

# Collective Bio-Entity Recognition in Scientific Documents using Hinge-Loss Markov Random Fields

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## ABSTRACT

Identifying biological entities such as genes and proteins from scientific documents is crucial for further downstream tasks such as question answering and information retrieval. This task is challenging because the same surface text can refer either to a gene or a protein based on the context. Traditional approaches such as Huang et al. [12] consider the words present in the surrounding text to infer the context. However, they fail to consider the semantics of these words which are better represented by contextual word embeddings such as BERT [6]. Deep learning based approaches, on the other hand, fail to make use of the relational structure of scientific documents. We introduce a novel probabilistic approach that jointly classifies all entity references using a class of undirected graphical models called hinge-loss Markov random fields [1]. Our approach can combine relational information with embedding-based word semantics. Further, our approach can be easily extended to incorporate new sources of information. Our initial evaluation on the JNLPBA shared task corpus [4] shows that our joint classification approach outperforms both traditional machine learning approaches and semantic models based on word embeddings by up to 7.5% on F1 score.

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## 1 INTRODUCTION

Bio-entity recognition systems which identify biological entities in unstructured scientific literature are crucial for information extraction, question answering and summarization [4]. Genes and proteins are two important entity classes recognised by these systems.

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Identifying genes and proteins in scientific literature is challenging as both entity types can have the same surface text. For example, consider the following two sentences:

*By UV cross-linking and immunoprecipitation, we show that SBP2 specifically binds selenoprotein mRNAs both in vitro and in vivo.*

*The SBP2 clone used in this study generates a 3173 nt transcript.*

The surface text *SBP2* in the first sentence corresponds to a protein, whereas in the second sentence it corresponds to a gene.

Several approaches have been proposed for the task of classifying entity references as genes and proteins [3, 7, 8, 11, 12, 24]. Traditional techniques such as Chen and Al-Mubaid [3] and Huang et al. [12] construct feature vectors using the words present in a context window around the surface text and use models such as support vector machines to classify these references. These techniques typically use a bag-of-words-based model to represent the context window and can capture the similarity and semantics of the words in the context. More recently, several BERT-based contextual embeddings trained on a large corpus of biological text have been proposed to address this challenge [9, 15]. However, embedding-based approaches such as Giorgi and Bader [8] treat sentences independently and do not make use of relational structure present in the data. For example, two references that have the same surface text and are present in the same abstract are both likely to be genes or proteins. Another drawback of the current approaches is the difficulty in extending them to incorporate new sources of information. There is a need for a robust, extensible framework that can jointly reason over all the references and can incorporate semantic information present in the word embeddings.

In this work, we propose a novel approach that leverages the flexibility of probabilistic programming to combine relational information with word semantics present in the contextual embeddings. We represent each reference as a node in the graph. Along with various sources of relational information such as references being present in the same abstract, we also include the semantic information found in embedding similarities as edges. We then make use of hinge-loss Markov Random Field (HL-MRF) [1], a class of undirected graphical models, to jointly reason over all references in the graph.

The contributions of our approach include:

- We propose a novel probabilistic approach that combines relational data with word semantics for the task of gene/protein classification.
- Our approach uses a probabilistic programming language and can be extended to include other sources of information.
- Initial experimental evaluation on the 2004 JNLPBA Shared Task corpus [4] shows that our approach is able to outperform traditional word-based models and semantic embedding-based models by up to 7.5% on F1 score.

## 2 RELATED WORK

We first give an overview of the various approaches proposed in literature for the task of gene/protein classification. We then describe work on word sense disambiguation, a closely related task.

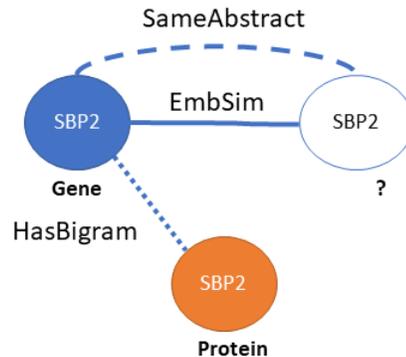
Collective entity disambiguation methods which use graphical models have been proposed [5, 25], but feature engineering for traditional classifiers is the primary focus of research on gene and protein name disambiguation [3, 12]. Chen and Al-Mubaid [3] utilize the information gain of words in their training corpus to construct features. In addition to information gain, Huang et al. [12] also investigated the co-occurrence relationships of words as part of their feature engineering. While both of these approaches ultimately utilize SVMs, more recent works such as Yoon et al. [24] apply deep learning methods and embedding representations of words for more general bio-entity recognition.

Word-sense disambiguation (WSD) is the task of identifying the meaning of words from context. Knowledge, often in a human-curated form such as a thesaurus or ontology, is a key part of many WSD approaches. A survey on various approaches for the task of WSD can be found in Navigli [18]. More recently, approaches that use embeddings [13] and deep learning methods [21] have been proposed. In our work, we propose a novel approach for the task of gene/protein WSD that leverages both relational information and embeddings to jointly reason over all references.

## 3 APPROACH

Our proposed approach combines relational information with semantics by representing them as a graph. Fig. 1 shows an example graph constructed for three references. The references are represented as nodes. Gene references are represented in blue and protein references are represented in orange. Unlabeled references are shown in white. There are two labeled references and one unlabeled reference. Relational information such as the fact that two references occur in the same abstract or happen to share a bigram in their *context windows* are represented as edges. Semantic information such as cosine similarity computed on the contextual embeddings of the references are also represented as edges.

Having constructed the graph, we combine these information sources and reason jointly over all the references using a hinge-loss Markov random field (HL-MRF). HL-MRFs are a class of conditional probabilistic models over continuous random variables that support modelling of richly structured relational data. HL-MRFs use hinge-loss feature functions and admit tractable and efficient inference. The continuous random variables in HL-MRFs allows us to incorporate similarity measures and confidences of other sources.



**Figure 1: Example graph containing three references represented as nodes. Relational and semantic information are represented as edges. Gene references are represented in blue and protein references are represented in orange. Unlabeled references are shown in white.**

We use a probabilistic programming language called probabilistic soft logic (PSL) to generate a HL-MRF from the given graph. We first provide a brief overview of PSL and then describe our proposed approach. For more details on PSL and HL-MRFs, we refer the reader to Bach et al. [1].

### 3.1 Probabilistic Soft Logic

PSL is a probabilistic programming language used to define a HL-MRF. PSL supports modeling of rich relational data using weighted logical clauses that encode statistical dependencies and structural constraints. For example, consider the rule:

$$w : \text{EXPLICITGENE}(A) \rightarrow \text{ISGENE}(A)$$

Here the predicate `EXPLICITGENE` is set to 1 if the surface text contains the term “gene”. This PSL rule states that  $A$  is likely to be a gene if the surface text contain the word *gene* (e.g. “*IL-2 gene*”). The logical atoms in PSL are represented using continuous random variables in the interval  $[0, 1]$ , and the rule satisfaction is computed using the Lukasiewicz relaxation [14] of Boolean logic. Each relation type in the constructed graph has a corresponding predicate that is used to specify rules.

Given a graph containing references and a set of rules, PSL generates a HL-MRF by instantiating each rule in the model with the references in the graph. This process is known as *grounding*. The logical atoms in the *ground* rules correspond to the random variables in the HL-MRF, and the ground rules correspond to hinge-loss feature functions. Given a set of random variables, some of which are observed  $X$ , a PSL model defines a probability distribution over the unobserved variables  $Y$  given by:

$$p(Y|X) = \frac{1}{Z} e^{-\sum_{j=1}^m w_j \phi_j(Y, X)}$$

where  $Z$  is the normalization constant,  $\phi_j$  is a *hinge-loss potential* and  $w_j$  is a positive weight associated with  $\phi_j$ . The hinge-loss

potentials are defined as follows:

$$\phi_j(Y, X) = \max\{l_j(Y, X), 0\}^p$$

where  $p \in \{1, 2\}$ ,  $l_j$  is the Lukasiewicz relaxation of the Boolean clause. Getting a maximum a posteriori (MAP) estimate for  $Y$  is a convex optimization task which PSL can perform efficiently.

### 3.2 PSL Model

We now describe the various rules that incorporate several information sources for the task of gene/protein classification.

**Contextual Semantic Similarity:** BERT-based contextual word embeddings capture the semantics of the words and are a crucial component of many state-of-the-art NLP approaches [16, 24]. Unlike traditional word embeddings such as Glove[19] and fasttext[17] that give each word string an embedding, contextual embeddings such as BERT[6] and ELMO[20] generate different embeddings for the same word based on the context. This allows us to handle references such as *SBP2*, where based on the context they could either refer to a gene or a protein. We use BioMed-RoBERTa [10], a model based on the RoBERTa architecture [16], which has been pretrained on 2.68 million scientific papers. Since these embeddings contain contextual information, a high level of similarity between the embeddings of two references indicates they are likely to be both genes or proteins. We introduce the predicate  $\text{EMBEDDINGSIMILARITY}(A, B)$  that captures the cosine similarity of reference A and reference B's embeddings. Because all references share significant semantic features, such as the fact that they are all nouns, they are highly similar. To address this, we set  $\text{EMBEDDINGSIMILARITY}(A, B)$  to be equal to 0 if it is below a fixed threshold  $\theta$ . In our experiments we set  $\theta$  to 0.98.

We then propagate the node labels based on the contextual semantic similarity using the the following rules:

$$\begin{aligned} \text{EMBEDDINGSIMILARITY}(A, B) \wedge \text{ISGENE}(A) &\rightarrow \text{ISGENE}(B) \\ \text{EMBEDDINGSIMILARITY}(A, B) \wedge \neg\text{ISGENE}(A) &\rightarrow \neg\text{ISGENE}(B) \end{aligned}$$

Computing similarity for all possible pairs of references is intractable. We use a strategy called *blocking* to identify potential pairs that are likely to have high similarity. In order to reduce the number of pairs for which we do a similarity computation, we only consider pairs that share at least two words in their *context*. This blocking strategy dramatically reduces computation time. In our experiments, we define the *context* of a reference to be the ten words which come before and after it.

**Contextual Word Similarity:** Two references with identical surface text and also have several *discriminative* words or bigrams in common are likely to belong to the same class. We define a predicate  $\text{HASWORD}(A, X)$  that is set to 1 if the word  $X$  is present in the context of A. To make sure we only look at discriminative words, we consider words that have high information gain (IG). IG

is defined as follows:

$$\begin{aligned} \text{IG}(w) &= -\sum_{i=1}^m P(c_i) \log P(c_i) \\ &+ P(w) \sum_{i=1}^m P(c_i | w) \log P(c_i | w) \\ &+ P(\bar{w}) \sum_{i=1}^m P(c_i | \bar{w}) \log P(c_i | \bar{w}) \end{aligned}$$

where  $w$  refers to a given word,  $\bar{w}$  refers to the absence of  $w$ ,  $m$  refers to the total number of classes (2 in our case, for gene/protein), and  $c_i$  refers to the specific class. We calculate the IG values for all words that occur frequently and chose the top- $k$  words that have the highest IG. We define the predicate  $\text{HIGHIG}(X)$  to be equal to 1 if a word  $X$  is frequent and occurs in this list of top- $k$  words. We use a frequency threshold of 300 and set  $k = 200$  in our experiments.

We introduce a predicate  $\text{SAMENAME}(A, B)$  which is set to 1 when A and B have the same surface text. We include the following rules in the model:

$$\begin{aligned} \text{SAMENAME}(A, B) \wedge \text{HASWORD}(A, X) \wedge \text{HASWORD}(B, X) \\ \wedge \text{HIGHIG}(X) \wedge \text{ISGENE}(A) &\rightarrow \text{ISGENE}(B) \\ \text{SAMENAME}(A, B) \wedge \text{HASWORD}(A, X) \wedge \text{HASWORD}(B, X) \\ \wedge \text{HIGHIG}(X) \wedge \neg\text{ISGENE}(A) &\rightarrow \neg\text{ISGENE}(B) \end{aligned}$$

We also include rules that propagate node labels between references that have the same surface text and have one or more common bigrams in the context. We introduce the predicate  $\text{HASBIGRAM}$  and include the following rules in the model:

$$\begin{aligned} \text{SAMENAME}(A, B) \wedge \text{HASBIGRAM}(A, X) \wedge \text{HASBIGRAM}(B, X) \\ \wedge \text{ISGENE}(A) &\rightarrow \text{ISGENE}(B) \\ \text{SAMENAME}(A, B) \wedge \text{HASBIGRAM}(A, X) \wedge \text{HASBIGRAM}(B, X) \\ \wedge \neg\text{ISGENE}(A) &\rightarrow \neg\text{ISGENE}(B) \end{aligned}$$

We experimented with feature selection approaches for bigrams, but found that bigrams are unique enough and do not require further filtering.

**Continuity Within Abstracts:** References in the same abstract that have the same surface text are likely to belong to the same class. To capture this, we include two rules:

$$\begin{aligned} \text{SAMEABSTRACT}(A, B) \wedge \text{SAMENAME}(A, B) \\ \wedge \text{ISGENE}(A) &\rightarrow \text{ISGENE}(B) \\ \text{SAMEABSTRACT}(A, B) \wedge \text{SAMENAME}(A, B) \\ \wedge \neg\text{ISGENE}(A) &\rightarrow \neg\text{ISGENE}(B) \end{aligned}$$

**Frequent Co-occurrence:** We define two references to be *adjacent* if they occur in the same abstract and no other reference occurs between them. We introduce the predicate  $\text{ADJACENT}(A, B)$  to be equal to 1 if references A and B are adjacent. If two pairs of adjacent references are correspondingly identical in their surface text, and three out of four of these are gene references, then the fourth is likely also a gene reference. We represent this with PSL

rules of the form:

$$\begin{aligned} & \text{ADJACENT}(A, B) \wedge \text{ADJACENT}(C, D) \\ & \wedge \text{SAME\_NAME}(A, C) \wedge \text{SAME\_NAME}(B, D) \\ & \wedge \text{IS\_GENE}(A) \wedge \text{IS\_GENE}(B) \\ & \wedge \text{IS\_GENE}(C) \rightarrow \text{IS\_GENE}(D) \end{aligned}$$

**Surface Text Observations:** The presence of discriminative terms in a reference’s surface text are a strong signal that it belongs to a particular class. For example, if a reference’s surface text contains the word "gene", as in "*IL-2 gene*", it is quite likely that it refers to a gene. We define the predicates  $\text{EXPLICIT\_GENE}(A)$  and  $\text{EXPLICIT\_PROTEIN}(A)$  that are equal to 1 if the surface text of the reference  $A$  contains the terms "gene" and "protein" respectively. We then include the following rules:

$$\begin{aligned} & \text{EXPLICIT\_GENE}(A) \rightarrow \text{IS\_GENE}(A) \\ & \text{EXPLICIT\_PROTEIN}(A) \rightarrow \neg \text{IS\_GENE}(A) \end{aligned}$$

We incorporate similar rules about words which are less explicit by first computing the mutual information (MI) of the word with respect to both the gene and protein class. MI is defined as:

$$MI_i(w) = \frac{N \times a}{(a + b) \times (a + c)}$$

Where  $N$  is the number of documents,  $a$  is the number of times  $w$  occurs in a document of class  $i$ ,  $b$  is the number of times  $w$  occurs in a document which doesn’t belong to class  $i$ , and  $c$  is the number of documents in class  $i$  which do not contain  $w$ . We then define the predicate  $\text{STRONG\_GENE}(X)$  to be equal to 1 if a word  $X$  occurs frequently and has a gene class MI value above a specified threshold.  $\text{STRONG\_PROTEIN}$  is defined similarly. We define the predicate  $\text{SURFACE\_TEXT\_HAS\_WORD}(A, X)$  to be equal to 1 when the surface text of reference  $A$  contains the word  $X$ .

Mutual information is strongly influenced by the marginal probability of the class with respect to which it is calculated [23]. As our dataset is imbalanced, we use different MI thresholds for each class. We set the gene-class MI threshold to 1.5 and the protein-class MI threshold to 1. We use a frequency threshold of 200 for both classes.

We then define the following rules:

$$\begin{aligned} & \text{STRONG\_GENE}(X) \wedge \text{SURFACE\_TEXT\_HAS\_WORD}(A, X) \\ & \rightarrow \text{IS\_GENE}(A) \\ & \text{STRONG\_PROTEIN}(X) \wedge \text{SURFACE\_TEXT\_HAS\_WORD}(A, X) \\ & \rightarrow \neg \text{IS\_GENE}(A) \end{aligned}$$

**Other Classifiers:** One of PSL’s unique strengths is its ability to incorporate information from multiple sources. We incorporate predictions from four other local classifiers, all of which use either a SVM or logistic regression model, which we use as baselines in our experimental evaluation. The details of these classifiers will be discussed in Section 4. As an example, we define the predicate  $\text{LR}(A)$  to be equal to 1 when a logistic regression-based classifier predicts reference  $A$  to be a gene and 0 otherwise. We include rules of the form:

$$\begin{aligned} & \text{LR}(A) \rightarrow \text{IS\_GENE}(A) \\ & \neg \text{LR}(A) \rightarrow \neg \text{IS\_GENE}(A) \end{aligned}$$

We add four rules of this form that correspond to the outputs of SVMs and logistic regression trained on the bag-of-words representation and the embeddings of the surface text.

## 4 EXPERIMENTAL EVALUATION

### 4.1 Experimental Results

We evaluate the effectiveness of our approach on the JNLPBA 2004 shared task [4]. The corpus contains 2,000 abstracts containing bio-entity references that are annotated as genes and proteins. There are 30,269 protein and 9,533 gene references.

We evaluate our approach in two different settings which we will refer to as the *completely-unlabeled* (CU) setting and the *partially-labeled* (PL) setting. In CU, we generate equally-sized folds by randomly assigning each abstract to a fold. In the CU setting, all references in an abstract are either unlabeled or completely labeled. In PL, we randomly assign each reference to one of the folds. In this setting, the abstracts are partially labeled. Some references within an abstract are labeled while others are unlabeled. For both CU and PL we create 10 folds and evaluate our model by performing 10-fold CV. We performed paired t-tests and all results in bold are statistically significant at the  $p = 0.05$  level.

### 4.2 Baselines

We compare the performance of our approach against two embedding-based semantic models and two context-based models. For the embedding-based semantic models, we generate the embeddings of the references using BioMed-RoBERTa and train a logistic regression and support vector machine using the embedding dimensions as features. We refer to these models as the *Embeddings SVM/LR* models or *embeddings-based SVM/LR* models. Similarly, for the context-based models we train a SVM and logistic regression using the bag-of-words representation consisting of unigrams and bigrams counts present in each reference’s context. We refer to these models as the *BoW SVM/LR* models or the *bag-of-words-based* models. For the embeddings SVM, we set the regularization parameter  $C = 0.05$ . For all other baselines we use the default settings associated with the model in SKLearn. For each reference we define the context as five words preceding it, the reference’s surface text, and the five words after it. Both these approaches classify each reference independently and fails to make use of relational data.

To analyze the effect of relational rules, we also perform an ablation study by comparing our proposed model to a PSL model that combines the four baselines. We refer to this as *Non-relational model* in Table 1 and Table 2.

For our PSL-based approach, we use all the rules mentioned in Section 3. We use BOWL[22] on the validation set to learn weights of the model. BOWL uses Gaussian process regression in a Bayesian optimization setting to search the space of model weights that maximize a user-defined metric. In our experiments, we use F1 as the metric. Since PSL outputs truth values in the range  $[0, 1]$  for each reference, we binarize the labels by considering all references with ISGENE value  $\geq 0.5$  to be genes.

The precision, recall, F1 score and accuracy for the Completely-Unlabeled setting is shown in Table 1. Among the baselines we observe that embedding-based approaches perform better than bag-of-words based models. This is due the semantic information

Model	F1	Accuracy	Precision	Recall
BoW SVM	0.811 ± 0.015	0.914 ± 0.009	0.854 ± 0.020	0.773 ± 0.018
BoW LR	0.718 ± 0.021	0.884 ± 0.011	0.857 ± 0.019	0.618 ± 0.031
Embeddings SVM	0.862 ± 0.017	0.937 ± 0.008	0.894 ± 0.016	0.833 ± 0.025
Embeddings LR	0.856 ± 0.018	0.933 ± 0.008	0.886 ± 0.020	0.829 ± 0.026
Non-relational model	0.863 ± 0.013	0.933 ± 0.007	0.848 ± 0.018	0.879 ± 0.014
<b>PSL</b>	<b>0.895 ± 0.014</b>	<b>0.951 ± 0.007</b>	<b>0.922 ± 0.020</b>	0.870 ± 0.016

**Table 1: Performance Metrics for Completely-Unlabeled Setting and Std. Deviations. PSL significantly outperforms baselines on F1 and accuracy.**

Model	F1	Accuracy	Precision	Recall
BoW SVM	0.820 ± 0.011	0.916 ± 0.005	0.845 ± 0.013	0.797 ± 0.015
BoW LR	0.731 ± 0.012	0.888 ± 0.005	0.863 ± 0.011	0.634 ± 0.015
Embeddings SVM	0.872 ± 0.008	0.941 ± 0.003	0.902 ± 0.011	0.844 ± 0.012
Embeddings LR	0.863 ± 0.011	0.937 ± 0.005	0.892 ± 0.010	0.836 ± 0.014
Non-relational model	0.871 ± 0.008	0.937 ± 0.003	0.854 ± 0.009	0.889 ± 0.011
<b>PSL</b>	<b>0.937 ± 0.007</b>	<b>0.970 ± 0.003</b>	<b>0.941 ± 0.006</b>	<b>0.934 ± 0.011</b>

**Table 2: Performance Metrics for Partially-Labelled Setting and Std. Deviations. PSL significantly outperforms baselines on F1 and accuracy.**

contained in the word embeddings. We also see that SVMs perform better than logistic regression.

PSL outperforms all baselines on F1 and accuracy. While the non-relational model has slightly higher recall, it has significantly lower precision. PSL’s improvement can be attributed to the fact that it combines semantic information with relational information and jointly infers the class labels for all references. In CU, PSL outperforms the strongest baseline, embedding-based SVMs, by 3.8% on F1 score. Moreover, PSL tends to have lower standard deviations when compared to other baselines.

The precision, recall, F1 score and accuracy for PLsetting is shown in Table 2. Similarly to the previous setting, we observe that PSL outperforms all other baselines. PSL has an improvement of 7.5% on F1 score over the embeddings-based SVM. This improvement comes from achieving a 4.3% increase in average precision and a 10.6% increase in average recall. The average accuracy also increases by 3% over the embeddings-based SVM.

All models perform better in the partially-labeled setting when compared to completely-unlabeled setting. For PSL, this improvement is due to the propagation of node labels between references in the same abstract. We hypothesize the improvement in the baselines is due to the increased overlap of words and bigrams in the references’ context windows as they are part of the same abstract.

## 5 CONCLUSION AND FUTURE WORK

In this paper, we proposed a probabilistic approach for the task of bio-entity recognition that combines semantic information using contextual embeddings with relational information. Further, our approach uses probabilistic programming and can easily incorporate other sources of information. Our initial experiments shows that the proposed approach is able to outperform purely semantic-based approaches as well as traditional bag-of-words approach.

In our future work, we will extend our approach to both extract and label bio-entities. We also intend to incorporate other sources of domain knowledge to help disambiguate references. A promising source of such knowledge is the UMLS Metathesaurus [2], a database that contains the relationships between and hierarchies of terms and words as they appear in a biomedical context.

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## REFERENCES

- [1] Stephen Bach, Matthias Broecheler, Bert Huang, and Lise Getoor. 2017. Hinge-Loss Markov Random Fields and Probabilistic Soft Logic. *JMLR* (2017).
- [2] O. Bodenreider. 2004. The Unified Medical Language System (UMLS): integrating biomedical terminology. *Nucleic Acids Res* 32 (2004), D267–270.
- [3] Ping Chen and Hisham Al-Mubaid. 2006. Context-based Term Disambiguation in Biomedical Literature. *FLAIRS* (2006).
- [4] Nigel Collier and Jin-Dong Kim. 2004. Introduction to the Bio-entity Recognition Task at JNLPBA. In *BioNLP*. COLING, Geneva, Switzerland, 73–78.
- [5] Hongjie Dai, Richard Tzong, Richard Tzong-Han Tsai, and Wen-Lian Hsu. 2012. Entity Disambiguation Using a Markov-Logic Network. (2012).
- [6] Jacob Devlin, Ming-Wei Chang, Kenton Lee, and Kristina Toutanova. 2018. BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding. *arXiv preprint arXiv:1810.04805* (2018).
- [7] Filip Ginter, Jorma Boberg, Jouni Järvinen, and Tapio Salakoski. 2004. New techniques for disambiguation in natural language and their application to biological text. *JMLR* 5 (2004), 605–621.
- [8] John M Giorgi and Gary D Bader. 2019. Towards reliable named entity recognition in the biomedical domain. *Bioinformatics* 36, 1 (2019), 280–286.
- [9] Suchin Gururangan, Ana Marasović, Swabha Swayamdipta, Kyle Lo, Iz Beltagy, Doug Downey, and Noah A. Smith. 2020. Don’t Stop Pretraining: Adapt Language Models to Domains and Tasks. In *ACL*.
- [10] Suchin Gururangan, Ana Marasović, Swabha Swayamdipta, Kyle Lo, Iz Beltagy, Doug Downey, and Noah A. Smith. 2020. Don’t Stop Pretraining: Adapt Language Models to Domains and Tasks. In *ACL*.

- [11] Vasileios Hatzivassiloglou, Pablo A Duboue, and Andrey Rzhetsky. 2001. Disambiguating proteins, genes, and RNA in text: a machine learning approach. *Bioinformatics* 17 (2001), S97–S106.
- [12] Changqin Huang, Jia Zhu, Xiaodi Huang, Min Yang, Gabriel Fung, and Qintai Hu. 2018. A Novel Approach for Entity Resolution in Scientific Documents Using Context Graphs. *Information Sciences* (2018).
- [13] Ignacio Iacobacci, Mohammad Taher Pilehvar, and Roberto Navigli. 2016. Embeddings for Word Sense Disambiguation: An Evaluation Study. In *ACL*.
- [14] George Klir. 1995. *Fuzzy sets and fuzzy logic : theory and applications*. Prentice Hall PTR, Upper Saddle River, N.J.
- [15] Jinhyuk Lee, Wonjin Yoon, Sungdong Kim, Donghyeon Kim, Sunkyu Kim, Chan Ho So, and Jaewoo Kang. 2020. BioBERT: a pre-trained biomedical language representation model for biomedical text mining. *Bioinformatics* 36, 4 (2020), 1234–1240.
- [16] Yinhan Liu, Myle Ott, Naman Goyal, Jingfei Du, Mandar Joshi, Danqi Chen, Omer Levy, Mike Lewis, Luke Zettlemoyer, and Veselin Stoyanov. 2019. RoBERTa: A Robustly Optimized BERT Pretraining Approach. *CoRR abs/1907.11692* (2019).
- [17] Tomas Mikolov, Edouard Grave, Piotr Bojanowski, Christian Puhersch, and Armand Joulin. 2018. Advances in Pre-Training Distributed Word Representations. In *LREC*.
- [18] Roberto Navigli. 2009. Word sense disambiguation. *Comput. Surveys* 41, 2 (2009), 1–69.
- [19] Jeffrey Pennington, Richard Socher, and Christopher D Manning. 2014. Glove: Global vectors for word representation. In *EMNLP*.
- [20] Matthew E. Peters, Mark Neumann, Mohit Iyyer, Matt Gardner, Christopher Clark, Kenton Lee, and Luke Zettlemoyer. 2018. Deep contextualized word representations. In *NAACL*.
- [21] A. K. M. Sabbir, Antonio Jimeno-Yepes, and Ramakanth Kavuluru. 2016. Knowledge-Based Biomedical Word Sense Disambiguation with Neural Concept Embeddings and Distant Supervision. *CoRR abs/1610.08557* (2016).
- [22] Sriram Srinivasan, Golnoosh Farnadi, and Lise Getoor. 2020. BOWL: Bayesian Optimization for Weight Learning in Probabilistic Soft Logic. In *AAAI Conference on Artificial Intelligence (AAAI)*.
- [23] Yiming Yang and Jan O. Pedersen. 1997. A Comparative Study on Feature Selection in Text Categorization. In *ICML*.
- [24] Wonjin Yoon, Chan Ho So, Jinhyuk Lee, and Jaewoo Kang. 2019. CollaboNet: collaboration of deep neural networks for biomedical named entity recognition. *Bioinformatics* 20, S10 (2019).
- [25] Weixin Zeng, Jiuyang Tang, Xiang Zhao, Bin Ge, and Weidong Xiao. 2018. Named Entity Disambiguation via Probabilistic Graphical Model with Embedding Features. In *NeurIPS*.