

Interpreting word embeddings using a distribution agnostic approach employing Hellinger distance

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Abstract. Word embeddings can encode semantic and syntactic features and have achieved many recent successes in solving NLP tasks. Despite their successes, it is not trivial to directly extract lexical information out of them. In this paper, we propose a transformation of the embedding space to a more interpretable one using the Hellinger distance. We additionally suggest a distribution-agnostic approach using Kernel Density Estimation. A method is introduced to measure the interpretability of the word embeddings. Our results suggest that Hellinger based calculation gives a 1.35% improvement on average over the Bhattacharyya distance in terms of interpretability and adapts better to unknown words.

Keywords: Word Embeddings · Interpretability · Computational Semantics.

1 Introduction

There have been many successes in the field of NLP due to the application of word embeddings [3]. There is a new forefront as well called contextual embeddings (e.g., BERT), which further increases the complexity of models to gain better performance. [2] showed there is only a small performance increase on average regard to complexity, but this performance varies on each employed task. Thus static embeddings still serve a good ground for initial investigations about the interpretability.

Prior research by [12] has investigated the issue of semantic encoding in word embeddings by assuming that the coefficients across each dimensions of the embedding space are distributed normally. This assumption may or may not hold for a particular embedding space (e.g. the normality assumption is unlikely to hold for sparse word representations), hence we argue for the necessity of similar algorithms that operate in a distribution-agnostic manner. We introduce such a model that allows the word embedding coefficients to follow arbitrary distributions by relying on Kernel Density Estimation (KDE). A further novelty of our work is that we propose the application of the Hellinger distance – as opposed to the Bhattacharyya distance – which could be a more suitable choice due to its bounded nature. We also make our source code publicly available¹ in order to foster the reproducibility of our experiments.

¹ https://github.com/ficstamas/word_embedding_interpretability

2 Related Work

Word embeddings can capture the semantic and syntactic relationships among words [9]. [15] was one of the first providing a comparison of several word embedding methods and showed that incorporating them into established NLP pipelines can also boost their performance.

There are several ways to incorporate external knowledge into NLP models. Related methods include the application of auto-encoders [16], embedding information during training [1] or after the training phase, called retrofitting [5]. One way to understand the semantic encoding of a dimension in embedding spaces is to link them to human interpretable features. [12] introduced the SEMCAT dataset and a method that relies on the Bhattacharyya distance for doing so. Their proposed method can produce a more interpretable space where each dimension encodes a predefined semantic category from the SEMCAT dataset, which was tested on GloVe [11] word embedding. There have been various approaches to find these semantic categories. Such an approach is to construct datasets in a way which involves human participants only [8], or in a semi-automated manner where the construction is based on statistics to make the connections between the members of semantic categories and curated later by human participants [13].

Our proposed approach relies on the application of the Hellinger distance, which has already been used in NLP for constructing word embeddings [7]. Note that the way we rely on the Hellinger distance is different from prior work in that we use it for improving the interpretability of some arbitrarily trained embedding, whereas in [7] the Hellinger distance served as the basis for constructing the embeddings.

3 Our Approach

In this paper we follow a process to produce interpretable word vectors which is similar to [12]. Unlike [12], who trained their own GloVe embeddings, in order to mitigate the variability due to training, we are using the pre-trained GloVe with 6 billion token as our embedding space with 300 dimensions. Furthermore the SEMCAT dataset is going to serve as the definition of the semantic categories. Instead of GloVe and SEMCAT other kinds of embeddings (e.g., fastText) and datasets incorporating semantic relations (e.g., the McRae dataset [8]) can be integrated into our framework.

3.1 Information Encoding of Dimensions

The assumption of normality of the embedding dimensions is statistically a convenient, however, empirically not necessarily a valid approach. As the normal distribution is simple and well-understood, it is also frequently used in predictive models, however, assuming normality could have its own flaws [14]. The assumption of normality plays an essential role in the method proposed by [12], that we relax in this paper.

If we try to express the information gain from a dimension regarding some concept, we can do so by measuring the distance between the concept's and dimension's distribution. In order to investigate the semantic distribution of semantic categories

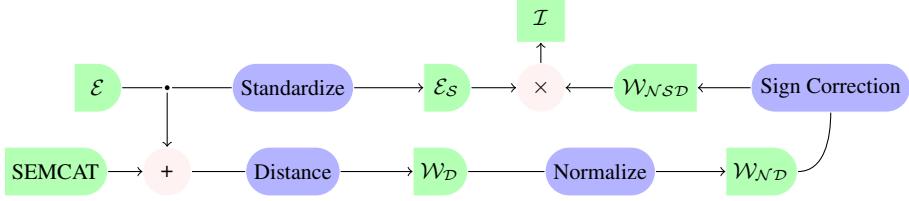


Fig. 1: The flowchart of the generation of the interpretable space \mathcal{I} . \mathcal{E} refers to the input word embeddings, whereas \mathcal{W}_D denotes the matrix describing the semantic distribution of the embedding. \mathcal{W}_D constructed from the distances of distributions of semantic category (from SEMCAT) - dimension pairs.

across all dimensions, we define $\mathcal{W}_D \in \mathbb{R}_{\geq 0}^{|d| \times |c|}$, with $|d|$ and $|c|$ denoting the number of dimensions of the embedding space and the number of semantic categories, respectively.

In this paper, we rely on two metrics, Bhattacharyya and Hellinger distances. The suggestion of Hellinger distance is an important step, as it is more sensitive to small distributional differences when the fidelity (overlap) of the two distributions is close to 1, which can be utilized in case of dense embeddings. Furthermore it is bounded on interval $[0, 1]$, which could be beneficial for sparse embeddings where the fidelity has a higher chance of being close to 0 (causing the Bhattacharyya distance to approach infinity).

First we separate the i th dimension's coefficients into category ($P_{i,j}$) and out-of-category ($Q_{i,j}$) vectors. A coefficient belongs to the $P_{i,j}$ vector if the associated word to that coefficient is an element of the j th semantic category, and it belongs to the $Q_{i,j}$ otherwise. It is going to be denoted for P and Q for short.

By assuming that P and Q are normally distributed, we can derive the closed form definitions for the Bhattacharyya and Hellinger distances as included in Eqn. (1) and (2), respectively. In the below formulas μ and σ denote the mean and standard deviation of the respective distributions.

$$D_B(P, Q) = \frac{1}{4} \ln \left(\frac{1}{4} \left(\frac{\sigma_p^2}{\sigma_q^2} + \frac{\sigma_q^2}{\sigma_p^2} + 2 \right) \right) + \frac{1}{4} \left(\frac{(\mu_p - \mu_q)^2}{\sigma_p^2 + \sigma_q^2} \right) \quad (1)$$

$$D_H(P, Q) = \sqrt{1 - \sqrt{\frac{2\sigma_p\sigma_q}{\sigma_p^2 + \sigma_q^2}} e^{-\frac{1}{4} \cdot \frac{(\mu_p - \mu_q)^2}{\sigma_p^2 + \sigma_q^2}}} \quad (2)$$

By discarding the assumption that P and Q are distributed normally, the more general formulas are included in Eqn. (3) and (4) for the Bhattacharyya and Hellinger distances

$$D_B(p, q) = -\ln \int_{-\infty}^{\infty} \sqrt{p(x)q(x)} dx \quad (3) \quad D_H(p, q) = \sqrt{1 - \int_{-\infty}^{\infty} \sqrt{p(x)q(x)} dx} \quad (4)$$

with the integrand being the Bhattacharyya coefficient, also called fidelity. In order to calculate the fidelity, we can apply Kernel Density Estimation (KDE) [6] for turning

the empirical distributions of coefficients P and Q into continuous (and not necessarily normally distributed) probability density functions p and q .

By calculating either the closed or the continuous form of distances, we can calculate $\mathcal{W}_D(i, j) = D(P_{i,j}, Q_{i,j})$, where D is any of the above defined distances.

3.2 Interpretable Word Vector Generation

We normalize \mathcal{W}_D so, that each semantic category vector in \mathcal{W}_{ND} sum up to 1 (ℓ_1 norm). This step is important because otherwise the dominance of certain semantic categories could cause an undesired bias. Additionally, $\mathcal{W}_{NSD}(i, j) = \text{sgn}(\Delta_{i,j})\mathcal{W}_{ND}(i, j)$, where $\Delta_{i,j} = \mu_{p_{i,j}} - \mu_{q_{i,j}}$ and sgn is the signum function. This form of sign correction is useful as a dimension can encode a semantic category in negative or positive direction and we have to keep the mapping of the words in each dimension.

We standardize the input word embeddings in a way that each dimension has zero mean and unit variance. We denote the standardized embeddings as \mathcal{E}_S and obtain the interpretable space of embeddings \mathcal{I} as the product of \mathcal{E}_S and \mathcal{W}_{NSD} .

3.3 Word Retrieval Test

In order to measure the semantic quality of \mathcal{I} , we used 60% of the words from each semantic category for training and 40% for validation. By using the training words, we are calculating the distance matrix \mathcal{W}_D using either one of the Bhattacharyya or the Hellinger distance. We select the largest k weights ($k \in \{15, 18, 30, 37, 62, 75, 125, 150, 250, 300\}$) for each category and replace the other weights with 0 (\mathcal{W}_D^S). We are doing that, so we can inspect the strongest encoding dimensions generalization ability. Then in the calculation pipeline (Figure 1) we are going to use \mathcal{W}_D^S instead of \mathcal{W}_D , and we continue the rest of the calculations as it was defined earlier, by that we are going to obtain the interpretable space \mathcal{I}_S . We are going to rely on the validation set and see whether the words of a semantic category are seen among the top n , $3n$ or $5n$ words in the corresponding dimension in \mathcal{I}_S , where n is the number of the test words varying across the semantic categories. The final accuracy is the weighted mean of the accuracy of the dimensions, where the weight is the number of words in each category for the corresponding dimension.

3.4 Measuring Interpretability

To measure the interpretability of the model, we are going to use a functionally-grounded evaluation method [4], which means it does not involve humans in the process of quantification. Furthermore we use continuous values to express the level of interpretability [10]. The metric we rely on is an adaptation of the one proposed in [12]. We desire to have a metric that is independent from the dimensionality of the embedding space, so models with different number of dimensions can be easily compared.

$$IS_{i,j}^+ = \frac{|S_j \cap V_i^+(\lambda \times n_j)|}{n_j} \quad (5) \quad IS_{i,j}^- = \frac{|S_j \cap V_i^-(\lambda \times n_j)|}{n_j} \quad (6)$$

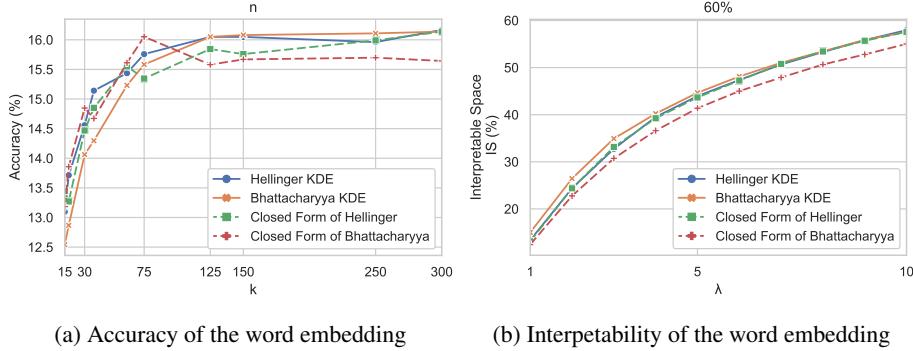


Fig. 2: Values from Table 1 with n test words in word retrieval test in Figure 2a and Table 2 with 60% of the categories used in Figure 2b.

In the same way we defined the interpretability score for the positive (5) and negative (6) directions. In both equations i represents the dimension ($i \in \{1, 2, 3, \dots, |d|\}$) and j the semantic categories ($j \in \{1, 2, 3, \dots, |c|\}$). S_j represents the set of words belonging to the j th semantic category, n_j the number of words in that semantic category. V_i^+ and V_i^- gives us the top and bottom words selected by the magnitude of their coordinate respectively in the i th dimension. $\lambda \times n_j$ is the number words selected from the top and bottom words, hence $\lambda \in \mathbb{N}$ is the relaxation coefficient, as it controls how strict we measure the interpretability. As the interpretability of a dimension-category pair, we take the maximum of the positive and negative direction, i.e. $IS_{i,j} = \max \{IS_{i,j}^+, IS_{i,j}^-\}$.

Once we have the overall interpretability ($IS_{i,j}$), we are going to calculate the categorical interpretability Eqn. (7). We thought that it is a too optimistic method to decide the interpretability level based on the maximum value in each selection. It is apparent from $IS_i = \max_j IS_{i,j}$, taking the max for every dimension would overestimate the true interpretability, because it would take the best-case scenario. Instead, we calculate Eqn. (7), where we have a condition on the selected i which is defined by Eqn. (8). We are going to select from the given interpretability scores provided by $IS_{i,j}$ (where j is fixed) the i th value where i is the maximum in the j th concept in $\mathcal{W}_D(i, j)$. This condition Eqn. (8) ensures that we are going to obtain the interpretability score from the dimensions where the semantic category is encoded. This method is more suitable to obtain the interpretability scores, because it is relying on the distribution of the semantic categories, instead of the interpretability score from each dimension.

$$IS_j = IS_{j^*,j}^* \times 100 \quad (7) \quad i_j^* = \arg \max_{i'} \mathcal{W}_D(i', j). \quad (8)$$

Finally, to get the overall interpretability of the embedding space, we have to calculate the average of the interpretability scores across the semantic categories, where C is the number of categories.

4 Results

We load the most frequent 50,000 words from the pre-trained embeddings similar to [12] and tested for their normality using the Bonferroni corrected Kolmogorov-Smirnov test for multiple comparisons. Our test showed that 183 of the dimensions are normally distributed ($p > 0.05$). [12] reported more dimensions to behave normally, which could be explained by the fact that the authors trained their own GloVe embeddings. We deem this as an indication for the need towards the kind of distribution agnostic approaches we propose by relying on KDE. During the application of KDE, we utilized a Gaussian kernel and a bandwidth of 0.2 throughout all experiments.

4.1 Accuracy and Interpretability

Table 1 and Table 2 contains the quantitative performance of the embeddings from two complementary angles, i.e. their accuracy and interpretability. These results are better to be observed jointly (Fig. 2) since it is possible to have a high score for interpretability but a low value for accuracy suggests that the original embedding has a high variance regarding to the probed semantic categories. Fig. 2a illustrates a small sample of the results where we can observe that a word’s semantic information is encoded in few dimensions, since relying on a reduced number of coefficients from \mathcal{W}_D achieves similar performance to the application of all the coefficients. Our results tend to have close values, which can be caused by the high number of normally distributed dimensions. The results show that the proposed method is at least as good as [12]’s method, but it can be applied to any embedding space without restrictions.

5 Conclusions

The proposed method can transform any non-contextual embedding into an interpretable one, which can be used to analyze the semantic distribution which can have a potential application in knowledge base completion.

We suggested the usage of Hellinger distance, which shows better results in terms of interpretability when we have more words per semantic categories. Furthermore, easier to analyze the Hellinger distance due to its bounded nature. By relying on KDE, our proposed method can be applied even in cases when the normality for the coefficients of the dimensions is not necessarily met. This allows our approach a broader range of input embeddings to be applicable over (e.g., sparse embeddings).

The proposed modification on interpretability calculation, opened another dimension of freedom. It let us compare the interpretability of word embeddings with different dimensionality. So for every embedding space, the compression of semantic categories can be observed and the modification gives us a better look at the encoding of semantic categories, because we probe the category words from dimensions where they are deemed to be most likely encoded.

k	15	18	30	37	62	75	125	150	250	300
n										
Closed form of Bhattacharyya	13.18	<u>13.85</u>	<u>14.84</u>	14.67	<u>15.61</u>	<u>16.05</u>	15.58	15.66	15.69	15.64
Closed form of Hellinger	<u>13.44</u>	13.27	14.46	14.85	15.55	15.34	15.84	15.75	15.99	16.13
Bhattacharyya KDE	12.54	12.86	14.06	14.29	15.23	15.58	<u>16.05</u>	<u>16.08</u>	<u>16.10</u>	16.13
Hellinger KDE	13.09	13.71	14.55	<u>15.14</u>	15.43	15.75	16.04	16.04	15.96	<u>16.16</u>
$3n$										
Closed form of Bhattacharyya	<u>25.76</u>	27.25	29.53	30.61	<u>32.92</u>	<u>33.71</u>	34.15	34.30	33.39	33.18
Closed form of Hellinger	25.35	26.87	29.74	<u>30.73</u>	32.36	<u>33.77</u>	34.03	<u>34.56</u>	<u>34.82</u>	34.73
Bhattacharyya KDE	24.76	26.20	29.06	<u>29.82</u>	31.72	32.16	33.59	33.48	33.63	33.57
Hellinger KDE	25.32	<u>27.39</u>	<u>29.88</u>	30.38	32.54	33.27	<u>34.27</u>	34.38	34.50	34.41
$5n$										
Closed form of Bhattacharyya	<u>34.53</u>	<u>36.43</u>	<u>39.65</u>	<u>40.56</u>	<u>43.24</u>	<u>43.51</u>	44.21	<u>45.03</u>	44.68	44.30
Closed form of Hellinger	33.92	36.05	39.15	40.41	42.87	43.30	44.59	44.15	45.00	44.94
Bhattacharyya KDE	33.07	34.41	37.90	39.15	42.55	43.01	44.30	44.68	<u>45.18</u>	<u>45.27</u>
Hellinger KDE	34.10	35.79	39.33	40.21	42.87	43.39	<u>44.73</u>	44.65	45.00	45.12

Table 1: Performance of the model on word category retrieval test for the top n , $3n$ and $5n$ where n is the number of test words varying across the categories. k ($\in \{15, 18, 30, 37, 62, 75, 125, 150, 250, 300\}$) is the number of top weight kept from \mathcal{W}_D in each category. The method was discussed in Section 3.3

λ	1	2	3	4	5	6	7	8	9	10
100% of the words										
GloVe	2.82	4.84	6.83	8.72	10.37	12.08	13.34	14.55	15.79	16.87
Closed form of Bhattacharyya	35.34	48.84	56.47	61.35	65.01	68.21	70.81	72.42	73.88	75.45
Closed form of Hellinger	<u>36.32</u>	<u>49.94</u>	<u>57.64</u>	<u>62.75</u>	<u>66.72</u>	<u>69.52</u>	<u>72.08</u>	<u>74.09</u>	<u>75.54</u>	76.72
Bhattacharyya KDE	35.47	49.05	56.69	61.60	65.35	68.37	70.57	72.53	74.02	75.31
Hellinger KDE	36.24	49.49	57.35	62.73	66.63	<u>69.56</u>	71.92	74.04	75.42	<u>76.78</u>
80% of the words										
GloVe	1.85	3.42	4.91	6.33	7.69	9.00	10.21	11.34	12.20	13.07
Closed form of Bhattacharyya	23.96	36.99	45.70	51.66	55.37	59.13	61.96	64.50	66.40	67.91
Closed form of Hellinger	24.36	38.36	<u>47.18</u>	<u>53.32</u>	<u>57.49</u>	<u>61.09</u>	63.35	<u>65.89</u>	<u>67.91</u>	<u>69.48</u>
Bhattacharyya KDE	<u>25.08</u>	<u>39.04</u>	46.80	52.70	57.10	60.73	63.18	65.26	67.16	68.62
Hellinger KDE	24.57	38.34	47.16	53.09	57.22	60.54	63.38	65.70	67.82	69.38
60% of the words										
GloVe	1.05	1.87	2.62	3.71	4.71	5.67	6.59	7.47	8.20	9.08
Closed form of Bhattacharyya	12.44	22.76	30.72	36.61	41.38	45.00	47.89	50.64	52.78	55.02
Closed form of Hellinger	13.12	24.36	33.14	39.24	43.66	47.25	50.76	53.42	55.69	57.57
Bhattacharyya KDE	<u>15.01</u>	<u>26.44</u>	<u>34.92</u>	<u>40.22</u>	<u>44.66</u>	<u>48.10</u>	<u>51.01</u>	<u>53.45</u>	<u>55.87</u>	57.56
Hellinger KDE	13.37	24.36	32.74	39.51	43.94	47.36	50.65	53.30	55.82	<u>57.95</u>

Table 2: Interpretability scores for the interpretable space \mathcal{I} with different λ parameter values ($\lambda = 1$ the most strict and $\lambda = 10$ the most relaxed) using different distances. The $r \in \{100, 80, 60\}$ percentage of the words kept from the semantic categories relative to category centers

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