



DEXTER: Deep Encoding of External Knowledge for Named Entity Recognition in Virtual Assistants

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Abstract

Named entity recognition (NER) is usually developed and tested on text from well-written sources. However, in intelligent voice assistants, where NER is an important component, input to NER may be noisy because of user or speech recognition error. In applications, entity labels may change frequently, and non-textual properties like topicality or popularity may be needed to choose among alternatives.

We describe a NER system intended to address these problems. We test and train this system on a proprietary user-derived dataset. We compare with a baseline text-only NER system; the baseline enhanced with external gazetteers; and the baseline enhanced with the search and indirect labelling techniques we describe below. The final configuration gives around 6% reduction in NER error rate. We also show that this technique improves related tasks, such as semantic parsing, with an improvement of up to 5% in error rate.

1. Introduction

NER is the process of labelling sequences of tokens in a sentence with a label representing some kind of semantic classification. Early NER approaches frequently relied on the use of patterns, rules and hand-crafted features for the identification of named entities [1, 2, 3], often supplemented with information from gazetteers. More recent approaches aim to learn to identify named entities and their types in a data-derived way [4, 5, 6, 7]. Typical NER systems are trained and tested on benchmark corpora such as CoNLL-2003 [8] or OntoNotes [9, 10], which are collections of documents derived from well-written sources. Such data are not representative of the language encountered in many practical applications that require NER as a component, such as natural language understanding in intelligent voice assistants, which is our focus here.

Firstly, for spoken language queries in a voice assistant, disambiguating between different entity classes purely based on semantic word representations and the context of the utterance is difficult. For example, in an utterance “Play Bohemian Rhapsody”, the entity “Bohemian Rhapsody” is both a popular song as well as a popular movie, and both entity classes are often referred to in the same context. Non-linguistic contextual information, such as temporal popularity, relevance of the entity to the current application, and other factors, are crucial for the NER model to effectively predict the correct entity class.

Secondly, data-driven methods, which rely heavily on patterns available in the training data without additional features, might not be able to handle less popular entities and templates with insufficient representation in the training data. For example, for an utterance like “Play One by U2”, a purely data-driven model with only word embeddings might be biased to predict the token “one” as non-entity text, whereas the user might actually be referring to the song called “One” by “U2”. (We have given the appropriate casing to this example, but an ASR system may not provide casing information at all).

Thirdly, models trained on data collected from the past are usually unable to recognize newly released films, songs, or albums. Time is always needed to collect and label enough training data to update models.

Finally, input to voice assistants is often noisy in various ways: speakers make errors and sometimes do not produce grammatically correct or complete sentences, and ASR systems often mis-recognize what has been said.

In this paper, we propose a novel method of encoding external knowledge about entities as part of NER model training. We show that by treating entities as objects with attributes (such as popularity, associated textual strings, entity class label) and encoding these entities through a neural network, the model learns correlations between the input tokens, the attributes of entities that these tokens belong to, and their true class labels. We design a search engine trained on spoken queries to provide these entity candidates, which makes the system more resilient to the speech errors and user variation that commonly occur in spoken dialog systems. We show that using this approach, we are able to perform significantly better than an NER model trained only using word and character embeddings, or models trained with additional implementations of gazetteer features. As well as improvements on NER, we also show that our technique can easily be extended to other language understanding tasks, such as semantic parsing, where we also see significant improvements over the baseline.

2. Related Work

External knowledge sources to improve NER task performance has been explored in previous literature. One approach has been the use of Wikipedia articles to synthetically generate training data. [11] classified Wikipedia articles into named entity types and then generated silver-standard training annotations for NER by transforming links between Wikipedia articles into named entity annotations by projecting the target article’s classifica-

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tions onto the anchor text. [12] used Wikipedia to automatically generate additional annotated data for training NER systems by extending annotations for non anchored strings using coreference information.

However, the most common approach has been through the use of gazetteer features. [7] proposed a new lexicon encoding scheme and matching algorithm by constructing uni-grams and bi-grams to make use of partial matches and combined the encoding scheme with a hybrid LSTM-CNN based neural NER model. [13] included gazetteer features in a NER model trained using hybrid semi-Markov conditional random fields (HSCRFs) by introducing an additional module that scores a candidate entity span by the degree to which the entity span softly matches the gazetteer. [14] enhanced gazetteer matching with multi-token and single-token matches in the same representation and combined the matching with a self-attention model to generate gazetteer embeddings.

In our approach, we do not use gazetteers directly, but harvest similar information from a knowledge graph. However, these token sequences are not the only properties associated with entities. Furthermore, unlike [14, 13], we do not assume that exact matching is either necessary or sufficient to be able to use this information. As described above, in a spoken dialog setting we cannot assume that input will be complete or correct. It is of course possible to devise complex encoding schemes for gazetteers to support partial matches, as in [7]. However, we instead use the knowledge graph to construct a search engine tuned to spoken queries to retrieve a ranked list of entity candidates. This approach enables our system to be robust to partial matches, speech errors, and other variations in named entities observed in usage.

3. Methodology and Design

In this section, we will explain the architecture of our NER system.

Incorporating External Resources: We conceptualize entities as objects that have various document properties associated with them: an entity class label, in particular. Entities that can have different class labels are different entities. To construct the properties associated with entities, we first crawl a knowledge graph, which is updated daily. This crawl gives us our universe of entities. From the text descriptions associated with nodes, and the relations they take part in (as indicated by incoming and outgoing edges in the graph), we construct n-grams of normalized (lower cased, stemmed, and with punctuation removed) tokens that may be used to refer to the entity. We augment these n-grams with aliases and acronyms mined from various sources. For example, the entity representing “San Francisco International Airport” will also be associated with “SFO”, “San Fran Airport”, etc. We then create an inverted index from these n-grams to the entities, and compute and store the tf-idf scores for all n-grams: tf is computed over the concatenation of all n-grams for an entity and idf is computed over the set of n-grams for all entities. We also compute and store a popularity score for each entity. This score is the prior probability based on frequency of occurrence in anonymized usage logs and engagement with first party apps.

We now have a list of around 10m entities with their associated properties and can efficiently search for candidate entities given an n-gram of tokens. We make this search more robust to ASR and user errors by training a “correction model” learned from common usage patterns. For example, “Cincinnati Bangles” would be corrected to “Cincinnati Bengals”, and “Conor

Gregor” would be corrected to “Conor McGregor”.

Note that the set of entity class labels derived from the knowledge graph is not identical to the final set of NE labels assigned by the network described in Section 3. There are 32 entity classes in the knowledge graph, and the network learns to map these to 23 NER labels. For example, the fine-grained entities “city”, “state”, “country” are all mapped to “location”. Some NER labels, like “dateTime”, in fact do not correspond to anything in the knowledge graph, and the network learns to assign this on the basis of properties of tokens in context. In effect, the knowledge graph entity classes serve as features for the network’s assignment of NER labels.

Dense Aggregation Layer: For a given input utterance, we tokenize it and construct all the n-grams that each token is part of, up to a specific window length. For example, a token is a member of one uni-gram, potentially two bi-grams, three tri-grams etc.

For each n-gram that the token is part of, we issue a query into the search engine, to get candidate lists of entities. We then use a simple linear scorer which uses features such as tf-idf score and popularity to generate a ranked list of these entities. From this ranked list, we select the top- k entities for each of the entity classes in our ontology to get a varied distribution of entities across all entity classes for every n-gram.

For every token in the utterance, we now have a list of entity candidates retrieved from the search engine for all the n-grams that the token is part of, up to a window size w . To get the cumulative importance of an entity for a token across its n-gram context, we concatenate the tf-idf scores of the entity across all the n-grams indexing it,¹ along with the popularity score of the entity. We then feed this vector through a single layer perceptron to obtain a score for the entity with respect to this token and its n-gram context. We do this for all the entities retrieved for that token.

More formally, for a token t and a retrieved entity candidate e_i (where i corresponds to the index of the entity in the complete listing of entities E), and a window size w , the tf-idf scores of e_i are considered with respect to all uni-, bi-, tri-, ..., w -grams that contain t . Let these scores be represented by $r_{1,1}$ for the unigram score; $r_{2,1}$ and $r_{2,2}$ for the two bigram scores; $r_{w,1} \dots r_{w,w}$ for the w w -gram scores. Let p be the popularity score of the entity and c represent the class of the entity as an integer. Then the vector created by the concatenation of tf-idf scores with the popularity score is:

$$\mathbf{r} = [r_{1,1}; r_{2,1}; r_{2,2}; \dots r_{w,1}; \dots; r_{w,w}; p]. \quad (1)$$

Let $o(\cdot)$ represent a function that converts an integer into a one-hot vector with as many dimensions as there are entity classes. We first multiply \mathbf{r} by this one-hot vector: $o(c)^T \cdot \mathbf{r}$. This gives us a matrix where one row contains the values from \mathbf{r} , with zeros elsewhere. We reshape the matrix to a vector v and pass v through a linear layer with activation function $a(\cdot)$, weight vector \mathbf{w} , and bias \mathbf{b} , yielding a single scalar as output. The parameters of the linear layer are shared across all the entities.

$$s_{e_i} = a(\mathbf{w} \cdot v + \mathbf{b}). \quad (2)$$

Once we have computed the scores for each entity retrieved for each token t , we create a vector for each token of length $|C|$, where C is the set of entity classes supported in our ontology. Then we put in the corresponding position of the vector

¹if an entity is not retrieved as part of an n-gram, we simply give it a tf-idf score of 0

the highest score that any entity of that class got for that token in that n -gram context, denoted by \mathbf{u}_t .

Capturing Contextual Entity Signals: To encourage the model to use contextual information, we also incorporate a layer of 1D CNNs on top of the dense aggregation layer. This layer provides several benefits. Firstly, the layer allows each token to have a contextual representation that includes features from neighbouring tokens. Secondly, this CNN layer can learn from complex dependencies present between tokens other than the current token, and across the different entity classes; for example, the presence of a music album helps disambiguate between the name of a music artist or a movie actor. Thirdly, the CNN adds two useful inductive biases: location invariance and edge detection [15, 16]. The location invariance ensures that features corresponding to similar utterances (such as song titles) are treated similarly irrespective of where they are present in the utterance. The ability of the correlation operation to detect edges enables the featurization to be biased to favor entities consistently retrieved across tokens for a certain entity class since a match over longer spans within an utterance is likely to be better than if each token were to match to a different entity.

The input to the convolution layer $f_{conv}(\cdot)$ is the output of the dense aggregation layer, with shape of $T \times |C|$. In this approach, we convolve with a window size of w (we set $w = 7$) centered at each token in the T dimension. Let the second dimension, of size $|C|$, represent the input channels. We set the number of convolutional filters (i.e., output channels) to be 32. The output representations

$$\mathbf{q}_t = f_{conv}(\mathbf{u}_{t-\frac{w-1}{2}} \cdots \mathbf{u}_{t+\frac{w-1}{2}}), \quad (3)$$

will be used in the following tasks as the DEXTER embedding.

NER Training: For training our baseline NER model, we use an architecture similar to [6] and [7] where for every token, character-level features are extracted by a bi-LSTM and concatenated with pre-trained GLoVe embeddings [17]. This character-word representation is passed through a sequence level bi-LSTM and fed into a CRF model to produce the final labels.

For our extended system, we concatenate our DEXTER embeddings produced as described in the previous section to these word and character embeddings before feeding the combined embeddings to the upper layers. The weights that contribute towards the DEXTER embeddings are learned end-to-end during training, without pre-training, additional loss signals, or supplementary training data.

Shallow Semantic Parsing: We also measure DEXTER’s impact on shallow semantic parsing, which involves jointly identifying the user’s intent and assigning a semantic label to each word in an utterance. For example, in “Play the movie Moana”, the model identifies the user intent as “play”, tags “movie” as the type of entity to be played, and tags “Moana” as the name of the movie. Unlike NER, the semantic parsing task is domain-specific, with each domain having a different set of intents and semantic labels. Furthermore, we are not looking for units above the word level: the semantic labels are assigned to every word in the utterance and are not only for named entities.

For this task, we compare against a model that uses a bi-LSTM with word embeddings and gazetteer features as input (similar to [18]), with our baseline showing performance without gazetteer features. We compare these settings with a version replacing the gazetteer with DEXTER, and show performance across 11 domains in Section 5.2. As in the case of our NER

setup, we train the DEXTER embeddings and the model end-to-end.

4. Datasets and Training Methodology

There is no public benchmark dataset that we are aware of that has the properties we need, and so we developed our own in-house one. We randomly sampled around 500k utterances belonging to entity rich domains like music and sports from usage logs, then anonymized and annotated them for NE labels. For the annotation, we followed a standard B-I-O tagging approach for NE labels designed specifically for our ontology, which consists of 23 fine-grained entity classes such as “song”, “artist”, “celebrity”, “athlete” etc. We use 70% of the graded data as our training set, 20% as development set and 10% data as a held-out test set. To evaluate the NER model performance, we report results on the “music”, “sports” and “movies & TV” domains, and use the standard NER-F1 metric used for the CoNLL-2003 shared task [8]. In our data, the average utterance length is 5.03 tokens. 32.30% of utterances contain no entities, 55.44% have 1 entity and 11.57% have 2 entities. 81.66% of all entities can be linked to the knowledge graph, of which 84% exactly match their canonical name, while the rest contain a user error (9%) or an ASR error (7%).

We train the NER model using a standard mini-batch gradient descent with a batch size of 128 and using the Adam optimizer [19] with an initial learning rate of 0.001. We evaluate the validation accuracy every 1000 training iterations, and decay the learning rate by a factor of 0.9 when the validation F1 score fails to improve by more than $1e-5$. We train the NER model until the learning rate falls below $1e-7$, for at most 50 epochs in total. We apply a dropout [20] of 0.6 to the input of the bi-directional LSTM layer to prevent over-fitting. The word embeddings and character embeddings both have 200 dimensions. The bidirectional-LSTM encoding the characters has a hidden state size of 100 dimensions. The bidirectional-LSTM whose output feeds into the CRF has 450 hidden state dimensions.

In the DEXTER embeddings module, we set the n -gram context window for tokens to 3 (uni-grams, bi-grams and tri-grams) and retrieve top-10 candidates per entity class for every n -gram search query issued to the search engine. In the CNN layer used to capture contextual similarity, we use 32 convolutional kernels of width 7. We apply padding of size 3 on either side, to keep the output dimension the same as that of the input. A tanh non-linearity is applied after the CNN layer.

5. Results

5.1. NER

Table 1: * indicates that the results improve statistically significantly ($p < 0.05$) over the (a) baseline, with the p -values shown in parentheses, calculated as the one-tailed p -value comparing the binomial distributions formed by assuming the utterance-level correctness of a setting as binomial variable. Note that all numbers reported are over 10 runs.

	movies & TV	music	sports
a	79.26	83.51	91.61
b	79.43	83.69	91.66
c	79.43	84.14	91.66
d	80.08	84.70	91.70
e	80.48* (5.5e-7)	85.10* (1.1e-8)	91.74 (0.098)

We compare the NER-F1 scores across five settings, taking existing or new implementations of comparable approaches: (a) a baseline for which we use the implementation from [6] which uses only word and character embeddings, (b) a system implemented similarly to [13] which uses a gazetteer-enhanced sub-tagger (using token embeddings in our case) and performs soft dictionary matching to generate gazetteer embeddings which are concatenated to the input word and character embeddings in (a), (c) a system with token matched gazetteer features implemented according to [1] concatenated to the input word and character embeddings in (a), (d) a system implemented according to [14] which uses self-attention and match span encoding to build enhanced gazetteer embeddings which are concatenated to the input word and character embeddings in (a) and finally, (e) our proposed approach using DEXTER embeddings concatenated to the input word and character embeddings in (a). All of the models are trained on 500k training data equally distributed amongst the three domains: music, movies & TV and sports. The gazetteers used in (b), (c) and (d) are constructed from a flattened version of the same knowledge graph used in (e) to keep the entity information consistent across all settings. The F1 scores are reported on the held-out test sets for the best model selected by our development sets.

From Table 1, we see that external knowledge is essential to get good accuracies in a fine-grained entity class setting. The models which use soft gazetteer features [13] and token-match gazetteer features [1] do relatively better than the baseline implementation of [6], which uses only word and character embeddings. The model which uses self-attention and multi-token match span encoding [14] to generate gazetteer embeddings does better still. Finally, our proposed approach which uses DEXTER embeddings further improves over all of the above described approaches and shows a statistically significant ($p < 0.05$) F1 score improvement of around 1% on average (5.7% reduction in error rate) across all three test sets over [6].

In Table 2, we perform an ablation study on different model settings and show the individual impact of our architecture’s components. The complete system is (a) and replacing (b) the single layer perceptron (SLP) (denoted by $\{w, b\}$ in Equation 3) from the best model setting with a max pooling aggregation leads to a drop in NER-F1 accuracy by around 0.83% points (averaged across the 3 domains). The single layer perceptron allows the model to learn the scaling across the tf-idf scores from different n-gram searches which a simple max pool aggregation does not provide. We also show (c) replacing the class-specific SLP with a class-agnostic SLP leads to an accuracy drop of around 0.1%. This accuracy drop could be explained by the fact that the distribution of attributes such as popularity within an entity class widely varies across entity classes, and the additional parameters in the class-specific model allow the system to capture this difference and scale across different distributions. Further, (d) tying the CNN weights so that the con-

volution operation performed uses the same set of convolution filters irrespective of the entity type causes the NER F-1 to drop by 0.16%. Finally, (e) when we remove the CNN layer from the network, the NER-F1 drops by 0.1 points (on average across all three test sets) which shows that the CNN allows the model to capture context across multiple tokens, thereby helping improve the NER accuracy.

5.2. Shallow Semantic Parser

In addition to showing the effectiveness of the DEXTER encoding on named entity recognition (Section 5.1), we also explore DEXTER in shallow semantic parsing, as described in Section 3. Space prevents detailed discussion, but we show that a token-match gazetteer feature approach improves over a model which uses only word and character embeddings, and that shallow semantic parser models trained with DEXTER significantly improve over models trained with token-match gazetteer features in 5 out of 11 domains in our test sets. This indicates the superiority of our encoding scheme. We see an improvement of around 5.4% reduction in error rate (averaged across all the 11 domains) over the model which uses only word and character embeddings and an improvement of around 3.1% over the model which also uses token-match gazetteers. In the domains that do not show statistically significant improvements even with DEXTER (such as “Photos”, “Notebook” and “Clock”), we hypothesize that this is due to the low coverage of NE spans for these domains in our knowledge graph, or because these domains have few named entities present.

6. Conclusion

We conclude illustrative examples. DEXTER improves NER in cases where the transcribed utterance is noisy, e.g. in “Find I know you did last summer”, where the user’s intent is to find the movie “I know **what** you did last summer”, the utterance does not provide the exact name of the entity and there is not enough information in the local context for the NER model to predict accurately. However, with DEXTER, we are able to recover by retrieving entities even if they only partially match, and by using attributes of the retrieved entity (popularity of the movie and tf-idf) allowing the NER model to detect the NE label correctly as a “movie”.

Secondly, DEXTER is able to improve NER in scenarios where the NE label is heavily influenced by current interests and fashions. For example, in “Play Godzilla”, the NE “Godzilla” is a famous movie as well as a very popular song by the world-renowned artist Eminem, and there is not enough context for the model to disambiguate effectively. However, in DEXTER, we retrieve entities belonging to multiple entity classes (such as “movie”, “song”, “artist”) and the trained single layer perceptron weights entities across different entity classes based on their attributes, such as freshness and popularity. Since at the relevant time (when it was released) the “movie” label would have been more popular than the “song”, the NER model was able to use this discriminatory feature and predict the NE label accurately. However, if the transcribed utterance was “Play the song Godzilla” or “Play Godzilla by Eminem”, our model respects the semantic context of the utterance (i.e., the user’s request is for the song to be played, as opposed to the movie) and predicts the “song” NE label even though the “movie” might have been more popular.

Table 2: Ablations

	movie & TV	music	sports
a	80.48	85.10	91.74
b	79.36	83.89	91.59
c	80.38	84.92	91.74
d	80.32	84.87	91.65
e	80.31	85.07	91.67

7. References

- [1] L. Ratnoff and D. Roth, “Design challenges and misconceptions in named entity recognition,” in *Proceedings of the Thirteenth Conference on Computational Natural Language Learning (CoNLL-2009)*. Boulder, Colorado: Association for Computational Linguistics, Jun. 2009, pp. 147–155. [Online]. Available: <https://www.aclweb.org/anthology/W09-1119>
- [2] J. R. Finkel and C. D. Manning, “Joint parsing and named entity recognition,” in *Proceedings of Human Language Technologies: The 2009 Annual Conference of the North American Chapter of the Association for Computational Linguistics*. Boulder, Colorado: Association for Computational Linguistics, Jun. 2009, pp. 326–334. [Online]. Available: <https://www.aclweb.org/anthology/N09-1037>
- [3] A. Ritter, S. Clark, Mausam, and O. Etzioni, “Named entity recognition in tweets: An experimental study,” in *Proceedings of the 2011 Conference on Empirical Methods in Natural Language Processing*. Edinburgh, Scotland, UK.: Association for Computational Linguistics, Jul. 2011, pp. 1524–1534. [Online]. Available: <https://www.aclweb.org/anthology/D11-1141>
- [4] A. Passos, V. Kumar, and A. McCallum, “Lexicon infused phrase embeddings for named entity resolution,” in *Proceedings of the Eighteenth Conference on Computational Natural Language Learning*. Ann Arbor, Michigan: Association for Computational Linguistics, Jun. 2014, pp. 78–86. [Online]. Available: <https://www.aclweb.org/anthology/W14-1609>
- [5] X. Ma and E. Hovy, “End-to-end sequence labeling via bi-directional LSTM-CNNs-CRF,” in *Proceedings of the 54th Annual Meeting of the Association for Computational Linguistics (Volume 1: Long Papers)*. Berlin, Germany: Association for Computational Linguistics, Aug. 2016, pp. 1064–1074. [Online]. Available: <https://www.aclweb.org/anthology/P16-1101>
- [6] G. Lample, M. Ballesteros, S. Subramanian, K. Kawakami, and C. Dyer, “Neural architectures for named entity recognition,” in *Proceedings of the 2016 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies*. San Diego, California: Association for Computational Linguistics, Jun. 2016, pp. 260–270. [Online]. Available: <https://www.aclweb.org/anthology/N16-1030>
- [7] J. P. Chiu and E. Nichols, “Named entity recognition with bidirectional LSTM-CNNs,” *Transactions of the Association for Computational Linguistics*, vol. 4, pp. 357–370, 2016. [Online]. Available: <https://www.aclweb.org/anthology/Q16-1026>
- [8] E. F. Tjong Kim Sang and F. De Meulder, “Introduction to the CoNLL-2003 shared task: Language-independent named entity recognition,” in *Proceedings of the Seventh Conference on Natural Language Learning at HLT-NAACL 2003*, 2003, pp. 142–147. [Online]. Available: <https://www.aclweb.org/anthology/W03-0419>
- [9] E. Hovy, M. Marcus, M. Palmer, L. Ramshaw, and R. Weischedel, “OntoNotes: The 90% solution,” in *Proceedings of the Human Language Technology Conference of the NAACL, Companion Volume: Short Papers*. New York City, USA: Association for Computational Linguistics, Jun. 2006, pp. 57–60. [Online]. Available: <https://www.aclweb.org/anthology/N06-2015>
- [10] R. Weischedel, M. Palmer, M. Marcus, E. Hovy, S. Pradhan, L. Ramshaw, N. Xue, A. Taylor, J. Kaufman, M. Franchini, M. El-Bachouti, R. Belvin, and A. Houston, “Ontonotes release 5.0,” Linguistic Data Consortium, Tech. Rep., 2013. [Online]. Available: <https://catalog.ldc.upenn.edu/docs/LDC2013T19/OntoNotes-Release-5.0.pdf>
- [11] A. Ghaddar and P. Langlais, “WiNER: A Wikipedia annotated corpus for named entity recognition,” in *Proceedings of the Eighth International Joint Conference on Natural Language Processing (Volume 1: Long Papers)*. Taipei, Taiwan: Asian Federation of Natural Language Processing, Nov. 2017, pp. 413–422. [Online]. Available: <https://www.aclweb.org/anthology/I17-1042>
- [12] J. Nothman, N. Ringland, W. Radford, T. Murphy, and J. Curran, “Learning multilingual named entity recognition from wikipedia,” in *Artificial Intelligence*. Elsevier, Jan. 2013, pp. 151–175.
- [13] T. Liu, J.-G. Yao, and C.-Y. Lin, “Towards improving neural named entity recognition with gazetteers,” in *Proceedings of the 57th Annual Meeting of the Association for Computational Linguistics*. Florence, Italy: Association for Computational Linguistics, Jul. 2019, pp. 5301–5307. [Online]. Available: <https://www.aclweb.org/anthology/P19-1524>
- [14] S. Peshterliev, C. Dupuy, and I. Kiss, “Self-attention gazetteer embeddings for named-entity recognition,” *arXiv preprint arXiv:2004.04060*, 2020.
- [15] Y. Lecun, L. Bottou, Y. Bengio, and P. Haffner, “Gradient-based learning applied to document recognition,” in *Proceedings of the IEEE*, 1998, pp. 2278–2324.
- [16] Y. Kim, “Convolutional neural networks for sentence classification,” in *Proceedings of the 2014 Conference on Empirical Methods in Natural Language Processing (EMNLP)*. Doha, Qatar: Association for Computational Linguistics, Oct. 2014, pp. 1746–1751. [Online]. Available: <https://www.aclweb.org/anthology/D14-1181>
- [17] J. Pennington, R. Socher, and C. Manning, “GloVe: Global vectors for word representation,” in *Proceedings of the 2014 Conference on Empirical Methods in Natural Language Processing (EMNLP)*. Doha, Qatar: Association for Computational Linguistics, Oct. 2014, pp. 1532–1543. [Online]. Available: <https://www.aclweb.org/anthology/D14-1162>
- [18] D. Muralidharan, J. R. A. Moniz, S. Gao, X. Yang, L. Li, J. Kao, S. Pulman, A. Kothari, R. Shen, Y. Pan *et al.*, “Noise-robust named entity understanding for virtual assistants,” *arXiv preprint arXiv:2005.14408*, 2020.
- [19] D. P. Kingma and J. Ba, “Adam: A method for stochastic optimization,” *arXiv preprint arXiv:1412.6980*, 2014.
- [20] N. Srivastava, G. Hinton, A. Krizhevsky, I. Sutskever, and R. Salakhutdinov, “Dropout: a simple way to prevent neural networks from overfitting,” *The journal of machine learning research*, vol. 15, no. 1, pp. 1929–1958, 2014.