CMU: Arc-Factored, Discriminative Semantic Dependency Parsing

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Abstract

We present an arc-factored statistical model for semantic dependency parsing, as defined by the SemEval 2014 Shared Task 8 on Broad-Coverage Semantic Dependency Parsing. Our entry in the open track placed second in the competition.

1 Introduction

The task of broad coverage semantic dependency parsing aims to provide a shallow semantic analysis of text not limited to a specific domain. As distinct from deeper semantic analysis (e.g., parsing to a full lambda-calculus logical form), shallow semantic parsing captures relationships between pairs of words or concepts in a sentence, and has wide application for information extraction, knowledge base population, and question answering (among others).

We present here two systems that produce semantic dependency parses in the three formalisms of the SemEval 2014 Shared Task 8 on Broad-Coverage Semantic Dependency Parsing (Oepen et al., 2014). These systems generate parses by extracting features for each potential dependency arc and learning a statistical model to discriminate between good arcs and bad; the first treats each labeled edge decision as an independent multiclass logistic regression (§3.2.1), while the second predicts arcs as part of a graph-based structured support vector machine (§3.2.2). Common to both models is a rich set of features on arcs, described in §3.2.3. We include a discussion of features found to have no discernable effect, or negative effect, during development (§4).

Our system placed second in the open track of the Broad-Coverage Semantic Dependency Parsing task (in which output from syntactic parsers and other outside resources can be used). We present our results in §5.

2 Formalisms

The Shared Task 8 dataset consists of annotations of the WSJ Corpus in three different semantic dependency formalisms. DM is derived from LinGO English Resource Grammar (ERG) annotations in DeepBank (Flickinger et al., 2012). PAS is derived from the Enju HPSG treebank using the conversion rules of Miyao et al. (2004). PCEDT is derived from the tectogrammatical layer of the Prague Czech-English Dependency Treebank (Hajič, 1998). See Figure 1 for an example.

The three formalisms come from very different linguistic theories, but all are represented as labeled directed graphs, with words as vertices, and all have “top” annotations, corresponding roughly to the semantic focus of the sentence. (A “top” need not be a root of the graph.) This allows us to use the same machinery (§3) for training and testing statistical models for the three formalisms.

3 Models

We treat the problem as a three-stage pipeline. The first stage prunes words by predicting whether they have any incoming or outgoing edges at all (§3.1); if a word does not, then it is not considered for any attachments in later stages. The second stage predicts where edges are present, and their labels (§3.2). The third stage predicts whether a predicate word is a top or not (§3.3). Formalisms sometimes
annotate more than one “top” per sentence, but we found that we achieve the best performance on all formalisms by predicting only the one best-scoring “top” under the model.

3.1 Singleton Classification

For each formalism, we train a classifier to recognize singletons, nodes that have no parents or children. (For example, punctuation tokens are often singletons.) This makes the system faster without affecting accuracy. For singleton prediction, we use a token-level logistic regression classifier, with features including the word, its lemma, and its part-of-speech tag. If the classifier predicts a probability of 99% or higher the token is pruned; this removes around 10% of tokens. (The classifier performs differently on different formalisms; on PAS it has perfect accuracy, while on DM and PCEDT accuracy is in the mid-90’s.)

3.2 Edge Prediction

In the second stage of the pipeline, we predict the set of labeled directed edges in the graph. We use the same set of edge-factorized features (§3.2.3) in two alternative models: an edge-independent multiclass logistic regression model (LOGISTICEDGE, §3.2.1); and a structured SVM (Taskar et al., 2003; Tsochantaridis et al., 2004) that enforces a determinism constraint for certain labels, which allows each word to have at most one outgoing edge with that label (SVMEDGE, §3.2.2). For each formalism, we trained both models with varying features enabled and hyperparameter settings and submitted the configuration that produced the best labeled $F_1$ on the development set. For DM and PCEDT, this was LOGISTICEDGE; for PAS, this was SVMEDGE. We report results only for the submitted configurations, with different features enabled. Due to time constraints, full hyperparameter sweeps and comparable feature sweeps were not possible.

3.2.1 LOGISTICEDGE Parser

The LOGISTICEDGE model considers only token index pairs $(i, j)$ where $|i - j| \leq 10$, $i \neq j$, and both $i$ and $j$ have been predicted to be non-singletons by the first stage. Although this prunes some gold edges, among the formalisms, 95%–97% of all gold edges are between tokens of distance 10 or less. Both directions $i \rightarrow j$ and $j \rightarrow i$ are considered between every pair.

Let $L$ be the set of $K + 1$ possible output labels: the formalism’s original $K$ edge labels, plus the additional label NOEDGE, which indicates that no edge exists from $i$ to $j$. The model treats every pair of token indices $(i, j)$ as an independent multiclass logistic regression over output space $L$. Let $x$ be an input sentence. For candidate parent index $i$, child index $j$, and edge label $\ell$, we extract a feature vector $f(x, i, j, \ell)$, where $\ell$ is conjoined with every feature described in §3.2.3. The multiclass logistic regression model defines a distribution over $L$, parametrized by weights $\phi$:

$$P(\ell | \phi, x, i, j) = \frac{\exp\{\phi \cdot f(x, i, j, \ell)\}}{\sum_{\ell' \in L} \exp\{\phi \cdot f(x, i, j, \ell')\}}.$$  

$\phi$ is learned by minimizing total negative log-likelihood of the above (with weighting; see below), plus $l_2$ regularization. AdaGrad (Duchi et al., 2011) is used for optimization. This seemed to optimize faster than L-BFGS (Liu and Nocedal, 1989), at least for earlier iterations, though we did no systematic comparison. Stochastic gradient steps are applied once a time from individual examples, and a gradient step for the regularizer is applied once per epoch.

The output labels have a class imbalance; in all three formalisms, there are many more NOEDGE examples than true edge examples. We improved $F_1$ performance by downweighting NOEDGE examples through a weighted log-likelihood objective, $\sum_{i, j} \sum_{\ell} w_{\ell} \log P(\ell | \phi, x, i, j)$, with $w_{\text{NOEDGE}} = 0.3$ (selected on development set) and $w_{\ell} = 1$ otherwise.

Decoding: To predict a graph structure at test-time for a new sentence, the most likely edge label is predicted for every candidate $(i, j)$ pair of unpruned tokens. If an edge is predicted for both directions for a single $(i, j)$ pair, only the edge with the higher score is chosen. (There are no such bidirectional edges in the training data.) This post-processing actually did not improve accuracy on DM or PCEDT, so did improve PAS by $\approx 0.2\%$ absolute $F_1$, but we did not submit LOGISTICEDGE for PAS.

3.2.2 SVMEDGE Parser

In the SVMEDGE model, we use a structured SVM with a determinism constraint. This constraint ensures that each word token has at most one outgoing edge for each label in a set of deterministic labels $L_d$. For example, in DM a predicate never has more than one child with edge label “ARG1.” $L_d$ was chosen to be the set of edges that were $>99.9\%$.
consider the fully dense graph of all edges between all words predicted as not singletons by the singleton classifier §3.1 (in all directions with all possible labels). Unlike LOGISTICEDGE, the label set $L$ does not include an explicit NOEDGE label. If $\psi$ denotes the model weights, and $f$ denotes the features, then an edge from $i$ to $j$ with label $\ell$ in the dense graph has a weight $c(i, j, \ell)$ assigned to it using the linear scoring function $c(i, j, \ell) = \psi \cdot f(x, i, j, \ell)$.

**Decoding:** For each node and each label $\ell$, one outgoing edge is possible. For the subgraph (largest sum of edge weights) of the dense graph subject to the determinism constraints. Its runtime is $O(n^2)$.

The model weights are trained using the structured SVM loss. If $x$ is a sentence and $y$ is a graph over that sentence, let the features be denoted $f(x, y) = \sum_{(i,j,\ell) \in y} f(x, i, j, \ell)$. The SVM loss for each training example $(x_i, y_i)$ is:

$$-\psi^T f(x_i, y_i) + \max_y \psi^T f(x_i, y) + \text{cost}(y, y_i)$$

where $\text{cost}(y, y_i) = \alpha|y \setminus y_i| + \beta|y_i \setminus y|$. $\alpha$ and $\beta$ trade off between precision and recall for the edges (Gimpel and Smith, 2010). The loss is minimized with AdaGrad using early-stopping on a development set.

### 3.2.3 Edge Features

Table 1 describes the features we used for predicting edges. These features were computed over an edge $e$ with parent token $s$ at index $i$ and child token $t$ at index $j$. Unless otherwise stated, each feature template listed has an indicator feature that fires for each value it can take on. For the submitted results, LOGISTICEDGE uses all features except Dependency Path v2, POS Path, and Distance Thresholds, and SVMEDGE uses all features except Dependency Path v1. This was due to SVMEDGE being faster to train than LOGISTICEDGE when including POS Path features, and due to time constraints for the submission we were unable to retrain LOGISTICEDGE with these features.

1 By this we mean that of the nodes that have at least one outgoing edge, 99.9% of them have only one outgoing edge. For DM, $L_d = L \cup \{"_\text{and}_{c}, _\text{or}_{c}, _\text{then}_{c}, _\text{loc}, _\text{mwe}\}$, for PCDTM, $L_d = \{\text{PHR}, _\text{INTF}, _\text{VOCAT}\}$.

### 3.2.4 Feature Hashing

The biggest memory usage was in the map from feature names to integer indices during feature extraction. For experimental expedience, we implemented multilens feature hashing (Weinberger et al., 2009), which hashes feature names to indices, under the theory that errors due to collisions tend to cancel. No drop in accuracy was observed.

### 3.3 Top Prediction

We trained a separate token-level binary logistic regression model to classify whether a token’s node had the “top” attribute or not. At decoding time, all predicted predicates (i.e., nodes where there is at least one outbound edge) are possible candidates to be “top”; the classifier probabilities are evalu-
Word vectors: Features derived from 64-dimensional vectors from (Faruqui and Dyer, 2014), including the concatenation, difference, inner product, and element-wise multiplication of the two vectors associated with a parent-child edge. We also trained a Random Forest on the word vectors using Liaw and Wiener’s (2002) R implementation. The predicted labels were then used as features in LOGISTICEDGE.

Brown clusters: Features derived from Brown clusters (Brown et al., 1992) trained on a large corpus of web data. Parent, child, and conjoined parent-child edge features from cluster prefixes of length 2, 4, 6, 8, 10, and 12. Conjunctions of those features with the POS tags of the parent and child tokens.

Active/passive: Active/passive voice feature (as in Johannsson and Nugues (2008)) conjoined with both the Linear Distance features and the Subcategorization Sequence features. Voice information may already be captured by features from the Stanford dependency–style parses, which include passivization information in arc labels such as nsubjpass and auxpass (de Marneffe and Manning, 2008).

Connectivity constraint: Enforcing that the graph is connected (ignoring singletons), similar to Flanigan et al. (2014). Almost all semantic dependency graphs in the training data are connected (ignoring singletons), but we found that enforcing this constraint significantly hurt precision.

Tree constraint: Enforces that the graph is a tree. Unsurprisingly, we found that enforcing a tree constraint hurt performance.

Table 2: Features and constraints giving negative results.

<table>
<thead>
<tr>
<th>Features</th>
<th>LP</th>
<th>LR</th>
<th>LF</th>
<th>LM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Word vectors</td>
<td>0.8446</td>
<td>0.8348</td>
<td>0.8397</td>
<td>0.0875</td>
</tr>
<tr>
<td>Brown clusters</td>
<td>0.9078</td>
<td>0.8851</td>
<td>0.8963</td>
<td>0.2604</td>
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<tr>
<td>Active/passive</td>
<td>0.7681</td>
<td>0.7072</td>
<td>0.7364</td>
<td>0.0712</td>
</tr>
<tr>
<td>Connectivity constraint</td>
<td>0.8402</td>
<td>0.8090</td>
<td>0.8241</td>
<td>0.1397</td>
</tr>
</tbody>
</table>

Table 3: Labeled precision (LP), recall (LR), F₁ (LF), and whole-sentence match (LM) on the held-out test data.

5 Experimental Setup

We participated in the Open Track, and used the syntactic dependency parses supplied by the organizers. Feature engineering was performed on a development set (§20), training on §§00–19. We evaluate labeled precision (LP), labeled recall (LR), labeled F₁ (LF), and labeled whole-sentence match (LM) on the held-out test data using the evaluation script provided by the organizers. LF was averaged over the formalisms to determine the winning system. Table 3 shows our scores.

6 Conclusion and Future Work

We found that feature-rich discriminative models perform well at the task of mapping from sentences to semantic dependency parses. While our final approach is fairly standard for work in parsing, we note here additional features and constraints which did not appear to help (contrary to expectation). There are a number of clear extensions to this work that could improve performance. While an edge-factorized model allows for efficient inference, there is much to be gained from higher-order features (McDonald and Pereira, 2006; Martins et al., 2013). The amount of information shared between the three formalisms suggests that a multitask learning (Evgeniou and Pontil, 2004) framework could lead to gains. And finally, there is additional structure in the formalisms which could be exploited (such as the deterministic processes by which an original PCEDT tree annotation was converted into a graph); formulating more subtle graph constraints that are able to capture this a priori knowledge of the graph structure could lead to improved performance. We leave such explorations to future work.

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