Global Neural CCG Parsing with Optimality Guarantees

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Abstract

We introduce the first global recursive neural parsing model with optimality guarantees during decoding. To support global features, we give up dynamic programs and instead search directly in the space of all possible subtrees. Although this space is exponentially large in the sentence length, we show it is possible to learn an efficient A* parser. We augment existing parsing models, which have informative bounds on the outside score, with a global model that has loose bounds but only needs to model non-local phenomena. The global model is trained with a new objective that encourages the parser to explore a tiny fraction of the search space. The approach is applied to CCG parsing, improving state-of-the-art accuracy by 0.4 F1. The parser finds the optimal parse for 99.9% of held-out sentences, exploring on average only 190 subtrees.

1 Introduction

Recursive neural models perform well for many structured prediction problems, in part due to their ability to learn representations that depend globally on all parts of the output structures. However, global models of this sort are incompatible with existing exact inference algorithms, since they do not decompose over substructures in a way that allows effective dynamic programming. Existing work has therefore used greedy inference techniques such as beam search (Vinyals et al., 2015; Dyer et al., 2015) or reranking (Socher et al., 2013). We introduce the first global recursive neural parsing approach with optimality guarantees for decoding and use it to build a state-of-the-art CCG parser.

We search directly in the space of all possible parse trees to allow global representations. Optimality guarantees come from A* search, which provides a certificate of optimality if run to completion with a heuristic that is a bound on the future cost. However, generalizing A* to global models is challenging; these models also break the locality assumptions used to efficiently compute existing A* heuristics (Klein and Manning, 2003; Lewis and Steedman, 2014). Rather than directly replacing these models, we show that they can simply be augmented by adding a score from a global model that is constrained to be non-positive and has a trivial upper bound of zero. The global model, in effect, only needs to model the remaining non-local phenomena.

The global model is learned by optimizing a learning objective that is directly tied to the search procedure. We introduce a violation-based objective that encourages steps along the correct parse derivation to be ranked higher than other candidates in the A* search agenda. This involves backpropagating a perceptron-loss through a Tree-LSTM when an incorrect candidate appears at the top of the agenda.

The combination of global representations and optimal decoding enables our parser to achieve state-of-the-art accuracy for Combinatory Categorial Grammar (CCG) parsing. Despite being intractable in the worst case, the parser in practice is highly efficient. It finds optimal parses for 99.9% of held-out sentences while exploring just 190 subtrees on average—allowing it to outperform beam search in both speed and accuracy.
2 Overview

Parser as hypergraph search Many parsing algorithms can be viewed as a search problem, where parses are specified by paths through a hypergraph.

A node $y$ in this hypergraph is a labeled span, representing structures within a parse tree, as shown in Figure 1. Each hyperedge $e$ in the hypergraph represents a rule production in a parse. The head node of the hyperedge $\text{HEAD}(e)$ is the parent of the rule production, and the tail nodes of the hyperedge are the children of the rule production. For example, consider the hyperedge in Figure 1b whose head is like bananas. This hyperedge represents a forward application rule applied to its tails, like and bananas.

To define a path in the hypergraph, we first include a special start node $\emptyset$ that represents an empty parse. $\emptyset$ has outgoing hyperedges that reach every leaf node, representing assignments of labels to words (supertag assignments in Figure 1). We then define a path to be a set of hyperedges $E$ starting at $\emptyset$ and ending at a single destination node. A path therefore specifies the derivation of the parse constructed from the labeled spans at each node. For example, in Figure 1, the set of bolded hyperedges form a path deriving a complete parse.

Each hyperedge $e$ is weighted by a score $s(e)$ from a parsing model. The score of a path $E$ is the sum of its hyperedge scores:

$$g(E) = \sum_{e \in E} s(e)$$

Viterbi decoding is equivalent to finding the highest scoring path that forms a complete parse.

Search on parse forests Traditionally, the hypergraph represents a packed parse chart. In this work, our hypergraph instead represents a forest of parses. Figure 1 contrasts the two representations.
In the parse chart, labels on the nodes represent local properties of a parse, such as the category of a span in Figure 1a. As a result, multiple parses that contain the same property include the same node in their path, (e.g. the node spanning the phrase Fruit flies with category NP). The number of nodes in this hypergraph is polynomial in the sentence length, permitting exhaustive exploration (e.g. CKY parsing). However, the model scores can only depend on local properties of a parse. We refer to these models as locally factored models.

In contrast, nodes in the parse forest are labeled with entire subtrees, as shown in Figure 1b. For example, there are two nodes spanning the phrase Fruit flies with the same category NP but different internal substructures. While the parse forest requires an exponential number of nodes in the hypergraph, the model scores can depend on entire subtrees.

A* parsing A* parsing has been successfully applied in locally factored models (Klein and Manning, 2003; Lewis and Steedman, 2014; Lewis et al., 2015; Lewis et al., 2016). We present a special case of A* parsing that is conceptually simpler, since the parse forest constrains each node to be reachable via a unique path. During exploration, we maintain the unique (and therefore highest scoring) path to a hyperedge e, which we define as PATH(e).

Similar to the standard A* search algorithm, we maintain an agenda A of hyperedges to explore and a forest F of explored nodes that initially contains only the start node 0.

Each hyperedge e in the agenda is sorted by the sum of its inside score g(PATH(e)) and an admissible heuristic h(e). A heuristic h(e) is admissible if it is an upper bound of the sum of hyperedge scores leading to any complete parse reachable from e (the Viterbi outside score). The efficiency of the search improves when this bound is tighter.

At every step, the parser removes the top of the agenda, e_{max} = argmax_{e \in A} (g(PATH(e)) + h(e)). e\_{max} is expanded by combining HEAD(e\_{max}) with previously explored parses from F to form new hyperedges. These new hyperedges are inserted into A, and HEAD(e\_{max}) is added to F. We repeat these steps until the first complete parse y^* is explored. The bounds provided by h(e) guarantee that the path to y^* has the highest possible score. Figure 1b shows an example of the agenda and the explored forest at the end of perfectly efficient search, where only the optimal path is explored.

**Approach** The enormous search space described above presents a challenge for an A* parser, since computing a tight and admissible heuristic is difficult when the model does not decompose locally.

Our key insight in addressing this challenge is that existing locally factored models with an informative A* heuristic can be augmented with a global score (Section 3). By constraining the global score to be non-positive, the A* heuristic from the locally factored model is still admissible.

While the heuristic from the local model offers some estimate of the future cost, the efficiency of the parser requires learning a well-calibrated global score, since the heuristic becomes looser as the global score provides stronger penalties (Section 5).

As we explore the search graph, we incrementally construct a neural network, which computes representations of the parses and allows backpropagation of errors from bad search steps (Section 4).

In the following sections, we present our approach in detail, assuming an existing locally factored model s_{local}(e) for which we can efficiently compute an admissible A* heuristic h(e).

## 3 Model

Our model scores a hyperedge e by combining the score from the local model with a global score that conditions on the entire parse at the head node:

\[ s(e) = s_{local}(e) + s_{global}(e) \]

In s_{global}(e), we first compute a hidden representation encoding the parse structure of y = HEAD(e). We use a variant of the Tree-LSTM (Tai et al., 2015) connected to a bidirectional LSTM (Hochreiter and Schmidhuber, 1997) at the leaves. The combination of linear and tree LSTMs allows the hidden representation of partial parses to condition on both the partial structure and the full sentence. Figure 2 depicts the neural network that computes the hidden representation for a parse.

Formally, given a sentence (w_1, w_2, ..., w_n), we compute hidden states h_t and cell states c_t in the for-
ward LSTM for $1 < t \leq n$:
\[
\begin{align*}
i_t &= \sigma(W_i[c_{t-1}, h_{t-1}, x_t] + b_i) \\
o_t &= \sigma(W_o[c_t, h_{t-1}, x_t] + b_o) \\
\tilde{c}_t &= \tanh(W_c[h_{t-1}, x_t] + b_c) \\
c_t &= i_t \odot \tilde{c}_t + (1 - i_t)c_{t-1} \\
h_t &= o_t \odot \tanh(c_t)
\end{align*}
\]
where $x_t$ denotes a learned word embedding for $w_t$.

We also construct a backward LSTM, which produces the analogous hidden and cell states starting at the end of the sentence, which we denote as $c'_t$ and $h'_t$ respectively. The start and end latent states, $c_{-1}$, $h_{-1}$, $c'_{n+1}$, and $h'_{n+1}$, are learned embeddings. This variant of the LSTM includes peephole connections and couples the input and forget gates.

The bidirectional LSTM over the words serve as a base case when we recursively compute a hidden representation for the parse $y$ using the tree-structured generalization of the LSTM:
\[
\begin{align*}
i_y &= \sigma(W^R_i[c_l, h_l, h_r, x_y] + b^R_i) \\
f_y &= \sigma(W^R_f[c_l, c_r, h_r, x_y] + b^R_f) \\
o_y &= \sigma(W^R_o[\tilde{c}_y, h_l, h_r, x_y] + b^R_o) \\
c_{1r} &= f_y \odot c_l + (1 - f_y) \odot c_r \\
\tilde{c}_y &= \tanh(W^R_c[h_l, h_r, x_y] + b^R_c) \\
c_y &= i_y \odot \tilde{c}_y + (1 - i_y) \odot c_{1r} \\
h_y &= o_y \odot \tanh(c_y)
\end{align*}
\]
where the weights and biases are parametrized by the rule $R$ that produces $y$ from its children, and $x_y$ denotes a learned embedding for the category at the root of $y$. For example, in CCG, the rule would correspond to the CCG combinator, and the label would correspond to the CCG category.

We assume that nodes are binary, unary, or leaves. Depending on the number of children, the left and right latent states, $c_l$, $h_l$, $c_r$, and $c_r$ are defined differently:

- In a binary node, $c_l$ and $h_l$ are the cell and hidden states of the left child, and $c_r$ and $h_r$ are the cell and hidden states of the right child.
- In a unary node, $c_l$ and $h_l$ are learned embeddings, and $c_r$ and $h_r$ are the cell and hidden states of the singleton child.

This definition of the global score ensures that it is non-positive—an important property for inference.

4 Inference

Using the hyperedge scoring model $s(e)$ described in Section 3, we can find the highest scoring path that derives a complete parse tree by using the A* parsing algorithm described in Section 2.

Admissible A* heuristic Since our full model adds non-positive global scores to the existing local scores, path scores under the full model cannot be greater than path scores under the local model. Upper bounds for path scores under the local model also hold for path scores under the full model, and we simply reuse the A* heuristic from the local model to guide the full model during parsing without sacrificing optimality guarantees.
Each hyperedge computing it when provably unnecessary. We split to compute. We introduce an optimization to avoid Lazy global scoring. The global score is expensive which is crucial for efficient learning (see Section 5).

Propagation through the search space after decoding, the hypergraph. This not only enables quick for-structured LSTM mirroring the explored subset of each parse, we incrementally build a single DAG-in the neural network. By maintain the latent states of the children and compute \( s_{global}(e) \) with an incremental forward pass over a single recursive unit in the neural network. By maintain the latent states of each parse, we incrementally build a single DAG-structured LSTM mirroring the explored subset of the hypergraph. This not only enables quick forward passes during decoding, but also allows back-propagation through the search space after decoding, which is crucial for efficient learning (see Section 5).

**Incremental neural network construction** The recursive hidden representations used in \( s_{global}(e) \) can be computed in constant time during parsing. When scoring a new hyperedge, its children must have been previously scored. Instead of computing the full recursion, we reuse the existing latent states of the children and compute \( s_{global}(e) \) with an incremental forward pass over a single recursive unit in the neural network. By maintain the latent states of each parse, we incrementally build a single DAG-structured LSTM mirroring the explored subset of the hypergraph. This not only enables quick forward passes during decoding, but also allows back-propagation through the search space after decoding, which is crucial for efficient learning (see Section 5).

**Lazy global scoring** The global score is expensive to compute. We introduce an optimization to avoid computing it when provably unnecessary. We split each hyperedge \( e \) into two successive hyperedges, \( e_{local} \) and \( e_{global} \), as shown in Figure 3. The score for \( e \), previously \( s(e) = s_{local}(e) + s_{global}(e) \), is also split between the two new hyperedges: 

\[
\begin{align*}
    s(e_{local}) &= s_{local}(e_{local}) \\
    s(e_{global}) &= s_{global}(e_{global})
\end{align*}
\]

Intuitively, this transformation requires \( A^* \) to verify that the local score is good enough before computing the global score, which requires an incremental forward pass over a recursive unit in the neural network. In practice, the lazy global scoring reduces the number of recursive units by over 91%, providing a 2.4X speed up.

5 Learning

During training, we assume access to sentences labeled with gold parse trees. For each gold parse tree \( \hat{y} \), we denote the gold derivation as \( \hat{E} \), which is the unique path from \( \emptyset \) to \( \hat{y} \) in the parse forest.

The space of possible parses is far larger than can be searched exhaustively, so the model must be trained to efficiently search for \( \hat{y} \) given the sentence. To encourage this behavior, we optimize an objective that is tightly coupled with the search procedure. During parsing, we would like hyperedges from the gold derivation to appear at the top of the agenda \( A \). When this condition does not hold, \( A^* \) is searching inefficiently, and we refer to this as violation of the agenda, which we formally define as:

\[
v(\hat{E}, A) = \max_{e \in A} (g(\text{PATH}(e)) + h(e)) - \max_{e \in A \cap \hat{E}} (g(\text{PATH}(e)) + h(e))
\]

where \( g(\text{PATH}(e)) \) is the score of the unique path to \( e \), and \( h(e) \) is the \( A^* \) heuristic. If all violations are zero, we find the gold parse without exploring any incorrect partial parses. Figure 1b shows such a case—if any other nodes were explored, they would be violations.

We define loss functions over these violations, which are minimized to encourage correct and efficient search. During training, we parse each sentence until either the gold parse is found or we reach computation limits. We record \( \mathcal{V} \), the list of non-zero violations of the agenda \( A \) observed while parsing the training sentence:

\[
\mathcal{V} = \langle v(\hat{E}, A) | v(\hat{E}, A) > 0 \rangle
\]

We can optimize several loss functions over \( \mathcal{V} \), as defined in Table 1. The greedy, early, and max-violation updates are roughly analogous to the violation-fixing updates proposed by Huang et al. (2012), but adapted to exact agenda-based parsing. The gold parse is unreachable only when we terminate the search, since we do not prune the search space. Therefore, the loss of the early update corresponds to the last violation. We also introduce a
Table 1: Loss functions optimized by the different update methods. The updates depend on the list of $T$ non-zero violations, $V = \{V_1, V_2, \ldots, V_T\}$, as defined in Section 5.

| Update       | Loss($V$)       |
|--------------|-----------------|
| Greedy       | $V_1$           |
| Early        | $\sum_{t=1}^{T} V_t$ |
| Max violation| $\max_{t=1}^{T} V_t$ |
| All violations| $\sum_{t=1}^{T} V_t$ |

new all-violations update, which minimizes the sum of all observed violations. The all-violations update encourages correct parses to be explored early (similar to the greedy update) while being robust to parses containing multiple deviations from the gold parse (similar to the early and max-violation update).

The violation losses are optimized with subgradient descent and backpropagation. For our experiments, $s_{\text{local}}(e)$ and $h(e)$ are kept constant. Only the parameters $\theta$ of $s_{\text{global}}(e)$ are updated. Therefore, a subgradient of a violation $v(\hat{E}, A)$ can be computed by summing subgradients of the global score.

$$\frac{\partial v(\hat{E}, A)}{\partial \theta} = \sum_{e \in \text{PATH}(e_{\text{max}})} \frac{\partial s_{\text{global}}(e)}{\partial \theta} - \sum_{e \in \text{PATH}(\hat{e}_{\text{max}})} \frac{\partial s_{\text{global}}(e)}{\partial \theta}$$

where $e_{\text{max}}$ denotes the hyperedge at the top of the agenda $A$ and $\hat{e}_{\text{max}}$ denotes the hyperedge in the gold derivation $\hat{E}$ that is closest to the top of $A$.

6 Experiments

6.1 Data
We trained our parser on Sections 02-21 of CCGbank (Hockenmaier and Steedman, 2007), using Section 00 for development and Section 23 for test. To recover a single gold derivation for each sentence to use during training, we find the right-most branching parse that satisfies the gold dependencies.

6.2 Experimental Setup
For the local model, we use the supertag-factored model of Lewis et al. (2016). Here, $s_{\text{local}}(e)$ corresponds to a supertag score if a HEAD($e$) is a leaf and zero otherwise. The outside score heuristic is computed by summing the maximum supertag score for every word outside of each span. In the reported results, we back off to the supertag-factored model after the forest size exceeds 500,000, the agenda size exceeds 2 million, or we build more than 200,000 recursive units in the neural network.

Our full system is trained with all-violations updates. During training, we lower the forest size limit to 2000 to reduce training times. The model is trained for 30 epochs using ADAM (Kingma and Ba, 2014), and we use early stopping based on development F1. The LSTM cells and hidden states have 64 dimensions. We initialize word representations with pre-trained 50-dimensional embeddings from Turian et al. (2010). Embeddings for categories have 16 dimensions and are randomly initialized. We also apply dropout with a probability of 0.4 at the word embedding layer during training. The neural networks are implemented using the CNN library.

6.3 Baselines
We compare our parser to several baseline CCG parsers: the C&C parser (Clark and Curran, 2007); C&C + RNN (Xu et al., 2015), which is the C&C parser with an RNN supertagger; Vaswani et al. (2016) who combine a bidirectional LSTM supertagger with a beam search parser using global features (Clark et al., 2015); and supertag-factored (Lewis et al., 2016), which uses deterministic $A^*$ decoding and an LSTM supertagging model.

6.4 Parsing Results
Table 2 shows parsing results on the test set. Our global features let us improve over the supertag-factored model by 0.6 F1. Vaswani et al. (2016) also use global features, but our optimal decoding leads to an improvement of 0.4 F1.

On the test data, the parser finds the optimal parse for 99.9% sentences before reaching our computational limits. On average, we parse 27.1 sentences.

Table 2: Labeled F1 for CCGbank dependencies on the CCGbank development and test set for our system Global $A^*$ and the baselines.

| Model               | Dev F1 | Test F1 |
|---------------------|--------|---------|
| C & C               | 83.8   | 85.2    |
| C & C + RNN         | 86.3   | 87.0    |
| Vaswani et al.      | 87.8   | 88.3    |
| Supertag-factored   | 87.5   | 88.1    |
| Global $A^*$        | 88.4   | 88.7    |

1 https://github.com/clab/cnn
6.5 Model Ablations

We ablate various parts of the model to determine how they contribute to the accuracy and efficiency of the parser, as shown in Table 3. For each model, the comparisons include the average number of parses explored and the percentage sentences for which an optimal parse can be found without backing off.

**Structure ablation** We first ablate the global score, $s_{global}(y)$, from our model, thus relying entirely on the local supertag-factors that do not explicitly model the parse structure. This ablation allows dynamic programming and is equivalent to the backoff model (supertag-factored in Table 3). Surprisingly, even in the exponentially larger search space, the global model explores fewer nodes than the supertag-factored model—showing that the global model efficiently prune large parts of the search space. This effect is even larger when not using dynamic programming in the supertag-factored model.

**Global structure ablation** To examine the importance of global features, we ablate the recursive hidden representation (span-factored in Table 3). The model in this ablation decomposes over labels for spans, as in Durrett and Klein (2015). In this model, the recursive unit uses, instead of latent states from its children, the latent states of the backward LSTM at the start of the span and the latent states of the forward LSTM at the end of the span. Therefore, this model encodes the lexical information available in the full model but does not encode the parse structure beyond the local rule production. While the dynamic program allows this model to find the optimal parse with fewer explorations, the lack of global features significantly hurts its parsing accuracy.

**Lexical ablation** We also show lexical ablations instead of structural ablations. We remove the bidirectional LSTM at the leaves, thus delexicalizing the global model. This ablation degrades both accuracy and efficiency, showing that the model uses lexical information to discriminate between parses. To understand the importance of contextual information, we also perform a partial lexical ablation by using word embeddings at the leaves instead of the bidirectional LSTM, thus propagating only lexical information from within the span of each parse. The degradation in F1 is about half of the degradation from the full lexical ablation, suggesting that a significant portion of the lexical cues comes from the context of a parse.

6.6 Update Comparisons

Table 4 compares the different violation-based learning objectives, as discussed in Section 5. Our novel all-violation updates outperform the alternatives. We attribute this improvement to the robustness over poor search spaces, which the greedy update lacks, and the incentive to explore good parses early, which the max-violation and early updates lack. Learning curves in Figure 4 show that the all-violations update also converges more quickly.

6.7 Decoder Comparisons

Lastly, to show that our parser is both more accurate and efficient than other decoding methods, we decode our full model using best-first search, reranking, and beam search. Table 5 shows the F1 scores with and without the backoff model, the portion of

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**Table 3:** Ablations of our full model (Global A*) on the development set. *Explored* refers to the size of the parse forest. Results show the importance of global features and lexical information in context.

| Model                   | Dev F1 | Optimal | Explored |
|-------------------------|--------|---------|----------|
| Supertag-factored       | 87.5   | 100.0%  | 402.5    |
| – dynamic program       | 87.5   | 97.1%   | 17119.6  |
| Span-factored           | 87.9   | 99.9%   | 176.5    |
| – dynamic program       | 87.8   | 99.5%   | 578.5    |
| Global A*               | 88.4   | 99.8%   | 309.6    |
| – lexical inputs        | 87.8   | 99.6%   | 538.5    |
| – lexical context       | 88.1   | 99.4%   | 610.5    |

**Table 4:** Parsing results trained with different update methods. Our full system uses all-violations updates and is the most accurate.
Table 5: Comparison of various decoders using the same model from our full system (Global A*). We report F1 with and without the backoff model, the percentage of sentences that the decoder can parse, and the time spent decoding relative to A*.

| Decoder               | Dev F1 | Dev F1 backoff | Relative Time |
|-----------------------|--------|----------------|---------------|
| Global A*             | 88.4   | 88.4 (99.8%)   | 1X            |
| Best-first            | 87.5   | 2.8 (6.7%)     | 293.4X        |
| 10-best reranking     | 87.9   | 87.9 (99.7%)   | 8.5X          |
| 100-best reranking    | 88.2   | 88.0 (99.4%)   | 72.3X         |
| 2-best beam search    | 88.2   | 85.7 (94.0%)   | 2.0X          |
| 4-best beam search    | 88.3   | 88.1 (99.2%)   | 6.7X          |
| 8-best beam search    | 88.2   | 86.8 (98.1%)   | 26.3X         |

the sentences that each decoder is able to parse, and the time spent decoding relative to the A* parser.

In the best-first search comparison, we do not include the informative A* heuristic, and the parser completes very few parses before reaching computational limits—showing the importance of heuristics in large search spaces. In the reranking comparison, we obtain n-best lists from the backoff model and rerank each result with the full model. In the beam search comparison, we use the approach from Clark et al. (2015) which greedily finds the top-n parses for each span in a bottom-up manner. Results indicate that both approximate methods are less accurate and slower than A*.

7 Related Work

Many structured prediction problems are based around dynamic programs, which are incompatible with recursive neural networks because of their real-valued latent variables. Some recent models have neural factors (Durrett and Klein, 2015), but these cannot condition on global parse structure, making them less expressive. Our search explores fewer nodes than dynamic programs, despite an exponentially larger search space, by allowing the recursive neural network to guide the search.

Previous work on structured prediction with recursive or recurrent neural models has used beam search—e.g. in shift reduce parsing (Dyer et al., 2015), string-to-tree transduction (Vinyals et al., 2015), or reranking (Socher et al., 2013)—at the cost of potentially recovering suboptimal solutions. In our setting, beam search is both less efficient and less accurate than optimal A* decoding. The CCG parser of Clark et al. (2015), most related to this work, also uses global features with a beam search parser. By using neural representations and exact search, we are able to improve over their results.

There have been several attempts to predict structures using A* parsing for locally factored models (Klein and Manning, 2003; Auli and Lopez, 2011; Lewis and Steedman, 2014). We generalize these methods to enable global features. Vaswani and Sagae (2016) apply best-first search to an unlabeled shift-reduce parser. Their use of error states is related to our global model that penalizes local scores. We demonstrated that best-first search is infeasible in our setting, due to the larger search space.

SEARN (Daumé III et al., 2009) learns a greedy policy for structured prediction by sampling classification examples over actions from single states. We similarly generate classification examples over hyperedges in the agenda, but we allow actions from multiple states to compete against each other.

8 Conclusion

We have shown for the first time that a parsing model with global features can be decoded with optimality guarantees. This enables the use of powerful recursive neural networks for parsing without resorting to approximate decoding methods. Experiments show that this approach is effective for CCG parsing, resulting in a new state-of-the-art parser. In future work, we will apply our approach to other structured prediction tasks, where neural networks—and greedy beam search—have become ubiquitous.
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