PSDVec: A toolbox for incremental and scalable word embedding

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ABSTRACT

PSDVec is a Python/Perl toolbox that learns word embeddings, i.e. the mapping of words in a natural language to continuous vectors which encode the semantic/syntactic regularities between the words. PSDVec implements a word embedding learning method based on a weighted low-rank positive semidefinite approximation. To scale up the learning process, we implement a blockwise online learning algorithm to learn the embeddings incrementally. This strategy greatly reduces the learning time of word embeddings on a large vocabulary, and can learn the embeddings of new words without re-learning the whole vocabulary. On 9 word similarity/analogy benchmark sets and 2 Natural Language Processing (NLP) tasks, PSDVec produces embeddings that has the best average performance among popular word embedding tools. PSDVec provides a new option for NLP practitioners.

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1. Introduction

Word embedding has gained popularity as an important unsupervised Natural Language Processing (NLP) technique in recent years. The task of word embedding is to derive a set of vectors in a Euclidean space corresponding to words which best fit certain statistics derived from a corpus. These vectors, commonly referred to as the embeddings, capture the semantic/syntactic regularities between the words. Word embeddings can supersede the traditional one-hot encoding of words as the input of an NLP learning system, and can often significantly improve the performance of the system.

There are two lines of word embedding methods. The first line is neural word embedding models, which use softmax regression to fit bigram probabilities and are optimized with Stochastic Gradient Descent (SGD). One of the best known tools is word2vec [1]. The second line is low-rank matrix factorization (MF)-based methods, which aim to reconstruct certain bigram statistics matrix extracted from a corpus, by the product of two low rank factor matrices. Representative methods/toolboxes include Hyperwords [2,5], GloVe [3], Singular [4], and Sparse [1]. All these methods use two different sets of embeddings for words and their context words, respectively. SVD based optimization procedures are used to yield two singular matrices. Only the left singular matrix is used as the embeddings of words. However, SVD operates on \( G^T G \), which incurs information loss in \( G \), and may not correctly capture the signed correlations between words. An empirical comparison of popular methods is presented in [5].

The toolbox presented in this paper is an implementation of our previous work [8]. It is a new MF-based method, but is based on eigendecomposition instead. This toolbox is based on [8], where we establish a Bayesian generative model of word embedding, derive a weighted low-rank positive semidefinite approximation problem to the Pointwise Mutual Information (PMI) matrix, and finally solve it using eigendecomposition. Eigendecomposition avoids the information loss in based methods, and the yielded embeddings are of higher quality than SVD-based methods. However eigendecomposition is known to be difficult to scale up. To make our method scalable to large vocabularies, we exploit the sparsity pattern of the weight matrix and implement a divide-and-conquer approximate solver to find the embeddings incrementally.

Our toolbox is named Positive-Semidefinite Vectors (PSDVec). It offers the following advantages over other word embedding tools:

1. The incremental solver in PSDVec has a time complexity \( O(\text{cd}^2 n) \) and space complexity \( O(\text{cd}) \), where \( n \) is the number of words in a vocabulary, \( d \) is the specified dimensionality of embeddings, and \( c \cdot n \) is the number of specified core words. Note that the space complexity does not increase with the
vocabulary. In contrast, other MF-based solvers, including the core embedding generation are of $O(n^3)$ time complexity and $O(n^2)$ space complexity.\(^6\) Hence asymptotically, PSDVec takes about $O(cd^2n^2)$ of the time and $O(cd^2n^3)$ of the space of other MF-based solvers.

2. Given the embeddings of an original vocabulary, PSDVec is able to learn the embeddings of new words incrementally. To our best knowledge, none of other word embedding tools provide this functionality; instead, new words have to be learned together with old words in batch mode. A common situation is that we have a huge general corpus such as English Wikipedia, and also have a small domain-specific corpus, such as the NIPS dataset. In the general corpus, specific terms may appear rarely. It would be desirable to train the embeddings of a general vocabulary on the general corpus, and then incrementally learn words that are unique in the domain-specific corpus. Then this feature of incremental learning could come into play.

3. On word similarity/analogy benchmark sets and common Natural Language Processing (NLP) tasks, PSDVec produces embeddings that has the best average performance among popular word embedding tools.

4. PSDVec is established as a Bayesian generative model [8]. The probabilistic modeling endows PSDVec clear probabilistic interpretation, and the modular structure of the generative model is easy to customize and extend in a principled manner. For example, global factors like topics can be naturally incorporated, resulting in a hybrid model [9] of word embedding and Latent Dirichlet Allocation [1]. For such extensions, PSDVec would serve as a good prototype. While in other methods, the regression objectives are usually heuristic, and other factors are difficult to be incorporated.

2. Problem and solution

PSDVec implements a low-rank MF-based word embedding method. This method aims to fit the PMI$(s, s)$ = log $P_{ik}(S)$ using $v_i^T v_s$, where $P(s)$ and $P(I) = \{P(s, s)\}$ are the empirical unigram and bigram probabilities, respectively, and $v_i$ is the embedding of $s$. The regression residuals $\text{PMI}(s, s) - v_i^T v_s$ are penalized by a monotonic transformation $f(\cdot)$ of $P(s, s)$, which implies that, for more frequent (therefore more important) bigram $s$, we expect it is better fitted. The optimization objective in the matrix form is

$$
\mathbf{V}^* = \arg \min_{\mathbf{V}} \|\mathbf{G} - \mathbf{V}\mathbf{V}^T\|_F^2 + \sum_{i=1}^{W} \mu_i \|v_i\|^2,
$$

(1)

where $\mathbf{G}$ is the PMI matrix, $\mathbf{V}$ is the embedding matrix, $\mathbf{H}$ is the bigram probabilities matrix, $\|\cdot\|_F$ is the Frobenius-norm, and $\mu_i$ are the Tikhonov regularization coefficients. The purpose of the Tikhonov regularization is to penalize overlong embeddings. The overlength of embeddings is a sign of overfitting the corpus. Our experiments showed that, with such regularization, the yielded embeddings perform better on all tasks.

Eq. (1) is to find a weighted low-rank positive semidefinite approximation to $\mathbf{G}$. Prior to computing $\mathbf{G}$, the bigram probabilities $\{P(s, s)\}$ are smoothed using Jelinek–Mercer Smoothing.

A Block Coordinate Descent (BCD) algorithm [13] is used to approach (1), which requires eigendecomposition of $\mathbf{G}$. The eigendecomposition requires $O(n^3)$ time and $O(n^2)$ space, which is difficult to scale up. As a remedy, we implement an approximate solution that learns embeddings incrementally. The incremental learning proceeds as follows:

1. Partition the vocabulary $S$ into $K$ consecutive groups $S_1, \ldots, S_k$. Take $K=3$ as an example. $S_1$ consists of the most frequent words, referred to as the core words, and the remaining words are noncore words.

2. Accordingly partition $G$ into $K \times K$ blocks as

$$
\begin{pmatrix}
G_{11} & G_{12} & G_{13} \\
G_{21} & G_{22} & G_{23} \\
G_{31} & G_{32} & G_{33}
\end{pmatrix},
$$

Partition $f(H)$ in the same way. $G_{1j}, f(H)_{1j}$ correspond to core-bigrams (consisting of two core words). Partition $V$ into

$$
\begin{pmatrix}
V_{1} & V_{2} & V_{3}
\end{pmatrix},
$$

3. For core words, set $\mu_i = 0$, and solve $\arg \min_{V} \|G_{11} - V_{1}V_{1}^T\|_F$, using eigendecomposition, obtaining core embeddings $V_1$.

4. Set $V_2 = V_{1}$, and find $V_3$ that minimizes the total penalty of the 12th and 21st blocks (the 22nd block is ignored due to its high sparsity):

$$
\arg \min_{V_3} \|G_{12} - V_2V_2^T\|_F + \|G_{21} - V_2^T V_{1}^T\|_F + \sum_{i=1}^{W} \mu_i \|v_i\|^2.
$$

The columns in $V_2$ are independent, thus for each $v_n$, it is a separate weighted ridge regression problem, which has a closed-form solution.

5. For any other set of noncore words $S_\ell$, find $V_\ell$ that minimizes the total penalty of the 1kth and k1th blocks, ignoring all other $kj$th and $jk$th blocks.

6. Combine all subsets of embeddings to form $V^\prime$. Here $V^\prime = \{V_1, V_2, V_3\}$.

3. Software architecture and functionalities

Our toolbox consists of 4 Python/Perl scripts: `extractwiki.py`, `gramcount.pl`, `factorize.py` and `evaluate.py`. Fig. 1 presents the overall architecture.

- `extractwiki.py` first receives a Wikipedia snapshot as input; it then removes non-textual elements, non-English words and

- \(^6\) Word2Vec adopts an efficient SGD sampling algorithm, whose time complexity is only $O(L)$, and space complexity $O(n)$, where $L$ is the number of word occurrences in the input corpus, and $k$ is the number of negative sampling words, typically in the range 5–20.
H = G, i.e., unregularized.

Numpy automatically parallelizes the computation to fully utilize a
performance of each method across 9 tasks.

C 4.2. Empirical results

footprint.

type of testsets are shipped with our toolkit, consisting of 7 word

of Tikhonov regularization on words, PSD-unreg denoted as
an unregularized PSDVec (by passing -t0 to factorize.py),
denoted as PSD-unreg.

3. gramcount.pl counts the frequencies of either unigrams or
bigrams in a word stream, and saves them into a file. In the
unigram mode (-m1), unigrams that appear less than certain
frequency threshold are discarded. In the bigram mode (-m2),
each pair of words in a text window (whose size is specified by
-n) forms a bigram. Bigrams starting with the same leading
word are grouped together in a row, corresponding to a row in
matrices H and G.

3. factorize.py is the core module that learns embeddings
from a bigram frequency file generated by gramcount.pl. A
user chooses to split the vocabulary into a set of core words and
a few sets of noncore words. factorize.py can: (1) in function
we_factorize_EM(), do BCD on the PMI submatrix of
core-core bigrams, yielding core embeddings; (2) given the core
embeddings obtained in (1), in block_factorize(), do a
weighted ridge regression w.r.t. noncore embeddings to fit
the PMI submatrices of core-noncore bigrams. The Tikhonov reg-
ularization coefficient μi for a whole noncore block can be
specified by -t. A good rule-of-thumb for setting μi is to in-
crease μi as the word frequencies decrease, i.e., give more
penalty to rarer words, since the corpus contains insufficient
information of them.

4. evaluate.py evaluates a given set of embeddings on 7 commonly
used testsets, including 5 similarity tasks and 2 analogy tasks.

4. Implementation and empirical results

4.1. Implementation details

The Python scripts use Numpy for the matrix computation. Numpy automatically parallelizes the computation to fully utilize a
multi-core machine.

The Perl script gramcount.pl implements an embedded
C++ engine to speed up the processing with a smaller memory
footprint.

4.2. Empirical results

Our competitors include: word2vec, PPMI and SVD in Hyper-
words, GloVe, Singular and Sparse. In addition, to show the effect
of Tikhonov regularization on “PSDvec”, evaluations were done on
an unregularized PSDVec (by passing “-t0” to factorize.py),
denoted as PSD-unreg. All methods were trained on an 12-core
Xeon 3.6 GHz PC with 48 GB of RAM.

We evaluated all methods on two types of testsets. The first
type of testsets are shipped with our toolkit, consisting of 7 word
similarity tasks and 2 word analogy tasks (Luong’s Rare Words is
excluded due to many rare words contained). Seven out of the
9 testsets are used in [5]. The hyperparameter settings of other
methods and evaluation criteria are detailed in [5,14,2]. The other
2 tasks are TOEFL Synonym Questions (TFL) [2] and Rubenstein &
Goodenough (ROG) dataset [12]. For these tasks, all 7 methods
were trained on the April 2015 English Wikipedia. All embeddings
except “Sparse” were 500 dimensional. “Sparse” needs more di-


46,409 ≈ 4), the ratio of vector lengths (500/50 = 10), the language efficiency, and the algorithm efficiency. We were most interested in the algorithm efficiency. To reduce the effect of different language efficiency of different methods, we took the ratio of the two training time to measure the scalability of each algorithm.

From Table 2, we can see that “PSDVec” exhibited a competitive absolute speed, considering the inefficiency of Python relative to C/C++. The scalability of “PSDVec” ranked the second best, worse than “Singular” and better than “word2vec”.

The reason that “PPMI” and “SVD” (based on “PPMI”) were so slow is that “hyperwords” employs an external sorting command, which is extremely slow on large files. The reason for the poor scalability of “Sparse” is unknown.

Table 3 shows the time and space efficiency of the incremental learning (“PSD-noncore” for noncore words) and MF-based learning (“PSD-core” for core words) on two corpora. The memory is halved using incremental learning, and is constant as the vocabulary size increases. As stated above, the per-word time complexity of “PSD-noncore” is O(c^2·d^4). The embedding dimensionality on Wikipedia is 10 times of that on RCV1, thus the speedup on the Wikipedia corpus is only around 1/8 of that on the RCV1 corpus.

5. Illustrative example: training on English Wikipedia

In this example, we train embeddings on the English Wikipedia snapshot in April 2015. The training procedure goes as follows:

1. Use extractwiki.py to cleanse a Wikipedia snapshot, and generate cleanwiki.txt, which is a stream of 2.1 billion words.
2. Use gramcount.pl with cleanwiki.txt as input, to generate top1grams-wiki.txt.
3. Use gramcount.pl with top1grams-wiki.txt and cleanwiki.txt as input, to generate top2grams-wiki.txt.
4. Use factorize.py with top2grams-wiki.txt as input, to obtain 25,000 core embeddings, saved into 25000-500-EM.vec.
5. Use factorize.py with top2grams-wiki.txt and 25000-500-EM.vec as input, and Tikhonov regularization coefficient set to 2, to obtain 55,000 noncore embeddings. The word vectors of totally 80,000 words are saved into 25000-80000-500-BLKEM.vec.
6. Repeat Step 5 twice with Tikhonov regularization coefficient set to 4 and 8, respectively, to obtain extra 50,000 × 2 noncore embeddings. The word vectors are saved into 25000-130000-500-BLKEM.vec and 25000-180000-500-BLKEM.vec, respectively.
7. Use evaluate.py to test 25000-180000-500-BLKEM.vec.

6. Conclusions

We have developed a Python/Perl toolkit PSDVec for learning word embeddings from a corpus. This open-source cross-platform software is easy to use, easy to extend, scales up to large vocabularies, and can learn new words incrementally without retraining the whole vocabulary. The produced embeddings performed stably on various test tasks, and achieved the best average score among 7 state-of-the-art methods.

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References

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