}}^{c_{max}} \text{nnz}(\mathcal{A}^{\mathbf{k}}_{\mathbf{hyp}}))$. Similarly, for a vertex of degree (i.e. number of hyperedges it is part of) δ there are $\delta!$ entries to be filled in the tensor $\mathcal{A}^{\delta}_{\mathbf{dual}}$. Per iteration complexity of the algorithm is $O(\sum_{\delta=\delta_{min}}^{\delta_{max}} \text{nnz}(\mathcal{A}^{\delta}_{\mathbf{dual}}))$. Now, as the k increases, the number of k cardinality hyperedge decrease, however the $\mathcal{A}^{\mathbf{k}}_{\mathbf{hyp}}$ tensor grows exponentially making it increasingly sparse and less informative (in information theoretic sense). Therefore, depending upon the cardinality distribution of a given dataset, we can choose a threshold value (α) for k beyond which we don't enumerate the permutations. Moreover, for enumeration till $k \leq \alpha$ in a scalable manner we propose to use hyperedge-centric distributed computation libraries like MESH (Heintz & Chandra, 2015; Heintz et al., 2017) and HyperX (Huang et al., 2015), for distributed enumeration per hyperedge. Similar argument goes for $\mathcal{A}^{\delta}_{\mathbf{dual}}$ where we ignore vertices with degree beyond a certain cut-off (β). These high degree vertices can be interpreted as highly popular person participating in a huge number of teams, but should the embeddings of these teams be related to each other is difficult to infer. In text data these high degree nodes correspond to words occurring in a large number of phrases, but this doesn't mean the sentences are related, rather its just that this word is quiet common. We can again employ MESH or HyperX for scalability till $\delta \leq \beta$.

In case of auto-encoder method the main scalability challenge lies in generating the noisy hyperedges. For a given hyperedge the intermediate sub-lattice from which p samples are drawn is of size $O(n^h)$, where h is max distance from the hyperedge considered. Once this sampling is performed we have total mp hyperedges as input for the auto-encoder, which is linear in the number of hyperedge as p will be a constant. The main challenge therefore, is to generate the noisy samples where we have to tackle exponential size sub-lattice per hyperedge. Again, as this sampling is done for each hyperedge separately (hyperedge-centric), we can therefore, use distributed computing for hypergraphs using MESH and HyperX, as mentioned before.

Furthermore, we also observe that even simple element-wise summation or averaging of node embeddings for the nodes (in a given hyperedge) also perform comparably when compared to hyperedge embedding alone. From this we can infer that depending upon the dataset, if we have less hyperedges and more nodes, than we would rather prefer to simply learn the hyperedge embedding directly rather than learning node embeddings and then performing aggregating operation over them. Aggregation might turn out be costly specially if average hyperedge size is large and the choice of aggregation function is an issue. Therefore, learning hyperedge embeddings directly seems to be escape the problem of choosing the aggregation function all together.

Choice of Method Both tensor based (using $\mathcal{A}^{\mathbf{k}}_{\mathbf{dual}}$) as well as auto-encoder methods proposed in this paper are able to generate embeddings for all cardinality hyperedges. However, the auto-encoder method *cannot* generate node embeddings unlike tensor method (using $\mathcal{A}^{\mathbf{k}}_{\mathbf{hyp}}$). On contrary, in auto-encoder technique we don't need to figure out α and τ parameters, and can work for all cardinality hyperedges. Another, thing to note is that tensors are inherently capable of retaining joint information because of their higher-order structure. Auto-encoder method implicitly (possibly lossy manner) leverage the higher order information embedded in network in form of node weights ($R(g_i)$) while performing the random walk sampling. Main advantage of auto-encoders is the crisp embedding achieved via multiple levels of non-linearity offered by deep neural networks. Although this non-linearity improves the accuracy of auto-encoder methods very slightly (Table 3) as compared to tensor method (bottom right corner of Table 1& 2), the computation cost of tensor is far less than the auto-encoder method (Table 4& 3). Intuitively, it seems that depending upon the task at hand, in some task the retention of joint hyperedge-level is important for modeling and lesser presence of non-linear structure in the data; or vice versa. But the low computational cost (as reflected in our tasks) makes tensor method definitely more lucrative. Together with the natural graph

theoretic interpretation, tensor methods in comparison to black-box approach of deep learning based auto-encoder, makes them even more viable.

Information Loss Many methods that we have developed so far make use of only pair-wise information. For example, the methods developed using Node2Vec in Section A.2 are based on the skip-gram model, which learns embedding of nodes while maximizing the conditional probability of a node given another node in a context (Eq. 14). Similarly, the spectral methods (Section A.3) are inherently two dimensional as they are based on matrix. Same is the case with skip-gram based sentence embedding (**h2v-dbow**). However, sentence embedding based on the **DM** architecture (**h2v-dm**) maximizes the conditional probability of a word given the previous set of words (*context*) without breaking this context (by concatenating or averaging the embedding of the previous words). However, the tensors principally capture the joint distribution over various cardinality hyperedges unlike conditional distribution like sentence embedding (**h2v-dm**) (which are more appropriate for sequences).

Improvements There are a few possible improvements which we can see in various approaches. In tensor approach when we extract a sub-hypergraph of a given k size hyperedges, it is possible that a significant part of nodes are left out (as they might not be a part of any k size hyperedge). This can possibly cause a cold start problem in the corresponding tensor decomposition. However, this does not mean that we will not get embedding for those nodes. It simply means that we might not achieve embeddings for these nodes from the decomposition of k-way tensors. But we can get embedding for these nodes from other tensors for a different k. However, we can mitigate the cold start problem in a principled manner using a graph regularization term $({}_k\mathbf{U}^{(\mathrm{j})^T}\mathbf{L}_k\mathbf{U}^{(\mathrm{j})})$ in our tensor decomposition objective function 3. Here, $\mathbf{L}$ is the graph laplacian of our choice. For example we can use $\mathbf{L_{hyp}}$ or $\mathbf{L_{graph}}$ when we perform tensor decomposition for node embeddings and use $\mathbf{L_{inv}}$ or $\mathbf{L_{dual}}$ for hyperedge embeddings. Lastly, the hypergraph autoencoder (**h2v-auto**) can only produce hyperedge embeddings and *not* the node embeddings. In this sense it is feeble to other methods.

Highlight Another distinguishing feature of our work is that we leverage the existing structure (group structure) within the data. Recent attempts along these lines in network literature (Grover & Leskovec, 2016; Tang et al., 2015b; Perozzi et al., 2014) argue that language models have ready-made context in the form of sentences or paragraphs to train the model, which are not available in networks, and therefore, they propose different ways to generate this context. In contrast, we focus on networks where the context is already present, e.g. collaboration networks where collaborative teams are hyperedges, or language hyper-networks where sentences are hyperedges.

5 Related Works

Hypergraphs were studied rigorously by Berge (1976; 1984) as a generalization of graphs and *directed* hypergraphs have been introduced by Bretto (2013). Hypergraph were argued for the first time as a model to naturally capture higher-order relationships between sets of objects across variety of domains by Estrada & Rodriguez-Velazquez (2005). Hypergraphs have been used to model complex networks in different fields including biology (Klamt et al., 2009), databases (Fagin, 1983) and data mining (Han et al., 1997; Zhou et al., 2007). Within machine learning, algorithms guided by the structure of hypergraph were introduced by Zhou et al. (2006) and have found applications in a variety of domains (Tian et al., 2009; Gao et al., 2013; Li & Li, 2013; Sharma et al., 2015; 2017). Simplicial complex (Munkres, 1984) based view of hypergraph using *hasse lattice* (Skiena, 1990) within machine learning has recently been proposed by Sharma et al. (2017).

Representation learning (RL) (Bengio et al., 2013) focuses on learning features (geometry) of the data (topology). Machine learning algorithms make use of these features for prediction. Traditionally these features are readily available within the data-set or are engineered manually. However, this is often a tedious and human labor-intensive process. RL addresses this issue by learning features automatically in a task-dependent supervised or a task-independent unsupervised manner.

Node Representations in Graph: Traditionally unsupervised node embedding learning has been dong using latent models like matrix factorization (Ahmed et al., 2013) or by community detection (Tang & Liu, 2011) based techniques for networks (Roweis & Saul, 2000; Belkin & Niyogi, 2001; Tenenbaum et al., 2000; Cox & Cox, 2000). In each case there is a vector of features learned for a node, each of whose entries reflects node's association with some latent dimension or a network

community. More recently, there has been a revived interest in graph embedding in form of *context* oriented techniques (Perozzi et al., 2014; Tang et al., 2015b; Grover & Leskovec, 2016). These techniques are inspired by recent unsupervised RL methods in NLP (Mikolov et al., 2013b; Le & Mikolov, 2014) where word embeddings are learned that are similar to words in a given neighborhood or *context*. These techniques differ in the manner they generate this context as well as in the objective which they optimize. Also there are supervised algorithms learn embeddings which are optimal for the specific task at hand. This results in high accuracy but incurs significant computational cost for training. Recently, several supervised learning algorithms have been proposed for network analysis (Tian et al., 2014; Xiaoyi et al., 2013) and for text networks in a semi-supervised setting (Tang et al., 2015a). Finally, we refer readers to a very recent and comprehensive survey on graph embedding methods by Cai et al. (2017).

Node Representations in Hypergraph: Learning embeddings for nodes within a hypergraph while incorporating the hypergraph topology using proxy graphs is introduced by Zhou et al. (2006). Using graph proxy destroys the hypredge-level joint information and thus, incur loss of information. Also, Agarwal et al. (2006) squarely criticize that such representations can be learned by constructing graphs, which are proxies for the hypergraph structure.

Set Representations: RL for sets using neural networks has been proposed recently (Vinyals et al., 2016), where a memory network is used to compose features sequentially but in an order invariant manner. In their very recent paper, Rezatofighi et al. (2016) have tried to answer this set ordering issue by the use of *random set theory*. However, they do not consider embedding but focus on learning set-level probabilities. More importantly, both of these works, do not consider the hypergraph structure of overlapping sets which is the main focus of this paper.

Tensors For comprehensive view of tensors, tensor decomposition as well as applications we refer to the survey by Kolda & Bader (2009). The connection between k-way tensor and k-uniform hypergraph eigen values was established by Qi (2005). The use of k-way symmetric tensor and their non-negative decomposition for uniform hypergraph partitioning was first introduced by Shashua et al. (2006). But they are again restricted to uniform hypergraphs.

6 Conclusion

In this paper we have proposed two methods to generate higher-order representations for both hyperedges (representing sets of nodes) and hypergraph nodes (that also take into account the hypergraph structure). First, is an auto-encoder based deep-learning method and second, is a tensor-based algebraic method. Both learning models are unique in the manner they leverage the existing structure present in network data as context. While introducing a new idea of a dual tensors corresponding to the hypergraph dual, we develop a novel approach of using factors from joint decomposition of k-way tensors corresponding to k-uniform sub-hypergraphs, as generic node & hyperedge representations. We show that that both methods perform comparably with several other baselines in terms of accuracy. We also observe that the proposed tensor based methods are more efficient and also have a natural hypergraph theoretic interpretation; unlike deep learning based black-box approach. We therefore, argue that we have proposed more general methods which are principally suited for hypergraphs (and therefore also for graphs) while maintaining accuracy and efficiency.

REFERENCES

Pubmed data. https://www.ncbi.nlm.nih.gov/pubmed/.

Sameer Agarwal, Kristin Branson, and Serge Belongie. Higher order learning with graphs. In *Proceedings of the 23rd international conference on Machine learning*, pp. 17–24. ACM, 2006.

Amr Ahmed, Nino Shervashidze, Shravan Narayanamurthy, Vanja Josifovski, and Alexander J Smola. Distributed large-scale natural graph factorization. In *Proceedings of the 22nd international conference on World Wide Web*, pp. 37–48. ACM, 2013.

Iftekhar Ahmed, Channing Brown, Andrew Pilny, Dora Cai, Yannick Atouba Ada, and Marshall Scott Poole. Identification of groups in online environments: The twist and turns of grouping groups. In *Privacy, Security, Risk and Trust (PASSAT) and 2011 IEEE Third Inernational Conference on Social Computing (SocialCom), 2011 IEEE Third International Conference on*, pp. 629–632. IEEE, 2011.

Anthony F Bartholomay. Molecular set theory: A mathematical representation for chemical reaction mechanisms. *Bulletin of Mathematical Biology*, 22(3):285–307, 1960.

Mikhail Belkin and Partha Niyogi. Laplacian eigenmaps and spectral techniques for embedding and clustering. In *NIPS*, volume 14, pp. 585–591, 2001.

Yoshua Bengio and Samy Bengio. Modeling high-dimensional discrete data with multi-layer neural networks. In *Advances in Neural Information Processing Systems*, pp. 400–406, 2000.

Yoshua Bengio, Aaron Courville, and Pascal Vincent. Representation learning: A review and new perspectives. *IEEE transactions on pattern analysis and machine intelligence*, 35(8):1798–1828, 2013.

Yoshua Bengio et al. Learning deep architectures for ai. *Foundations and trends® in Machine Learning*, 2(1):1–127, 2009.

C. Berge. *Graphs and hypergraphs*, volume 6. Elsevier, 1976.

Claude Berge. *Hypergraphs: combinatorics of finite sets*, volume 45. Elsevier, 1984.

Alain Bretto. Hypergraph theory. *An introduction. Mathematical Engineering. Cham: Springer*, 2013.

Samuel R Bulò and Marcello Pelillo. A game-theoretic approach to hypergraph clustering. In *Advances in neural information processing systems*, pp. 1571–1579, 2009.

Hongyun Cai, Vincent W Zheng, and Kevin Chen-Chuan Chang. A comprehensive survey of graph embedding: Problems, techniques and applications. *arXiv preprint arXiv:1709.07604*, 2017.

Evangelia Christakopoulou and George Karypis. Hoslim: higher-order sparse linear method for top-n recommender systems. In *Pacific-Asia Conference on Knowledge Discovery and Data Mining*, pp. 38–49. Springer, 2014.

Joshua Cooper and Aaron Dutle. Spectra of uniform hypergraphs. *Linear Algebra and its Applications*, 436(9):3268–3292, 2012.

Trevor F Cox and Michael AA Cox. *Multidimensional scaling*. CRC press, 2000.

Mukund Deshpande and George Karypis. Item-based top-n recommendation algorithms. *ACM Transactions on Information Systems (TOIS)*, 22(1):143–177, 2004.

Ernesto Estrada and Juan A Rodriguez-Velazquez. Complex networks as hypergraphs. *arXiv preprint physics/0505137*, 2005.

R. Fagin. Degrees of acyclicity for hypergraphs and relational database schemes. *Journal of the ACM (JACM)*, 30(3):514–550, 1983.

Shenghua Gao, Ivor Wai-Hung Tsang, and Liang-Tien Chia. Laplacian sparse coding, hypergraph laplacian sparse coding, and applications. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 35(1):92–104, 2013.

Aditya Grover and Jure Leskovec. node2vec: Scalable feature learning for networks. In *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, San Francisco, CA, USA, August 13-17, 2016*, pp. 855–864, 2016. doi: 10.1145/2939672.2939754.

E.H. Han, G. Karypis, V. Kumar, and B. Mobasher. *Clustering based on association rule hypergraphs*. University of Minnesota, Department of Computer Science, 1997.

Benjamin Heintz and Abhishek Chandra. Enabling scalable social group analytics via hypergraph analysis systems. In *HotCloud*, 2015.

Benjamin Heintz, Shivangi Singh, Rankyung Hong, Guarav Khandelwal, Corey Tesdahl, and Abhishek Chandra. Mesh: A flexible distributed hypergraph processing system. 2017.

Jin Huang, Rui Zhang, and Jeffrey Xu Yu. Scalable hypergraph learning and processing. In *Data Mining (ICDM), 2015 IEEE International Conference on*, pp. 775–780. IEEE, 2015.

TaeHyun Hwang, Ze Tian, Rui Kuangy, and Jean-Pierre Kocher. Learning on weighted hypergraphs to integrate protein interactions and gene expressions for cancer outcome prediction. In *Data Mining, 2008. ICDM'08. Eighth IEEE International Conference on*, pp. 293–302. IEEE, 2008.

S. Klamt, U.U. Haus, and F. Theis. Hypergraphs and cellular networks. *PLoS computational biology*, 5(5):e1000385, 2009.

Tamara G Kolda and Brett W Bader. Tensor decompositions and applications. *SIAM review*, 51(3): 455–500, 2009.

Quoc V Le and Tomas Mikolov. Distributed representations of sentences and documents. In *ICML*, volume 14, pp. 1188–1196, 2014.

Lei Li and Tao Li. News recommendation via hypergraph learning: encapsulation of user behavior and news content. In *Proceedings of the sixth ACM international conference on Web search and data mining*, pp. 305–314. ACM, 2013.

Tomas Mikolov, Kai Chen, Greg Corrado, and Jeffrey Dean. Efficient estimation of word representations in vector space. *arXiv preprint arXiv:1301.3781*, 2013a.

Tomas Mikolov, Ilya Sutskever, Kai Chen, Greg Corrado, and Jeffrey Dean. Distributed representations of words and phrases and their compositionality. In *Proceedings of the 26th International Conference on Neural Information Processing Systems*, NIPS'13, pp. 3111–3119, 2013b.

James R Munkres. *Elements of algebraic topology*, volume 2. Addison-Wesley Menlo Park, 1984.

Bryan Perozzi, Rami Al-Rfou, and Steven Skiena. Deepwalk: Online learning of social representations. In *Proceedings of the 20th ACM SIGKDD international conference on Knowledge discovery and data mining*, pp. 701–710. ACM, 2014.

Liqun Qi. Eigenvalues of a real supersymmetric tensor. *Journal of Symbolic Computation*, 40(6): 1302–1324, 2005.

Seyed Hamid Rezatofighi, Anton Milan, Ehsan Abbasnejad, Anthony Dick, Ian Reid, et al. Deepsetnet: Predicting sets with deep neural networks. *arXiv preprint arXiv:1611.08998*, 2016.

Sam T Roweis and Lawrence K Saul. Nonlinear dimensionality reduction by locally linear embedding. *Science*, 290(5500):2323–2326, 2000.

Ankit Sharma, Rui Kuang, Jaideep Srivastava, Xiaodong Feng, and Kartik Singhal. Predicting small group accretion in social networks: A topology based incremental approach. In *2015 IEEE/ACM International Conference on Advances in Social Networks Analysis and Mining (ASONAM)*, pp. 408–415. IEEE, 2015.

Ankit Sharma, Terrence J Moore, Ananthram Swami, and Jaideep Srivastava. Weighted simplicial complex: A novel approach for predicting small group evolution. In *Pacific-Asia Conference on Knowledge Discovery and Data Mining*, pp. 511–523. Springer, 2017.

Amnon Shashua, Ron Zass, and Tamir Hazan. Multi-way clustering using super-symmetric non-negative tensor factorization. *Computer Vision–ECCV 2006*, pp. 595–608, 2006.

Steven Skiena. Hasse diagrams. *Implementing Discrete Mathematics: Combinatorics and Graph Theory With Mathematica*, pp. 163, 1990.

Richard Socher, Alex Perelygin, Jean Wu, Jason Chuang, Christopher Manning, Andrew Ng, and Christopher Potts. Parsing With Compositional Vector Grammars. In *EMNLP*. 2013.

Steven H Strogatz. Exploring complex networks. *Nature*, 410(6825):268–276, 2001.

Karthik Subbian, Charu Aggarwal, and Jaideep Srivastava. Content-centric flow mining for influence analysis in social streams. In *Proceedings of the 22nd ACM international conference on Conference on information & knowledge management*, pp. 841–846. ACM, 2013.

Jian Tang, Meng Qu, and Qiaozhu Mei. Pte: Predictive text embedding through large-scale heterogeneous text networks. In *Proceedings of the 21th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, pp. 1165–1174. ACM, 2015a.

Jian Tang, Meng Qu, Mingzhe Wang, Ming Zhang, Jun Yan, and Qiaozhu Mei. Line: Large-scale information network embedding. In *Proceedings of the 24th International Conference on World Wide Web*, pp. 1067–1077. ACM, 2015b.

Lei Tang and Huan Liu. Leveraging social media networks for classification. *Data Mining and Knowledge Discovery*, 23(3):447–478, 2011.

Joshua B Tenenbaum, Vin De Silva, and John C Langford. A global geometric framework for nonlinear dimensionality reduction. *science*, 290(5500):2319–2323, 2000.

Fei Tian, Bin Gao, Qing Cui, Enhong Chen, and Tie-Yan Liu. Learning deep representations for graph clustering. In *AAAI*, pp. 1293–1299, 2014.

Ze Tian, TaeHyun Hwang, and Rui Kuang. A hypergraph-based learning algorithm for classifying gene expression and arraycgh data with prior knowledge. *Bioinformatics*, 25(21):2831–2838, 2009.

Pascal Vincent, Hugo Larochelle, Yoshua Bengio, and Pierre-Antoine Manzagol. Extracting and composing robust features with denoising autoencoders. In *Proceedings of the 25th international conference on Machine learning*, pp. 1096–1103. ACM, 2008.

Pascal Vincent, Hugo Larochelle, Isabelle Lajoie, Yoshua Bengio, and Pierre-Antoine Manzagol. Stacked denoising autoencoders: Learning useful representations in a deep network with a local denoising criterion. *Journal of Machine Learning Research*, 11(Dec):3371–3408, 2010.

Oriol Vinyals, Samy Bengio, and Manjunath Kudlur. Order matters: Sequence to sequence for sets. In *ICLR*, 2016.

Li Xiaoyi, Li Hui Du Nan, et al. A deep learning approach to link prediction in dynamic networks. In *Proceedings of the 2013 SIAM International Conference on Data Mining. Philadelphia, PA, USA: SIAM*, 2013.

D. Zhou, J. Huang, and B. Scholkopf. Learning with hypergraphs: Clustering, classification, and embedding. *Advances in Neural Information Processing Systems*, 19:1601, 2007.

Dengyong Zhou, Jiayuan Huang, and Bernhard Schölkopf. Learning with hypergraphs: Clustering, classification, and embedding. In *Advances in neural information processing systems*, pp. 1601–1608, 2006.

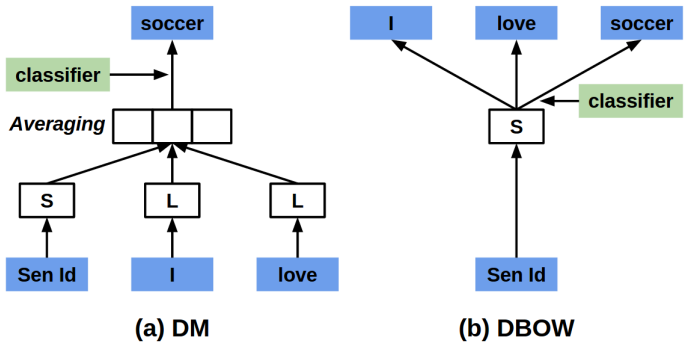

Figure 4: Distributed memory (DM) and Distributed bag of words (DBOW) versions of Sen2Vec for a sentence "I love soccer".

A APPENDIX

A.1 HYPEREDGE2VEC USING SENTENCE EMBEDDINGS

As mentioned before, the most commonly used model for studying complex interactions in networks is graphs, where each edge represents a dyadic interaction between nodes Strogatz (2001). Therefore, even if the original interaction is not dyadic like a set of researchers (3 or more) collaborating on a publication, we shall break down this joint interaction into dyadic interactions. Even though a large number of complex network data naturally occurs as hypergraphs Estrada & Rodriguez-Velazquez (2005), the popularity of "think like dyadic edges" and not like sets seems to us as a hindrance, specifically when the end aim is to model the joint distribution at the level of sets. In this paper, as it is obvious, we go by "think like set" paradigm, specifically, when the data is naturally occurring as network of sets (i.e., a hypergraph). Therefore, if we think of hyperedge as a set, a natural question arises is that are there any existing techniques that learn embeddings at set level? We, henceforth, explore the most popular discrete data on which representation learning has been applied is text data.

Recently, Le & Mikolov (2014) proposed two representation learning methods for sentences as shown in Figure 4: a) a distributed memory (**DM**) model, and b) a distributed bag of words (**DBOW**) model. In the DM model, every sentence in the dataset G is represented by a d dimensional vector in a shared lookup matrix $S \in \mathbb{R}^{|G| \times d}$. Similarly, every word in the vocabulary Ω is represented by a d dimensional vector in another shared lookup matrix $L \in \mathbb{R}^{|\Omega| \times d}$. Given an input sentence $\mathbf{v} = (v_1, v_2 \cdots v_m)$, the corresponding sentence vector from S and the word vectors from L are averaged to predict the next word in a context. More formally, let ϕ denote the mapping from sentence and word ids to their respective vectors in S and L, the DM model minimizes the following objective:

$$J(\phi) = -\sum_{t=k}^{m-k} \log P(v_t | \mathbf{v}; v_{t-k+1}, \cdots, v_{t-1}) \tag{8}$$

$$= -\sum_{t=k}^{m-k} \log \frac{\exp(\omega(v_t)^T \mathbf{z})}{\sum_i \exp(\omega(v_i)^T \mathbf{z})} \tag{9}$$

where $\mathbf{z}$ is the average of $\phi(\mathbf{v}), \phi(v_{t-k+1}), \cdots, \phi(v_{t-1})$ *input* vectors, and $\omega(v_t)$ is the *output* vector representation of word $v_t \in \Omega$. The sentence vector $\phi(\mathbf{v})$ is shared across all (sliding window) contexts extracted from the same sentence, thus acts as a distributed memory.

Instead of predicting the next word in the context, the DBOW model predicts the words in the context independently given the sentence id as input. More formally, DBOW minimizes the following objective:

$$J(\phi) = -\sum_{t=k}^{m-k} \sum_{j=t-k+1}^{t} \log P(v_j|\mathbf{v}) \tag{10}$$

$$= -\sum_{t=k}^{m-k} \sum_{j=t-k+1}^{t} \log \frac{\exp(\omega(v_j)^T \phi(\mathbf{v}))}{\sum_i \exp(\omega(v_i)^T \phi(\mathbf{v}))} \tag{11}$$

Both the methods take sentences as input and return embeddings for words as well as the sentence. To apply the sentence embedding models directly to hyperedges, as our first method we generate a proxy sentence for each hyperedge by leveraging the contextual information in the hyperedge.

A proxy sentence $\mathbf{v}_i$ is formed for each hyperedge $g_i \in G$ as a sequence made by concatenating all the permutations of the nodes (as words) in the hyperedge and further repeating this sequence as many time this hyperedge occurred. For example, for a three node hyperedge $g_i = \{1, 4, 7\}$ which has occurred two times we make the following sentence $\mathbf{v}_i$: {1,4,7,1,7,4,7,1,4,7,4,1,4,1,7,4,7,1,1,4,7,1,7,4,7,1,4,7,4,1,
4,1,7,4,7,1} of length 12 (6 permutations times 2 occurrence). In this scheme we have permutations and repetitions. We take all the permutations hoping that it should fool the sequence based model to get a sequence independent embedding. On the other hand, repetition of the permutations acts similarly to observing the same sequence of words several times in the text corpus. Of course one can think of other alternative schemes, but the point we are trying to make is that naturally observed hyperedges captures important contextual information that can be leveraged to achieve better representations. We refer to the node-hyperedge embedding pairs resulting from **DM**, **DBOW** models as **h2v-dm** and **h2v-dbow**, respectively.

A.2 HYPEREDGE2VEC USING NODE2VEC

Grover & Leskovec (2016) propose a representation method for nodes in a graph called Node2Vec, which uses the skip-gram model Mikolov et al. (2013b) with the intuition that neighborhood nodes within a graph should have similar representations. The objective of the skip-gram model for graphs can be defined as:

$$J(\phi) = -\sum_{v \in V} \log P(N(v)|\phi(v)) \tag{12}$$

$$= -\sum_{v \in V} \sum_{n_i \in N(v)} \log P(n_i|\phi(v)) \tag{13}$$

$$= -\sum_{v \in V} \sum_{n_i \in N(v)} \log \frac{\exp(\omega(n_i)^T \phi(v))}{\sum_{x \in V} \exp(\omega(x)^T \phi(v))} \tag{14}$$

where as before, ϕ and ω denote the *input* and the *output* vector representations of the nodes. The neighboring nodes $N(v)$ form the *context* for node v. Node2Vec uses a biased random walk which adaptively combines breadth first search (BFS) and depth first search (DFS) to find the neighborhood of a node. The walk attempts to capture two properties of a graph often used for prediction tasks in networks: i) homophily and ii) structural equivalence. According to homophily, nodes in the same group or community should have similar representations. Structural equivalence suggests that nodes with similar structural roles (hub, bridge) should have similar representations. In a real-world network, nodes exhibit mixed properties.

Our aim is to find both node and hyperedge level embeddings by taking into account the hypergraph structure. For the former, we leverage the adjacency matrix associated with a hypergraph Zhou et al. (2006), which is defined as:

$$\mathbf{A_{hyp}} = \mathbf{H}^T \mathbf{W_e} \mathbf{H} - \mathbf{D_v} \tag{15}$$

where $\mathbf{W_e}$ is a diagonal matrix containing the weights of each hyperedge and $\mathbf{D_v}$ is a diagonal matrix containing the degree of each vertex. We take the weight of a hyperedge as its occurrence number, i.e. $\mathbf{W_e}(i,i) = R(g_i), \forall\{i \in \{1, ..., n\}\}$. The adjacency matrix ($\mathbf{A_{hyp}} \in \mathbb{R}^{|V| \times |V|}$) associates a weight between a pair of nodes while taking into account the weights of all the hyperedges that encompass a pair of nodes. The weighted graph associated with $\mathbf{A_{hyp}}$ in some sense serves as a proxy to the actual hypergraph structure. We can provide $\mathbf{A_{hyp}}$ as input to Node2Vec and

hypothesize that the random walk over this proxy hypergraph should allow the skip-gram model to learn more meaningful node level embeddings which can be combined to construct hyperedge level embeddings. We refer to these node level embeddings as **N2V-hyp**.

We still have not met our second objective to learn hyperedge embeddings directly. We again wish to leverage Node2Vec for our purpose. However, Node2Vec only works for graphs by performing random walk over nodes. Therefore, we ask ourselves the question, that can we treat hyperedges as nodes? There can be other ways of doing so, but here we suggest two techniques. In the first technique, we simply consider the *hypergraph dual* Berge (1984), whose incidence matrix is $\mathbf{H_{dual}} = \mathbf{H}^T$. The adjacency matrix associated with the hypergraph dual is:

$$\mathbf{A_{dual}} = \mathbf{H_{dual}}^T \mathbf{W_v} \mathbf{H_{dual}} - \mathbf{D_e} = \mathbf{H} \mathbf{W_v} \mathbf{H}^T - \mathbf{D_e} \tag{16}$$

where $\mathbf{W_v}$ is a diagonal matrix containing the weights of each node and $\mathbf{D_e}$ is a diagonal matrix containing the degree of each hyperedge. We assume no weights on the nodes and take $\mathbf{W_v} = \mathbf{I}$. The matrix $\mathbf{A_{dual}} \in \mathbb{R}^{|G| \times |G|}$ represents another hypergraph, but the roles of nodes and hyperedges have now switched. For example, in case of words and sentences, the hyperedges were sentences, but in the hypergraph dual the words become hyperedges and the nodes within a word's hyperedge represent all the sentences in which the word has appeared. We again give $\mathbf{A_{dual}}$ (i.e., a graph proxy for the dual hypergraph) as input to Node2Vec, but this time we get output as the embeddings for the hyperedges associated with the nodes in dual. We refer to these hyperedge embeddings as **h2v-dual**.

In the second technique, we consider the following adjacency matrix $\mathbf{A_{inv}} \in \mathbb{R}^{|G| \times |G|}$:

$$\mathbf{A_{inv}} = \mathbf{H} \mathbf{H}^T \tag{17}$$

associated with what we refer to as the *inverted hypergraph*. This inverted hypergraph is a graph (unlike the dual which is a hypergraph) and there is an edge between two nodes if the hyperedges corresponding to the nodes in the original hypergraph have nodes in common. Weight of this edge is the number of common nodes. We again give $\mathbf{A_{inv}}$ as input to Node2Vec to get embeddings for the hyperedges associated with the nodes in inverted hypergraph. We refer to these hyperedge embeddings as **h2v-inv**.

A.3 Hyperedge2vec Using Spectral Embeddings

These set of methods extract embeddings as the eigenvectors associated with Laplacian matrices corresponding to the various adjacency matrices discussed in the previous section. We consider the following graph Laplacians:

$$\mathbf{L_{graph}} = \mathbf{I} - \mathbf{D_v}^{-1/2} \mathbf{A_{graph}} \mathbf{D_v}^{-1/2} \tag{18}$$

where $\mathbf{A_{graph}} = \mathbf{H}^T \mathbf{W_e} \mathbf{H}$ is the weighted graph associated with the graph corresponding to adjacency matrix $\mathbf{A}$,

$$\mathbf{L_{hyp}} = \mathbf{I} - \mathbf{D_v}^{-1/2} \mathbf{A_{hyp}} \mathbf{D_v}^{-1/2} \tag{19}$$

$$\mathbf{L_{inv}} = \mathbf{I} - \mathbf{D_e}^{-1/2} \mathbf{A_{inv}} \mathbf{D_e}^{-1/2} \tag{20}$$

$$\mathbf{L_{dual}} = \mathbf{I} - \mathbf{D_e}^{-1/2} \mathbf{A_{dual}} \mathbf{D_e}^{-1/2} \tag{21}$$

We get the d eigenvectors associated with the smallest d eigenvalues of the above graph Laplacians as the embeddings. We get vertex embeddings using Eq. 19 and hyperedge embedding using Eq. 21, and we refer to them together as **e2v-hyp**. Similarly, we get another pair of vertex embeddings (using Eq. 18) and hyperedge embedding (using Eq. 21). We refer to the later pair as **e2v**.