

# Discontinuous Combinatory Constituency Parsing

Zhousi Chen and Mamoru Komachi

Faculty of Systems Design  
Tokyo Metropolitan University  
6-6 Asahigaoka, Hino, Tokyo 191-0065, Japan  
{chen-zhousi@ed., komachi@}tmu.ac.jp

## Abstract

We extend a pair of continuous combinator-based constituency parsers (one binary and one multi-branching) into a discontinuous pair. Our parsers iteratively compose constituent vectors from word embeddings without any grammar constraints. Their empirical complexities are subquadratic. Our extension includes 1) a *swap* action for the orientation-based binary model and 2) biaffine attention for the chunker-based multi-branching model. In tests conducted with the Discontinuous Penn Treebank and TIGER Treebank, we achieved state-of-the-art discontinuous accuracy with a significant speed advantage.

## 1 Introduction

Discontinuity is common in natural languages, as illustrated in Figure 1. Children from a discontinuous constituent are not necessarily consecutive because each can group with its syntactic cousins in the sentence rather than its two adjacent neighbors. Although this relaxation makes discontinuous parsing more challenging than continuous parsing, it becomes more valuable for studies and applications in non-configurational languages (Johnson, 1985), where word order does not determine grammatical function. With gradually saturated continuous parsing accuracy (Zhou and Zhao, 2019; Kitaev and Klein, 2018, 2020; Xin et al., 2021), discontinuous parsing has started gaining more attention (Fernández-González and Gómez-Rodríguez, 2020a, 2021; Corro, 2020).

Typically, constituency parsers are divided into two genres (not including methods employing dependency parsing, e.g., Fernández-González and Gómez-Rodríguez [2020b]): 1) Global parsers use a fixed chart to search through all parsing possibilities for a global optimum. 2) Local parsers rely on fewer local decisions, which leads to lower complexities. The global parser complexi-

ties start at least from binary  $O(n^3)$  (Kitaev and Klein, 2018) or  $m$ -ary  $O(n^4)$  (Xin et al., 2021), resulting in low speeds for long parses. Global parsers introduce numerous hypotheses, whereas a local shift-reduce process or incremental parse exhibits more linguistic interests with fewer outputs (Yoshida et al., 2021; Kitaev et al., 2022). Neural global parsers dominate both continuous and discontinuous parsing (Corro, 2020; Ruprecht and Mörbitz, 2021) in terms of F1 score, but they do not exhibit a strong accuracy advantage over other parsers. Although local parsers may in some cases produce ill-formed trees, global parsers do not guarantee the selection of gold-standard answers from their charts.

We propose extending a pair of local parsers to achieve high speed, accuracy, and convenient investigation for both binary and multi-branching parses. Chen et al. (2021) proposed a pair of continuous parsers employing bottom-up vector compositionality. We dub these as neural combinatorial constituency parsers (**NCCP**) with binary **CB** and multi-branching **CM**. To the best of our knowledge, they possess the top parsing speeds for continuous constituency. **CB** reflects a linguistic branching tendency, whereas **CM** represents unsupervised grammatical headedness through composition weight. **CM** is among the few parsers that do not require preprocessing binarization (Xin et al., 2021) but possess a high parsing speed. We dub our extension as **DCCP** with binary **DB** and multi-branching **DM**. The mechanisms with neural discontinuous combinators are shown in Figure 2.

Specifically, our combinators take a sentence-representing vector sequence as input and predict layers of concurrent tree-constructing actions. Two mechanisms are employed. **DB** triggers an action if the orientations of two neighboring vectors agree. A *swap* action exchanges the vectors;

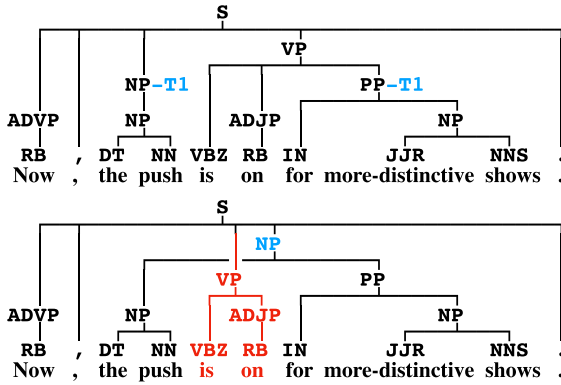


Figure 1: Evang and Kallmeyer (2011, DPTB) recover discontinuity from continuous Penn Treebank (Marcus et al., 1993, PTB) with trace nodes (blue).

a *joint* action composes a new vector with them. **CB** only possesses a *joint* action. Meanwhile, **DM** takes discontinuous vectors to form biaffine attention matrices and decides their groups collectively; the remaining continuous vectors resort to chunking decisions, as with **CM**. **NCCP** and **DCCP** are unlexicalized supervised greedy parsers.

The contributions of our study are as follows:

- We propose a pair of discontinuous parsers<sup>1</sup> (i.e., binary and multi-branching) by extending continuous parsers of Chen et al. (2021).
- We demonstrate the effectiveness of our work on the Discontinuous Penn Treebank (Evang and Kallmeyer, 2011, DPTB) and the TIGER Treebank (Brants et al., 2004). Our parsers achieve new state-of-the-art discontinuous F1 scores and parsing speeds with a small set of training and inferring tricks, including discontinuity as data augmentation, unsupervised headedness, automatic hyperparameter tuning, and pre-trained language models.

## 2 Related Work

**Global Parsing.** The chart for binary continuous parsing (Kitaev and Klein, 2018) is triangular, as shown in black in Figure 3. The horizontal dimension enumerates the position of each node (i.e., each bit as a word). The vertical C indicates the number of continuous cases included in each node. Nodes at height  $h$  share combinatorics of

<sup>1</sup> Our code with all model configuration files is available at <https://github.com/tmu-nlp/UniTP>.

complexity  $h$ . Consequently, a binary continuous chart parser has a fixed  $\sum_{h=0}^n (n-h) \cdot h \sim O(n^3)$  complexity for the CKY decoding algorithm.

In  $m$ -ary and/or discontinuous cases (i.e., for multi-branching arity  $m$  and/or fan-out  $k$  of each constituent), the chart is superior to that of binary continuous parsing in terms of complexity. Both horizontal and vertical axes expand to diversify the combination of discrete bits of each lexical node. Because of the expansion,  $m$ -ary continuous global parsing (Xin et al., 2021) has  $O(n^4)$  complexity, whereas binary discontinuous parsing has exponential complexity at  $O(n^{3k})$  (Corro, 2020; Stanojevic and Steedman, 2020), where  $k \in \{1, 2\}$  are special cases for binary CFG (likely in Chomsky Normal Form [CNF]) and binary Linear Context-Free Rewriting Systems with maximum fan-out 2 (Stanojevic and Steedman, 2020, LCFRS-2).  $M$ -ary discontinuous parsing, which certainly has a higher complexity, is not yet available for global parsing.

For efficiency, expensive rules are commonly restricted by LCFRS-2 parsers (Corro, 2020; Stanojevic and Steedman, 2020; Ruprecht and Mörbitz, 2021). A tricky  $O(n^3)$  variant of Corro (2020) covering major rules has produced the best results. However, the variant excludes 2% sophisticated discontinuous rules on TIGER Treebank. Limited by the simplified grammar, their discontinuous scores are low, especially for recalls. A global optimum does not guarantee a gold parse, leaving room for local parsing.

**Local Parsing.** Local parsers do not observe the chart framework and only consider one greedy or a few hypotheses. **Transition-based** parsers with a *swap* or *gap* action have sequential actions and low complexities (Maier, 2015; Coavoux and Crabbé, 2017). Multiple *swaps* or *gaps* combine to construct a large discontinuous constituent. In contrast, **stack-free** parsing can directly pick up a distant component with one attachment search (Coavoux and Cohen, 2019). **Easy-first** (Nivre et al., 2009; Versley, 2014) and **chunker-based** (Ratnaparkhi, 1997; Collobert, 2011) run rapidly.

Fernández-González and Gómez-Rodríguez (2020a) redirected discontinuity to **dependency** parsing via pointer networks and obtained significant accuracy improvement among greedy parsers. However, it is difficult to determine whether such improvement originates from the model or the extra head information. In contrast, Fernández-

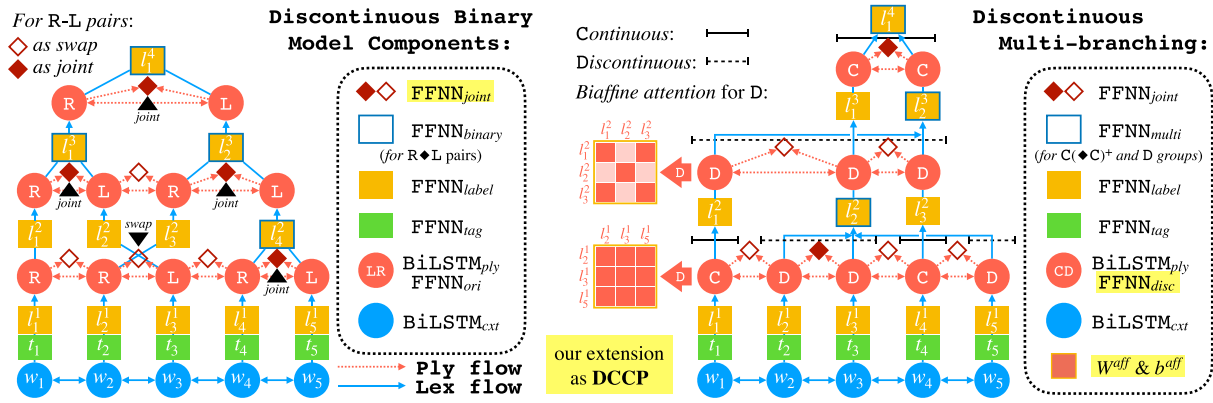


Figure 2: Mechanism examples. Left: **DB** produces *swap* to facilitate traveling of discontinuous nodes and *joint* to combine adjacent nodes. Right: **DM** leverages biaffine attention to identify and combine discontinuous groups.

Layer & Fan-out	Bits	#×C	#×D
#3 $k = 1$	1111	1 × 3	1 × 7
#2 $k = 2$	1101 1011	2 × 2	4 × 3
#2 $k = 1$	1110 0111	2 × 2	
#1 $k = 2$	1010 1001 0101	3 × 1	6 × 1
#1 $k = 1$	1100 0110 0011	3 × 1	
#0 $k = 1$	1000 0100 0010 0001	0	0

Figure 3: Fan-out and input sizes increase Continuous and Discontinuous combinatory global parser cases.

González and Gómez-Rodríguez (2020b) **reordered** input words in at most  $O(n^2)$  complexity and redirected to various continuous parsers.

### 3 Discontinuous Combinatory Parsing

We call a level of partial derivations or subtrees a **ply** (Jurafsky and Martin, 2009), as depicted in Figure 4. Similar to the state of a transition-based parser, each of which leads to an action, ply is the state for **DCCP**, each of which leads to a sequence of concurrent actions for itself.

Starting with a sequence of words  $(x_1, \dots, x_n)$  as an initial ply, we assemble an unlabeled discontinuous parse tree in a bottom-up manner by applying concurrent actions to the roots of subtrees in the ply and iterating until sequence length  $n = 1$ .

#### 3.1 Binary Ply: Joint and Swap

For a binary tree, two actions are sufficient:

$$\begin{aligned}
 action(x_i \oplus x_{i+1}) &\in \{joint, swap\} \\
 joint : compose(x_i, x_{i+1}) &\rightarrow x_i \\
 swap : (x_i, x_{i+1}) &\rightarrow (x_{i+1}, x_i).
 \end{aligned} \quad (1)$$

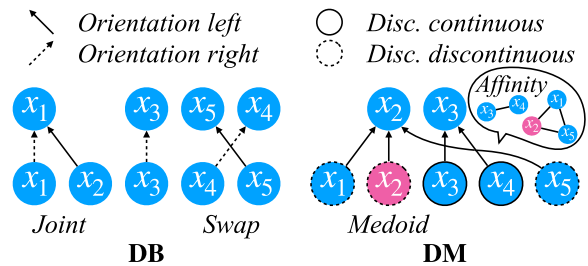


Figure 4: **DCCP** plies with concurrent actions.

One *joint* reduces the sequence length by one; the *swap* does not affect the sequence length but affects its order. The binary function *compose* is a binary neural combinator. The concatenation “ $\oplus$ ” only works for adjacent nodes.

However, concurrent adjacent actions would conflict in a ply (e.g., two *swaps* for  $(x_1, x_2, x_3)$  leaves an undecidable  $x_2$ ). In other words, they need a resolution. We adopt a solution of

$$\begin{aligned}
 orientation(x_i) &\in \{0, 1\} \\
 orientation(x_i) - orientation(x_{i+1}) &= 1,
 \end{aligned} \quad (2)$$

where each *orientation* indicates either *left* (0) or *right* (1) and the adjacent node pair of  $(x_i, x_{i+1})$  contains the agreeing orientations. Thus, only under this circumstance, **DB** activates *joint* or *swap* by  $action(x_i \oplus x_{i+1})$  without conflict.

**Summary.** All nodes in a **DB** ply are derived by Formula 1 under the condition of Formula 2 to form a new ply. As exemplified in Figure 4 for **DB**,  $(x_1, x_2)$  and  $(x_4, x_5)$  meet the condition of Formula 2 and have respective *joint* and *swap* actions. Meanwhile,  $x_3$  takes neither action and remains in the ply, because the *orientations* of  $x_2$

and  $x_4$  do not agree with  $x_3$ , regardless of  $x_3$ 's orientation.

### 3.2 Multi-branching Ply: Affinity and Chunk

We characterize whether  $x_i$  and  $x_j$  from a ply are two siblings of the same parent constituent as

$$\text{affinity}(x_i, x_j) \in \{0, 1\}, \quad (3)$$

where 0 denotes false and 1 denotes true. Thus, **DM** decides a *discontinuity* action of  $x_i$  and then forwards it to a group action for either a *discontinuous* or *continuous* constituent as in Formula 4:

$$\begin{aligned} & \text{action}(x_i) \in \{\text{discontinuous}, \text{continuous}\} \\ & \text{discontinuous :} \\ & \mathcal{G} = \{x_j \mid \text{affinity}(x_i, x_j) = 1\} \\ & \text{medoid} \in \{j \mid x_j \in \mathcal{G}\} \\ & \text{compose}(\mathcal{G}) \rightarrow x_{\text{medoid}} \\ & \text{continuous :} \\ & \mathcal{G} = \{x_j \mid lb < i \leq rb, lb < j \leq rb, \text{ and} \\ & \text{affinity}(x_j, x_{j+1}) = \mathbb{1}(j \notin \{lb, rb\})\} \\ & \text{compose}(\mathcal{G}) \rightarrow x_{lb+1}, \end{aligned} \quad (4)$$

whereas “ $\mathbb{1}(\cdot)$ ” is the indicator function. We select one *medoid* for each *discontinuous* constituent to determine its position in the modified ply, whereas the choice of *medoid* for *continuous* constituents makes no difference. *Continuous* nodes split into segments of  $(x_{lb+1}, \dots, x_{rb})$  with  $(lb, lb + 1)$  and  $(rb, rb + 1)$  as boundaries. Function *compose* is a flexible  $m$ -ary neural combinator with  $m \in \mathbb{N}$ .

Dozat and Manning (2017) characterized each dependency tree as a sparse asymmetric matrix via biaffine attention, with each sole positive signal in a row (or column) indicating a lexical dependency (from a word to its head or vice versa). Nevertheless, lexical dependency is not available for constituency parsing, and biaffine attention becomes expensive at  $O(n^2)$  complexity.

In contrast, we designate *discontinuous affinity* as a small dense symmetric biaffine attention matrix and control its computational size of  $O(n^2)$ . Otherwise, *continuous affinity* for adjacent nodes takes a special form of

$$\text{chunk}(x_i \oplus x_{i+1}) = \text{affinity}(x_i, x_{i+1})$$

with a simpler  $O(n)$  complexity.

**Summary.** Via fast chunking or a small biaffine attention matrix, **DM** balances to increase its efficiency. As exemplified in Figure 4 for **DM**, *discontinuous*  $(x_1, x_2, x_5)$  are grouped as one because of their mutual *affinity*, which is equivalent to a  $3 \times 3$  biaffine attention matrix of ones. Node  $x_2$  is selected as the *medoid* for the constituent's location in the new ply. Meanwhile, *continuous*  $(x_3, x_4)$  forms a constituent for  $\text{chunk}(x_i \oplus x_{i+1}) = \text{affinity}(x_i, x_{i+1}) = \mathbb{1}(i \notin \{2, 4\})$  and  $i \in [2, 4]$ .

### 3.3 Oracle

We state the conversion from tree into layers of action signals for fully supervised training. For convenience, we merge **DM**'s *chunk* semantics into *joint* to unify **DB**'s and **DM**'s interstice signals. The common signals are

$$(x_{1:n}, t_{1:n}, l_{1:n_h}^{1:H}, j_{1:n_h-1}^{1:H-1}),$$

where  $x$  represents a sentence with  $n$  words,  $n$  POS tags,  $H$  layers of labels, and  $H - 1$  layers of joints, respectively. “:” indicates sequence range (e.g., ply height  $h \in [1, H]$ ). **DB** features in

$$(o_{1:n_h}^{1:H-1}),$$

containing  $H - 1$  layers of orientations. For **DM**, our extension includes *discontinuity* and *affinity* biaffine attention matrices with *medoids*,

$$(d_{1:n_h}^{1:H-1}, a_{[1:d_h, 1:d_h]}^{1:H-1}),$$

where  $d_h = \sum_{i=1}^{n_h} d_i^h \leq n_h$  indicates a number of discontinuous nodes that is no larger than the number of total nodes in layer  $h$ .

**Empty Node and Unary Branch.** Similar to a range of previous works (Chen et al., 2021; Shen et al., 2018; Kitaev and Klein, 2020; Corro, 2020), we adopt an empty label “ $\emptyset$ ” for our substructure (e.g., binarization). Additionally, we collapse each unary branch into a single node and join their constituent labels according to their hierarchical order (e.g., S+VP as derivation  $S \rightarrow VP$ ) with easy restoration during inference. Unary collapse is productive for label type, as shown in Table 1.

**Binarization  $\rho^{\text{DB}}$ .**  $C$  children of a constituent join one by one via their *orientation* and *joint* signals. For  $c \in [1, C)$ ,  $[1, c]$ -th children are set to *orientation right* (1) and  $(c, C]$ -th are set to

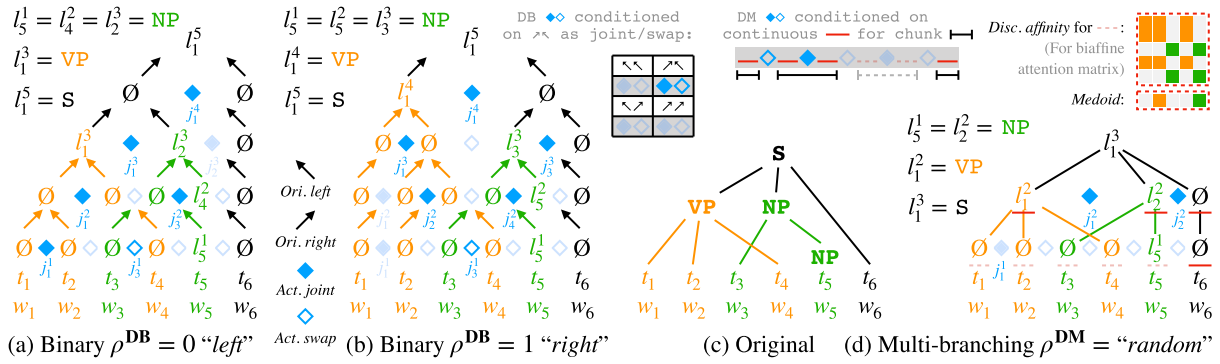


Figure 5: Examples illustrating the principle of stratification. The original m-ary tree (c) is binarized and stratified into (a) and (b) with numeric factors  $\rho^{\text{DB}}$ , whereas (c) is stratified into (d) with a categorical *medoid* factor *random*. In (d),  $w_2$  and  $w_5$  are randomly selected as *medoids* for discontinuous parents  $l_1^2$  and  $l_1^2$  with more or less twisted descendant lines. We color constituent components and show disabled *joints* with light blue “ $\diamond$ ” and “ $\circ$ .”

Corpus	Label Type		Label Token
	Total	Collapsed	Frequency%
DPTB	126	99	3.82%
TIGER	80	55	0.72%

Table 1: Label type and token in our oracle format.

*orientation left* (0). Neighboring children have positive *joint* signals if they are siblings. Otherwise, negative *joints* swap them toward their siblings. We normalize a factor  $\rho^{\text{DB}} = \frac{c-1}{C-2} \in [0, 1]$  for treebank binarization. In continuous parsing,  $\rho^{\text{DB}} \in \{0, 1\}$  implies CNF.

As illustrated in Figure 5 (a) & (b), we obtain layers of action signals from the binarization of (c). As an extension to CNF, we use the beta distribution  $\rho^{\text{DB}} \sim \text{Beta}(\alpha_{\text{left}}, \alpha_{\text{right}}) \in (0, 1)$  to create augmented samples with  $\alpha_{\text{left}}, \alpha_{\text{right}} \in (0, +\infty)$ .

**Medoid  $\rho^{\text{DM}}$ .** We use a set of categorical *medoid* factors  $\rho^{\text{DM}} \in \{\text{random}, \text{leftmost}, \text{rightmost}\}$  to stratify a multi-branching tree: 1) *random* picks a random child with uniform probability, whereas 2) *leftmost* and 3) *rightmost* take the two ends of a discontinuous group.

In Figure 5 (d),  $w_1$  and  $w_4$  are randomly selected as *medoids*. Meanwhile,  $l_1^2$  and  $l_1^2$  would exchange their places if  $w_3$  and  $w_4$  were selected. *Medoid* is different from headedness (Zwicky, 1985). It is an intermediate variable for locating a discontinuous constituent.

### 3.4 Model Implementation

NCCP and DCCP have the same bottom-up iteration on a *ply* and share two types of neu-

### Algorithm 1: Combinatory Parsing

```

1 Function PARSE ( $x_{1:n}$ ):
2    $ply \leftarrow []$  and  $n_h \leftarrow n$  with height  $h \leftarrow 1$ ;
3    $x_{1:n_h}^h \leftarrow \text{BiLSTM}_{\text{cxt}}(\text{embeddings of } x_{1:n});$ 
4   for  $i \leftarrow 1$  to  $n$  do
5      $\hat{t}_i \leftarrow \text{FFNN}_{\text{tag}}(x_i^h);$ 
6      $\hat{l}_i^h \leftarrow \text{FFNN}_{\text{label}}(x_i^h);$ 
7     append a tree with  $(x_i, \hat{t}_i, \hat{l}_i^h)$  to  $ply$ ;
8   while  $n_h > 1$  do
9      $z_{1:n_h}^h \leftarrow \text{BiLSTM}_{\text{ply}}(x_{1:n_h}^h);$ 
10     $x_{1:n_{h+1}}^{h+1} \leftarrow \text{FOLD}(ply, x_{1:n_h}^h, z_{1:n_h}^h);$ 
11     $h \leftarrow h + 1$ ;
12    for  $i \leftarrow 1$  to  $n_h$  do
13       $\hat{l}_i^h \leftarrow \text{FFNN}_{\text{label}}(x_i^h);$ 
14      label  $i$ -th tree of  $ply$  with  $\hat{l}_i^h$ ;
15  return the sole tree in  $ply$ ;

```

ral components: bidirectional Long Short-Term Memory (BiLSTM) and feedforward neural network (FFNN).

In Algorithm 1,  $\text{BiLSTM}_{\text{cxt}}$  contextualizes the sequence of words  $x_{1:n}$  as embeddings  $x_{1:n_h}^1$  and  $\text{BiLSTM}_{\text{ply}}$  contextualizes the ply sequence  $x_{1:n_h}^h$  for either **DB** FOLD in Algorithm 2 or **DM** FOLD in Algorithm 3, either of which modifies *ply* and constructs new layers of embeddings  $x_{1:n_{h+1}}^{h+1}$ . The necessity of  $\text{BiLSTM}_{\text{cxt}}$  and  $\text{BiLSTM}_{\text{ply}}$  contextualization was empirically examined with NCCP. Meanwhile,  $\text{FFNN}_{\text{tag}}$  and  $\text{FFNN}_{\text{label}}$  predict the lexical tags and constituent labels based on contextualized individual embeddings without grammar constraint.

When actions do not modify *ply* at inference phase, PARSE terminates with a VROOT label for the current *ply*. We define CONDENSE as a

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**Algorithm 2: Binary Ply**

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```

1 Function FOLD ( $ply, x_{1:n}, z_{1:n}$ ):
2   for  $i \leftarrow 1$  to  $n$  do
3      $\hat{o}_i^h \leftarrow \text{FFNN}_{ori}(z_i)$ ;
4      $\hat{j}_i^h \leftarrow \text{FFNN}_{joint}(z_i \oplus z_{i+1})$ ;
5     w.r.t. Subsection 3.1, apply actions to  $ply$ 
       and  $x_i \leftarrow \text{COMPOSE}(x_i, x_{i+1})$ ;
6   return CONDENSE ( $x_{1:n}$ );
7 Function COMPOSE ( $x_L, x_R$ ):
8    $\lambda \leftarrow \sigma \text{FFNN}_{binary}(x_L \oplus x_R)$ ;
9   return  $\lambda \odot x_L + (1 - \lambda) \odot x_R$ ;

```

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process reenumerating ply nodes regardless their inconsecutive and unordered indices following the actions (e.g.,  $\text{CONDENSE}(x_1, x_3, x_5, x_4) \rightarrow (x_1, x_2, x_3, x_4)$ )

$$\text{CONDENSE} : (n \text{ ply nodes}) \rightarrow (x_1, \dots, x_n)$$

**Binary Combinator.** The FOLD of **DB** is shown in Algorithm 2. The COMPOSE function uses sigmoid activation “ $\sigma$ ” to create a pair of complementary gates  $\lambda$  and  $(1 - \lambda)$  for  $x_L$  and  $x_R$ .  $\lambda$  is a vector of the same size as the embeddings.

**Multi-branching Combinator.** The **DM** FOLD has vectors  $z_{1:n}$  and  $\Delta_{1:n}$  in exchangeable shapes in Algorithm 3. We choose  $\Delta_{1:n}$  because it performs empirically optimal. Otherwise, Algorithms 2 and 3 should look more identical. Meanwhile,  $\lambda_i$  in COMPOSE with  $\sum_i^G \lambda_i = \mathbf{1}$  from *Softmax* is the adaptive gating vector for  $x_i$ . We consider the average of  $\lambda_i$  (i.e.,  $\bar{\lambda}_i$ ) as the *unsupervised headedness* for inference and visualization. Thus, **DM** is able to *infer* with a special factor:

$$\rho^{\text{DM}} = u_{\text{head}},$$

which takes  $\text{medoid} \leftarrow \arg \max_{i \in G} \bar{\lambda}_i$  as the group medoid.

To identify discontinuous groups in the *affinity* biaffine attention matrix, **DM** takes  $M = \sigma \hat{a}_{[1:D, 1:D]}^h$  for value range  $(0, 1)$  ( $D = \sum_i \hat{d}_i^h$ ) and booleanizes it into  $B \leftarrow M > \theta$ . It 1) tries default threshold  $\theta = 0.5$  as the natural selection for sigmoid activation and **checks** whether all the following statements are true:

- $B$  is symmetric (i.e.,  $B = B^\top$ ),
- any rows  $v, w \in B$  are  $v \neq 0$ ,
- either  $v = w$  or  $v^\top \cdot w = 0$ .

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**Algorithm 3: Multi-branching Ply**

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```

1 Function FOLD ( $ply, x_{1:n}, z_{1:n}$ ):
2    $(\bar{z}_{1:n} \oplus \bar{z}_{1:n}) \leftarrow z_{1:n}$  (forward & backward);
3   for  $i \leftarrow 1$  to  $n$  do
4      $\hat{d}_i^h \leftarrow \text{FFNN}_{disc}(z_i)$ ;
5      $\Delta_i \leftarrow (\bar{z}_i - \bar{z}_{i-1}) \oplus (\bar{z}_i - \bar{z}_{i+1})$ ;
6      $\hat{j}_i^h \leftarrow \text{FFNN}_{joint}(\Delta_i \oplus \Delta_{i+1})$ ;
7     foreach  $i, j$ -th discontinuous  $\hat{d}_{v,w}^h$  do
8        $\hat{a}_{[i,j]}^h \leftarrow x_v^\top \cdot W^{\text{aff}} \cdot \Delta_w + b^{\text{aff}}$ ;
9     find discontinuous groups by checking  $\hat{a}^h$ ;
10    foreach group indices  $\mathcal{G}$  and its medoid do
11      w.r.t Subsection 3.2, apply actions to  $ply$ 
        and  $x_{\text{medoid}} \leftarrow \text{COMPOSE}(\Delta_{\mathcal{G}}, x_{\mathcal{G}})$ ;
12    return CONDENSE ( $x_{1:n}$ );
13 Function COMPOSE ( $\Delta_{\mathcal{G}}, x_{\mathcal{G}}$ ):
14    $\lambda_{\mathcal{G}} \leftarrow \text{Softmax}(\text{FFNN}_{multi}(\Delta_{\mathcal{G}}))$ ;
15   return  $\sum_i^{\mathcal{G}} \lambda_i \odot x_i$ ;

```

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It succeeds in most cases. Otherwise, it 2) tries a value from  $M$  as  $\theta$ , **checks** and loops again. We order the thresholds by their distances to the default 0.5. If all 2) fail, it 3) simply falls back into grouping all nodes as one and counts one FAIL.

**Basic Losses.** We choose HINGE-LOSS for binary prediction and CROSS-ENTROPY for multi-class prediction, following **NCCP**. Respecting the context in Algorithms 1–3, our basic loss items are

$$L_{\text{tag}}, L_{\text{label}}, L_{\text{ori}}, L_{\text{jnt}}, L_{\text{disc}}, L_{\text{aff}}^D$$

by accumulating their items across all layers. For example,  $L_{\text{aff}}^D \leftarrow \sum_{i,j,h} \text{HINGE-LOSS}(a_{[i,j]}^h, \hat{a}_{[i,j]}^h)$  with  $D$  for *discontinuous affinity*. We have additional loss items in the next subsection.

**Complexity.** Extreme cases provide the upper bounds for our theoretical complexity. **DB** takes  $\frac{n}{2}$  fully swapping plies and  $\frac{n}{2}$  fully joining plies. Each ply costs  $O(n)$  recurrency; the bound is  $O(n^2)$ . Every **DM** ply involves a matrix for all nodes and decreases  $n$  only by one. Assume that we limit **check** 2) to some fixed sizes. Each ply costs  $O(n^2)$ ; the bound is  $O(n^3)$ .

However, **DCCP** has an empirical  $O(n^2)$  complexity with strong linearity, as shown in Figure 6. **DB** has higher linear coefficients because of its slow binary combination. Meanwhile, **DM** shows stronger quadratic tendency because of biaffine



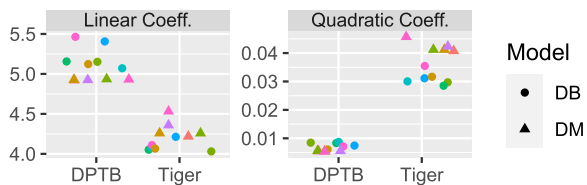


Figure 6: Quadratic linear regression (LR) on sentence length vs. parsing node count on stratified **DCCP** treebanks. **DM** counts in biaffine attention matrix nodes. Colors show binarization and medoid strategies. Cubic LR gives all negative cubic terms highly close to zero.

attention. Yet, their coefficient magnitudes are on par with one another.

### 3.5 Training Tricks

**Data Augmentation.** Figure 7 first summarizes (e) basic data augmentation with binarization for **DB** and *medoid* for **DM** (including (a), (b), and (d) in Figure 5). The beta distribution can resemble a uniform *random* distribution or other biased distributions to detect linguistic branching tendency with specific  $(\alpha_{left}, \alpha_{right})$ .

Then, we further leverage the intermediate non-terminal node “ $\emptyset$ ” to create more  $\emptyset$ -subtrees. The augmentation is an inspiration of **CM**’s deterministic `_SUB` node, which balances subtree heights and boosts both accuracy and efficiency. (Non-`_SUB` trees remain at their original heights.) However, (g)  $\emptyset$ -subtree is random and creates imbalance. It creates only one stretching branch by iteratively grouping nodes with possibility  $\rho_{\emptyset}$ , which has three significant impacts:

- Random stretching branches add mild variations to the context as states for robust ply actions in `FOLD`.
- Random discontinuity creates **DB** orientation layers that cannot be created by  $\rho^{\text{DB}}$  binarization.
- They reduce large (possibly continuous) constituents into smaller (possibly discontinuous) pieces without adding a large payload to the biaffine attention, which narrows the gap between **DB** and **DM** (**DM** is more vulnerable to dramatic many-to-one `COMPOSE`).

Taking NP “a good day” for instance, any of “a day,” “a good,” and “good day” can be an

intermediate option for creating the NP. On the one hand, these options create varied contexts for the remaining parts of a ply. On the other hand, assume that “a day” (which is not a  $\rho^{\text{DB}}$  product) is selected. **DM** learns to discern it with the other possible “a day” in biaffine attention based on their context.

**Model Robustness.** To further randomize **DB** training, we introduce (f) *ply shuffle* and its resultant losses  $L_{ori}^{shfl}$  and  $L_{jnt}^{shfl}$ . It shuffles  $x_{1:n_h}^h$  with respect to each constituent, takes the new sequence to `BiLSTMply` and `FOLD`, and reuses the ply of *orientation* and *joint* for those additional losses. For example, a VP to the left of an NP gets shuffled to the right with the same ply “right  $\blacklozenge$  left” producing the additional loss items.

*Continuous affinity* and *discontinuous affinity* in **DM** undergo different identification processes. To minimize the difference, we introduce (h)  $L_{aff}^C$  and  $L_{aff}^X$  for *continuous* and *interply affinity*, in addition to cardinal  $L_{aff}^D$ . These reduce the risk of biaffine attention forwarding incorrect nodes, which would evoke exposure bias. We use positive rates  $\beta_c$  and  $\beta_x$  for  $\beta_c \cdot \sigma(\hat{d}_i^h)$  and  $\beta_x \cdot \sigma(x_w^{h\tau} \cdot W^{aff} \cdot \Delta_w^h + b^{aff})$  to limit the sample size, where layers  $\bar{h} \neq h$  contain *discontinuous* nodes. Failable signals are more likely to form losses via `HINGE-LOSS`.

In summary, the additional loss items are

$$L_{ori}^{shfl}, L_{jnt}^{shfl}, L_{aff}^C, L_{aff}^X.$$

## 4 Experiment

**DCCP** takes frozen pre-trained FastText as static word embedding (PWE) or fine-tuned 12-layer pre-trained XLNet and BERT as contextualized embedding of pre-trained language models (PLM) as lexical input<sup>2</sup> and parses on English DPTB and German TIGER treebanks. See Table 2.

**Two-stage Training for a PWE Model.** The first stage (**S1**) requires approximately 300 epochs

<sup>2</sup>To compare to other parsers with a lexical component, **NCCP** used pre-trained FastText or FastText trained on PTB. The former slightly increased F1 score by 0.2. We choose BERT (<https://www.deepset.ai/german-bert>) for German and adopt `FFNNext` instead of `BiLSTMext` for model connection following **NCCP**.

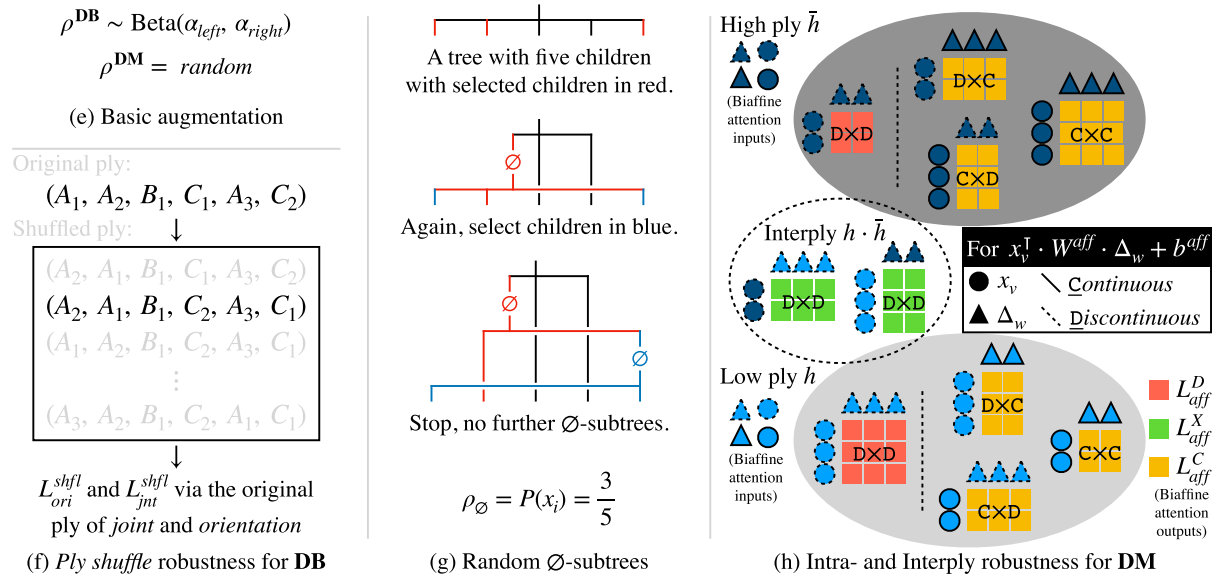


Figure 7: (e) Beta distribution is equivalent to uniform *random* when  $\alpha_{left} = \alpha_{right} = 1$ . Otherwise, it is for detecting branching tendency with **DB**. (f) Constituent children get shuffled and create additional losses.  $(A_1, A_2, A_3)$ ,  $B_1$ , and  $(C_1, C_2)$  belong to three different constituents. (g)  $\emptyset$ -subtree creates discontinuity from continuity with a random stretching branch. (h) In-ply continuous nodes and interply nodes are chosen for **DM** biaffine attention.

DCCP model dimension		300		
BiLSTM <sub>ctx</sub> / BiLSTM <sub>ply</sub> layers		6 / 2		
FFNN <sub>{tag, label, ori, jnt, disc}</sub> layers		2		
Optimizer		Adam		
(1-epoch $\gamma$ warm-up, linear decay, and early stop.)				
Drop out rate (recurrent)		0.4 (0.2)		
Batch size (non-training)		80 (160)		
Parameter sizes (w/o PLM)				
BiLSTM <sub>ctx</sub>	+CB	+CM	+DB	+DM
3.25M	0.36M	0.55M	1.32M	1.45M

Table 2: Fixed model hyperparameters and model parameter sizes of **NCCP** and **DCCP**. **CB** & **CM** have a single-layer BiLSTM<sub>ply</sub> of fewer model parameters.

with general hyperparameters. Loss functions are sum of all loss items:

$$L_{DB}^{S1} = L_{tag} + L_{label} + L_{jnt} + L_{ori} + L_{ori}^{shfl} + L_{jnt}^{shfl}$$

$$L_{DM}^{S1} = L_{tag} + L_{label} + L_{jnt} + L_{disc} + \sum_{i \in D, X, C} L_{aff}^i$$

Adam optimizer’s learning rate is  $\gamma = 10^{-3}$ . **DB** uses uniform binarization  $\alpha_{left} = \alpha_{right} = 1$ . **DM** uses  $\emptyset$ -subtree ratio  $\rho_{\emptyset} = 0.25$ , robustness  $\beta_c = 0.1$ , and  $\beta_x = 1$  for both efficiency and accuracy.

The second stage (**S2**) involves 100 short trials with a Bayesian optimization (BO) tool (Akiba et al., 2019, *optuna*); each trial requires less than 30 epochs and brings hyperparameter adjustment:

$$L_{DB}^{S2} = \alpha_{tag} \cdot L_{tag} + \dots + \alpha_{jnt}^{shfl} \cdot L_{jnt}^{shfl}$$

$$L_{DM}^{S2} = \beta_{tag} \cdot L_{tag} + \dots + \sum_{i \in D, X, C} (\beta_i \cdot L_{aff}^i).$$

Trials follow practical constraints: learning rate  $\gamma \in (10^{-6}, 10^{-3})$ , beta’s  $\alpha_{left}, \alpha_{right} \in (10^{-3}, 10^3)$  instead of  $(0, +\infty)$ , and  $[0, 1]$  for the others.

PLM models also use general hyperparameters with learning rate  $10^{-6}$  at **S1**. PLMs are frozen during the first 50 epochs to avoid noise pollution and then are fine-tuned with learning rate  $3 \times 10^{-6}$ . They inherit explored hyperparameters from PWE models at **S2**, except for learning rate  $3 \times 10^{-6}$ .

#### 4.1 Overall Results

Table 3 shows F1 scores of recent neural discontinuous parsers under comparable conditions on test sets. We follow their reported number of significant digits and reduce the effects of random initialization with an average of five runs. The details are shown in Table 4.

**DCCP** models achieved state-of-the-art performance in terms of discontinuous F1 scores and parsing speeds. Although speed tests are



Model			DPTB test set			TIGER test set		
	Type	Complexity	F1	D.F1	Speed	F1	D.F1	Speed
<b>without pre-trained language model</b>								
Coavoux et al. (2019)	Trans-Gap	$O(n)$	91.0	71.3	80	82.7	55.9	126
Coavoux and Cohen (2019)	Stack-Free	$O(n^2)$	90.9	67.3	38	82.5	55.9	64
Pointer-based VG20 w/ Ling et al. (2015)	Seq-Labeling	$O(n^2)$	88.8	45.8	611	77.5	39.5	568
Pointer-based FG22 w/ Ling et al. (2015)	Multitask†	$O(n^2)$	–	–	–	<b>86.6</b>	<b>62.6</b>	–
Stanojevic and Steedman (2020)	Chart	$O(n^6)$	90.5	67.1	–	83.4	53.5	–
Corro (2020)	Chart	$O(n^3)$	<b>92.9</b>	64.9	355	85.2	51.2	474
Ruprecht and Mörbitz (2021) w/ flair	Chart	–	91.8	76.1	86	85.1	61.0	80
<b>DB</b> w/ FastText (en & de)	Combinator	$O(n^2)$	92.0	75.6	<b>940</b>	84.9	60.1	<b>1160</b>
<b>DM</b> w/ FastText (en & de)	Combinator	$O(n^3)$	92.1	<b>78.1</b>	<b>970</b>	85.1	62.0	<b>1300</b>
<b>with pre-trained language model</b>								
Pointer-based VG20 w/ BERT <sub>BASE</sub>	Seq-Labeling	$O(n^2)$	91.9	50.8	80	84.6	51.1	80
Pointer-based FG22 w/ BERT <sub>BASE</sub>	Multitask†	$O(n^2)$	–	–	–	89.8	<b>71.0</b>	–
Corro (2020) w/ BERT	Chart	$O(n^3)$	94.8	68.9	–	<b>90.0</b>	62.1	–
Ruprecht and Mörbitz (2021) w/ BERT	Chart	–	93.3	80.5	57	88.3	69.0	60
FG21 w/ XLNet (en) or BERT <sub>BASE</sub> (de)	Reorder-Chart	$O(n^3)$	95.1	74.1	179	88.5	63.0	238
FG21 w/ XLNet (en) or BERT <sub>BASE</sub> (de)	Reorder-Trans	$O(n^2)$	<b>95.5</b>	73.4	133	88.5	62.7	157
<b>DB</b> w/ XLNet (en) or BERT <sub>BASE</sub> (de)	Combinator	$O(n^2)$	94.8	76.6	<b>275</b>	89.5	69.7	<b>424</b>
<b>DM</b> w/ XLNet (en) or BERT <sub>BASE</sub> (de)	Combinator	$O(n^3)$	95.0	<b>83.0</b>	<b>375</b>	89.6	70.9	<b>535</b>

Table 3: Overall performance of recent discontinuous parsers. Speeds in sentences per second were obtained in tests conducted on incomparable hardware and software platforms. Ours and Vilares and Gómez-Rodríguez (2020, VG20) were conducted on a GeForce GTX 1080 Ti with a PyTorch implementation, and that of Fernández-González and Gómez-Rodríguez (2021, FG21) was conducted on a GeForce RTX 3090. Fernández-González and Gómez-Rodríguez (2022, FG22) involved lexical dependency information†.

DPTB (test)		F1	D.F1
PWE	<b>DB</b>	91.97±0.05	75.62±0.82
	<b>DM</b>	92.06±0.10	78.14±0.69
PLM	<b>DB</b>	94.84±0.24	76.62±2.07
	<b>DM</b>	95.04±0.06	83.04±0.79
TIGER (test)		F1	D.F1
PWE	<b>DB</b>	84.88±0.08	60.08±0.37
	<b>DM</b>	85.11±0.13	62.02±0.71
PLM	<b>DB</b>	89.48±0.16	69.68±0.55
	<b>DM</b>	89.61±0.09	70.93±0.63

Table 4: Means and standard deviations of five runs on test sets with four significant digits. **DM** outperforms **DB**. Development sets reflect similar variability.

conducted on different platforms, our parsers lead by a significant margin. In terms of overall F1 score, our parsers outperform some chart parsers (Stanojevic and Steedman, 2020; Ruprecht and Mörbitz, 2021) and slightly underperform the overall best outline, as characterized in **boldface**.

## 4.2 Ablation Study

We ablate the PWE models in two-stage training, as shown in Table 5. We only show one repre-

Model (Stage)	DPTB (dev)		TIGER (dev)		
	F1	D.F1	F1	D.F1	
<b>DB</b>	(0, 0, 0)	90.93	63.28	87.73	56.49
	(0, 1, 1)	91.61	69.84	88.70	61.15
	(1, 0, 1)	91.62	<b>74.25</b>	87.93	59.85
	(1, 1, 0)	91.48	70.97	89.05	63.32
	( $\ddagger$ (1, 1, 1))	<b>91.72</b>	66.82	<b>89.28</b>	<b>63.49</b>
( <b>S1</b> )	$\ddagger$ (1, 1, 1)	<b>91.72</b>	66.82	<b>89.28</b>	<b>63.49</b>
( <b>S2</b> )	$\leftrightarrow$ <i>optuna</i>	92.25	76.60	89.59	66.03
<b>DM</b>	(0, 0, 0)	91.62	79.37	88.30	62.41
	(0, 1, 1)	91.44	78.70	88.61	65.10
	(1, 0, 1)	91.74	79.02	89.64	67.40
	(1, 1, 0)	91.84	77.37	<b>89.78</b>	67.78
	( <b>S1</b> )	$\ddagger$ (1, 1, 1)	<b>92.16</b>	<b>80.29</b>	89.77
( <b>S2</b> )	$\leftrightarrow$ <i>optuna</i>	92.37	82.76	89.84	68.45

Table 5: Ablation in two-stage training on development F1 scores. Triplets in  $\{0, 1\}$  indicate turning on and off ( $\rho_\emptyset, \rho^{\text{DB}} \sim \text{Beta}(1, 1)$ , *shuffle*) for **DB** and ( $\rho_\emptyset, \beta_c, \beta_x$ ) for **DM**. Variants of “ $\ddagger$ ” are **S1**—the start of **S2**.

sentative run with ablation because of the similar low variability on development sets. **DB** has two data augmentation items  $\rho_\emptyset$  and  $\rho^{\text{DB}}$  as well as one model item *ply shuffle*. On  $\rho_\emptyset$  refers to  $\rho_\emptyset = 0.25$  and off  $\rho_\emptyset = 0$ . Off Beta(1, 1) refers to a static

Model	Dev set	$\rho_{\emptyset} = 0$	0.1	‡0.25	0.5
<b>DB</b>	<b>DPTB</b>	91.61	91.79	91.72	<b>91.95</b>
	<b>TIGER</b>	88.70	89.04	<b>89.28</b>	89.25
<b>DM</b>	<b>DPTB</b>	91.44	91.80	<b>92.16</b>	89.86
	<b>TIGER</b>	88.61	89.45	<b>89.77</b>	88.61

Table 6: **DM** is sensitive to  $\rho_{\emptyset}$  with dev F1 scores. All variants are based on  $(\rho_{\emptyset}, 1, 1)$  in Table 5 with specific  $\rho_{\emptyset}$  as the variable for **DB** and **DM**.

Test set	DM Medoid $\rho^{\text{DM}}$	F1	D.F1
<b>DPTB</b>	<i>uhead</i>	<b>95.05</b>	<b>83.58</b>
	<i>leftmost</i>	95.00	81.64
	<i>rightmost</i>	95.03	82.47
	<i>random (min)</i>	95.01	82.18
	<i>random (max)</i>	95.04	83.17
<b>TIGER</b>	<i>uhead</i>	<b>89.62</b>	<b>71.61</b>
	<i>leftmost</i>	89.56	71.43
	<i>rightmost</i>	89.56	70.92
	<i>random (min)</i>	89.55	71.26
	<i>random (max)</i>	89.61	71.52

Table 7: **DM** medoid factor  $\rho^{\text{DM}} = uhead$  offers stable gains even without head information during training. We tested  $\rho^{\text{DM}} = random$  five times.

$\rho^{\text{DB}} = 0.5$  and  $(0, 0, 0)$  shows the performance of bare **DB** models.

On the flip side, **DM**'s  $(0, 0, 0)$  contains randomness because of  $\rho^{\text{DM}} = random$ . We do not intend to examine a static  $\rho^{\text{DM}}$  as **DB** yields negative results. Based on effective training tricks, the variants enter the BO process at **S2**. **DCCP** shows its sensitivity to  $\rho_{\emptyset}$  in Table 6.

### 4.3 Inference with Unsupervised Headedness

Both **CM** and **DM** provide unsupervised headedness  $\bar{\lambda}$ . Chen et al. (2021) were unable to test the benefits of **CM**'s unsupervised headedness because it is a final product that cannot affect parsing. However, **DM**'s medoid affects parsing performance. On PLM **DM**, we select different  $\rho^{\text{DM}}$  categories, which affect the location of all discontinuous constituent, and examine their generalization on test sets, as shown in Table 7. All models are trained with  $\rho^{\text{DM}} = random$  but inference with  $\rho^{\text{DM}} = uhead$  exerts positive gains on accuracy.

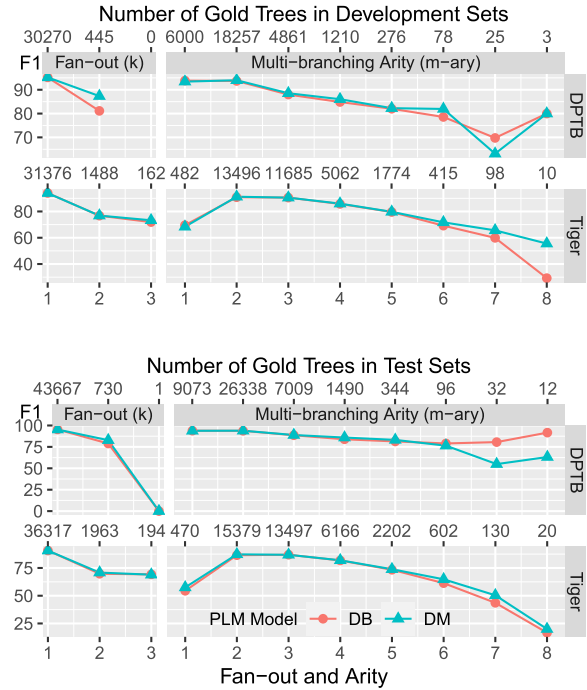


Figure 8: **DB** and **DM**'s discontinuity and multi-branching performance. Because the TIGER Treebank is richer in discontinuity, **DM** exhibits higher F1 scores.

## 5 Discussion

**Properties of DCCP Models.** Table 3 exhibits high speeds and near state-of-the-art accuracies of **DCCP** compared to recent works. **DCCP** inherits many properties from **NCCP**. **CB** and **CM** are special cases of **DB** and **DM** without *swap* and *discontinuous* actions. All models contain compact components without grammar restriction. Each model has no more than 4.7M parameters apart from PWE or PLM, as listed in Table 2.

The variability of all models is low, except for the discontinuous F1 score of PLM **DB** on DPTB, as shown in Table 4. The main cause may not be the random initialization but the different training processes of PWE and PLM models—PLM models use the configuration of PWE models at **S2**. Those degraded PLM models adopted low  $\rho_{\emptyset}$  configurations (e.g.,  $\rho_{\emptyset} = 0.078$ ). Because DPTB has less discontinuity and overall F1 scores are used for model evaluation, high variability in discontinuous F1 scores becomes more common without several BO trials; this phenomenon is also reflected in Table 5. **DB** lacks explicit discontinuity, and the selection of hyperparameters seems to be necessary on DPTB.

Figure 8 presents the F1 scores for discontinuity and multi-branching. We select PLM models

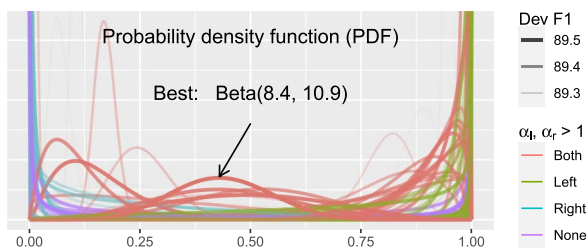


Figure 9: Beta distribution visualization for TIGER DB at S2. See their hyperparameters in Figure 10.

whose overall F1 scores are close (i.e., most F1 differences are less than 0.1 and **DB**'s performance is high). **DM** exhibits persistent advantages over **DB** when these properties are frequent. We further determined that **CM** has the same gains over **CB** starting identically from 4-ary nodes with minor score differences on (D)PTB under the same  $\rho_\emptyset = 0$  condition, as shown in Table 9. The result supports the argument of Xin et al. (2021), which asserts that  $m$ -ary constituency parsing without binarization preserves some natural advantages, e.g., predicate-argument structure. Specifically,  $\rho_\emptyset > 0$  shifts **DM**'s multi-branching advantage to frequent low-arity trees, favoring the overall scores on DPTB, while it enhances both discontinuity and multi-branching advantages on TIGER, as shown in Table 10, in agreement with Table 6.

The training process of **CB** with CNF binarization has a slight impact on parsing accuracy. Chen et al. (2021) obtained the best **CB** with Bernoulli distribution  $P(\rho^{\text{DB}} = 0) = 0.85$  (i.e.,  $P(\rho^{\text{DB}} = 1) = 0.15$  or L85R15 in their format ‘‘L%R%’’) on PTB. They argued that such binarization brings orientation balance.

Similarly, **DB**'s S2 exhibits a slightly leftward exploration with the beta distribution, as shown in Figure 9. DPTB has a similar situation. Yet, the optimized distributions are relatively uniform and symmetric, which qualifies our uniform randomness with  $\rho^{\text{DB}}$  at S1 and indicates a desired property for future language-agnostic practice.

For unsupervised headedness, Chen et al. (2021) reported that **CM** absolutely picks determiners (DT) as heads for major NP. **DM** continues and further grammatically picks more noun phrases (NP) as NP heads, as shown in Table 8.

**Linguistic Properties by DCCP.** From Figure 8, we learned that TIGER is more challenging in discontinuity. Incorrect discontinuity prediction

Parent (#)	Head child by maximum weight
NP (14.4K) from <b>CM</b>	DT (4.5K); NP (4.3K); NNP (1.6K); JJ (922); NN (751); NNS (616); etc. (1.6K; 12 of 50 types with ‘‘*’’)
NP(14.3K) from <b>DM</b>	NP (4.7K); DT (4.5K); NNP (1.6K); JJ (786); NN (715); NNS (565); etc. (1.4K; 15 of 49 types with ‘‘*’’)

Table 8: **CM** & **DM** unsupervised NP headedness from (D)PTB test sets. ‘‘\*’’ denotes minority NPs having DTs as non-head children (i.e., DTs are strong NP heads).

seems to cascade to multi-branching prediction, resulting in degradation of both properties. Meanwhile, DPTB is largely transformed from PTB by typed traces and automatic rules, where the multi-branching accuracy stays more stable.

As seen in Table 7,  $\rho^{\text{DM}} = \text{rightmost}, \text{leftmost}$  yielded the second best F1 and D.F1 scores on DPTB and TIGER, respectively. The reversed setting yielded poor results, even if not the worst. The observation implies that many English heads locate rightward (right-branching) and that German heads tend to locate leftward (verb-second word order, V2). German has abundant separable verbs with their prefixes at the right-hand side of the clauses.

**Error Rates of DCCP.** Greedy parsers allow ill-formed outputs without a single root, especially in case of single-model inference. Our models yielded a few invalid parses, as demonstrated in Table 11. **DM** models produce more errors. However, unsuccessful decomposition of biaffine attention matrices might not be the direct cause, as also shown in Figure 11.  $\rho_\emptyset > 0$  variants cleared the matrices that could not be decomposed with any  $\theta$  (FAIL). Similar to **CM**, this genre suffers from more failures. Specifically, the ply size cannot be reduced to one during the iteration. Greedy parsers must suffer the defect because of their simplicity. However, invalid parses can contribute positive F1 scores and global parsers can yield inaccurate parses.

We applied methods such as Boolean matrix factorization and singular value decomposition. However, they did not provide any improvement and significantly slowed down the speed. This is

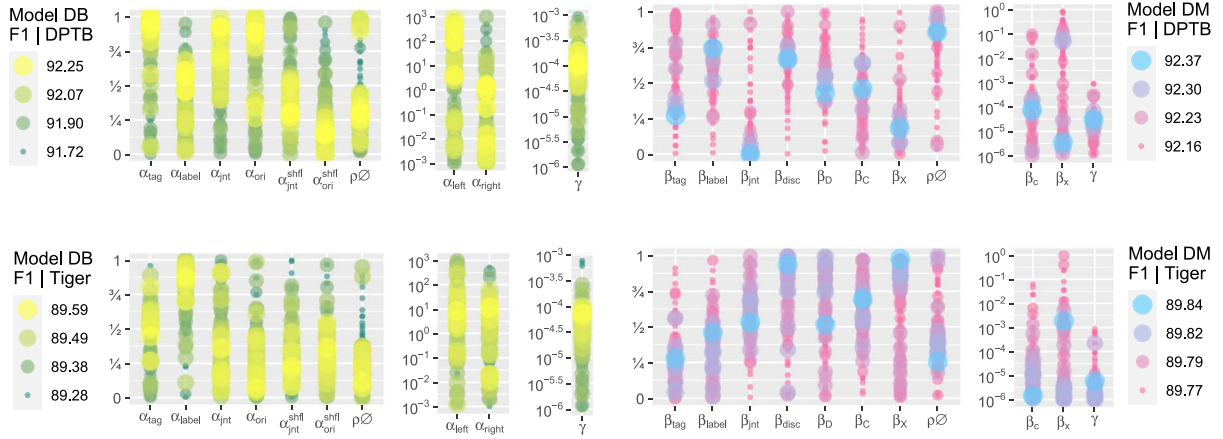


Figure 10: The BO process starts with **S1** dev F1 scores (i.e., a small dot at each legend bottom) and ends with a range of scores in **S2**. While the models are not sensitive to hyperparameters (e.g., all gains are less than 0.54), their preferences are different on respective corpora. On TIGER,  $\alpha_{ori} < \alpha_{ori}^{shll}$  and high ( $\beta_C$ ,  $\beta_X$ ) are preferable.

Prop.	Gold Tree	PWE		$\rho_{\emptyset} = 0$		$\rho_{\emptyset} > 0$		PLM		$\rho_{\emptyset} = 0$		$\rho_{\emptyset} > 0$	
		CB	CM	DB	DM	DB	DM	CB	CM	DB	DM	DB	DM
1	9,073	<b>92.25</b>	92.02	<b>91.43</b>	91.35	<b>91.68</b>	91.53	93.80	<b>94.33</b>	93.36	<b>93.41</b>	<b>93.91</b>	93.82
2	26,338	<b>90.41</b>	89.94	<b>89.87</b>	89.68	89.95	<b>90.02</b>	<b>94.41</b>	94.33	93.47	<b>93.65</b>	93.77	<b>93.92</b>
3	7,009	<b>84.17</b>	83.56	<b>83.50</b>	83.34	83.60	<b>83.79</b>	<b>90.27</b>	89.81	88.31	<b>88.60</b>	88.57	<b>88.87</b>
4	1,490	77.87	<b>78.95</b>	78.19	<b>79.82</b>	78.50	<b>78.86</b>	<b>87.42</b>	86.51	83.98	<b>86.50</b>	83.88	<b>85.90</b>
5	344	74.19	<b>77.29</b>	76.14	<b>78.46</b>	74.97	<b>78.87</b>	81.42	<b>84.06</b>	78.61	<b>85.15</b>	81.38	<b>83.17</b>
6	96	70.05	<b>78.35</b>	72.90	<b>80.63</b>	<b>77.39</b>	76.29	78.64	<b>80.00</b>	79.23	<b>83.50</b>	<b>79.02</b>	76.44
7	32	64.71	<b>86.15</b>	73.53	<b>87.10</b>	<b>76.47</b>	71.43	<b>76.47</b>	70.18	75.76	<b>77.42</b>	<b>80.60</b>	54.90
8	12	64.00	<b>72.73</b>	81.82	<b>85.71</b>	75.00	<b>80.00</b>	78.26	<b>86.96</b>	78.57	<b>83.33</b>	<b>91.67</b>	63.16
9	3	<b>100.00</b>	75.00	<b>100.00</b>	75.00	<b>100.00</b>	50.00	<b>100.00</b>	75.00	<b>100.00</b>	85.71	85.71	<b>100.00</b>
$k > 1$	731	–	–	73.95	<b>77.60</b>	75.68	<b>78.94</b>	–	–	78.62	<b>83.04</b>	78.65	<b>82.71</b>
All	44,397	<b>92.54</b>	92.08	91.99	<b>92.02</b>	92.00	<b>92.00</b>	<b>95.71</b>	95.44	94.70	<b>94.79</b>	95.08	<b>95.09</b>

Table 9: Multi-branching and discontinuous F1 scores of **NCCP** and **DCCP** on (D)PTB test sets. We grouped  $k > 1$  because only one tree has fan-out  $k = 2$  in the test set. The scores of **CB** and **CM** are from Chen et al. (2021).

Prop.	Gold Tree	PWE $\rho_{\emptyset} = 0$		$\rho_{\emptyset} > 0$		PLM $\rho_{\emptyset} = 0$		$\rho_{\emptyset} > 0$	
		DB	DM	DB	DM	DB	DM	DB	DM
1	470	45.37	<b>49.14</b>	51.64	<b>55.32</b>	55.16	<b>56.84</b>	54.45	<b>57.48</b>
2	15,379	81.83	<b>82.57</b>	82.25	<b>83.36</b>	85.91	<b>86.34</b>	86.50	<b>87.31</b>
3	13,497	<b>80.58</b>	80.41	80.95	<b>81.05</b>	<b>85.96</b>	85.35	<b>86.93</b>	86.89
4	6,166	<b>73.43</b>	73.34	74.04	<b>74.36</b>	<b>80.71</b>	79.93	81.76	<b>81.92</b>
5	2,202	63.66	<b>64.14</b>	64.27	<b>65.15</b>	71.09	<b>72.40</b>	73.37	<b>73.88</b>
6	602	50.72	<b>52.85</b>	51.62	<b>55.13</b>	59.30	<b>63.61</b>	61.32	<b>64.79</b>
7	130	36.25	<b>43.38</b>	40.53	<b>44.91</b>	45.51	<b>55.02</b>	43.59	<b>50.37</b>
8	20	11.24	<b>24.39</b>	16.44	<b>19.51</b>	<b>24.32</b>	24.24	16.67	<b>20.00</b>
9	6	12.90	<b>66.60</b>	21.43	<b>28.57</b>	16.67	<b>33.33</b>	12.90	<b>54.55</b>
$k = 1$	36,317	<b>85.95</b>	85.92	<b>86.41</b>	86.39	<b>89.85</b>	89.75	<b>90.69</b>	90.66
$k = 2$	1,963	<b>59.88</b>	59.64	59.95	<b>62.05</b>	<b>71.15</b>	67.53	69.78	<b>70.85</b>
$k = 3$	194	57.46	<b>59.83</b>	58.89	<b>60.61</b>	<b>68.23</b>	63.91	<b>69.21</b>	68.95
All	38,474	<b>84.56</b>	84.50	84.99	<b>85.08</b>	<b>88.82</b>	88.57	89.55	<b>89.58</b>

Table 10: Multi-branching and discontinuous test F1 scores of **DCCP** on TIGER. Fan-out is detailed in  $k$ .

Test set	DPTB	TIGER
<b>Total trees</b>	2,416	4,998
<b>DB's ill-formed parses</b>	1	2
<b>DM's ill-formed parses</b>	15	47
Biaffine attention matrices	594	7,278
$\theta = 0.5$ solutions	587	7,114
Average of tries if $\theta \neq 0.5$	12.4	42.9
FAIL + identity matrices	0+4	0+81

Table 11: Errors in **DCCP** PLM models with  $\rho_{\emptyset} > 0$ . A **FAIL** causes a matrix of ones, whereas a  $\theta$  close to one yields an identity matrix—an expensive null action.

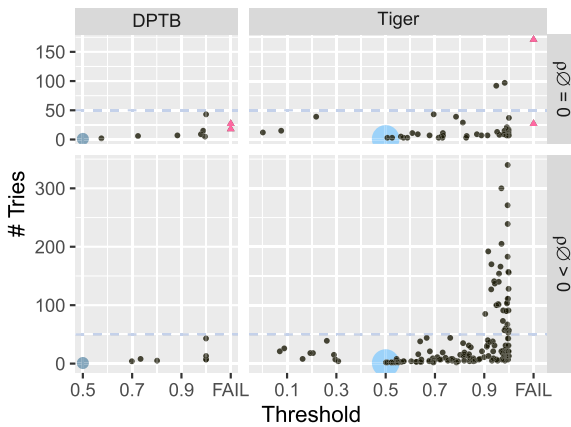


Figure 11: The numbers of tries to decompose biaffine attention matrices on test sets. “▲” marks **FAIL**s.

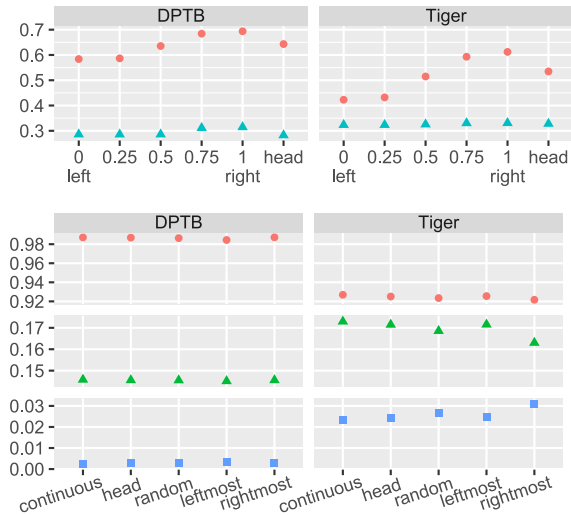


Figure 12: Signal polarity in corpora **DPTB** (sections 2–24) and **TIGER**. Top: **DB** signal polarity to  $\rho^{\text{DB}}$  with *orientation right* “•” and *joint* “▲” Bottom: **DM** signal polarity to stratifying *medoid* factor  $\rho^{\text{DM}}$  with *affinity* “•,” *joint* “▲” and *discontinuity* “■.” *Continuous* and *head* are referential only, looking for the least *discontinuity* and leveraging head information. (All  $\rho_{\emptyset} = 0$ .)

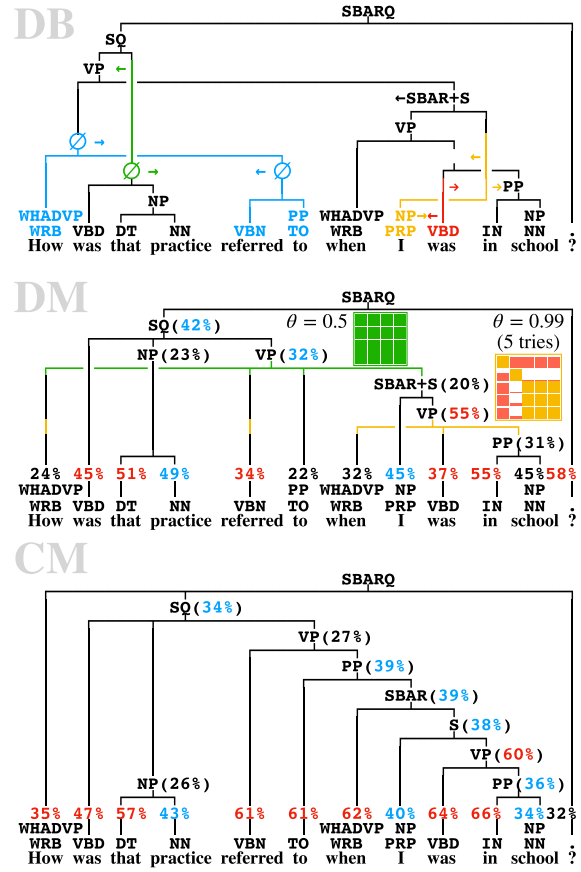


Figure 13: An exact matched **DPTB** sample from PLM **DB** and **DM** models versus **CM** on **PTB**. The parse contains complex nested clauses that **CM** must fail to capture, and it becomes ungrammatical in the continuous scenario. **DB**'s outputs include orientations depicted as arrows and their traveling traces colored for groups. Meanwhile, **DM** produces two biaffine attention matrices, one of which has a highly biased but correct threshold  $\theta = 0.99$ . Bar heights indicate values in matrices and their colors indicate the relationship to  $\theta$ .

because  $\theta \neq 0.5$  cases are few. Our sequential tries to decompose might be naïve, but they are effective. In Figure 11, the number of tries does not significantly increase under  $\theta < 0.9$  within 50 tries. For  $\theta \geq 0.9$ , although some tries are expensive, we will see that they are worthy in the next section. The imbalanced signals from both datasets account for the bias of  $\theta$ —more than 92% of the biaffine attention signals are ones, as shown in Figure 12. All affinity biases (i.e.,  $b^{\text{aff}} \in [-1.60, -0.84]$ ) are significant negative numbers for counteraction.

**Weakness.** The design of *affinity* as biaffine attention is an initial but coarse attempt, which



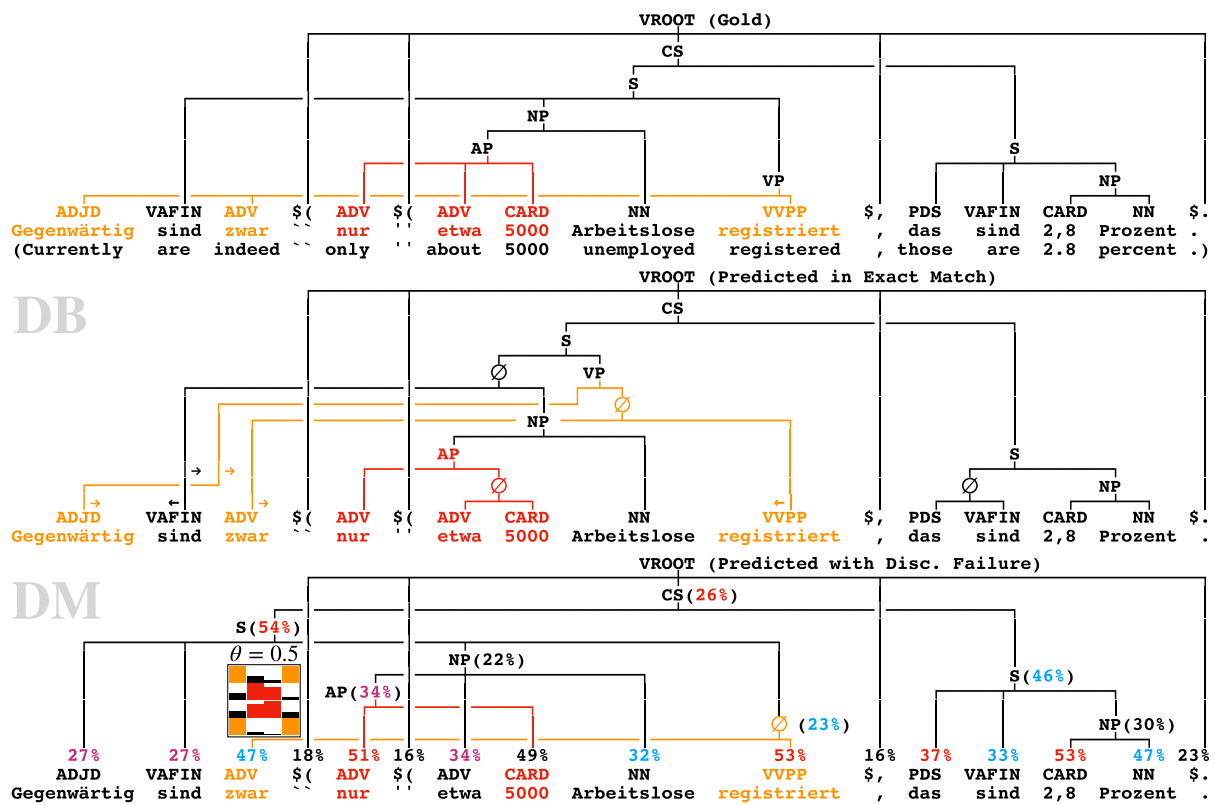


Figure 14: A TIGER parse. **DB** natively with  $\emptyset$ -subtrees achieved the exact match but **DM** erred with  $\rho_\emptyset = 0$ .

brings imbalance. If one encoded *dependency within constituent* to biaffine attention instead, both signal balance and multi-grammar parsing might be better addressed. However, based on the context of constituency parsing, we leave this topic for future study.

## 6 Sample Analysis

**Continuous vs. Discontinuous Parsing.** Figure 13 highlights the value of discontinuous parsing by demonstrating the respective **CM** parse. Conspicuously, the branching tendency of the continuous parse is to the right, while it is not obvious for the discontinuous parsing. Meanwhile, we observed instances of similar unsupervised headedness weights. This sample is not trivial, which challenges our PLM DCCP models.

**Parsing Process of DCCP.** In Figure 13, **DB** shows sinuous travel traces of “I,” “was,” and larger  $\emptyset$ -subtree nodes that involve the turning of orientations. The varying context leads them to achieve complex movement. **DB** also created some grammatical substructures for “How,” “referred,” “to,” “was,” “in,” and “school.”

Meanwhile, the **DM** parse is more dramatic. The formation of the lower discontinuous VP involves five nodes, two of which are irrelevant words “How” and “referred” triggered by incorrect *discontinuity* signals. They are discontinuous but for the higher VP. The two nodes create a noisy bi-affine attention matrix because their grammatical roles are compatible with the lower VP. Trained for extra robustness, the matrix decomposition with five tries found the right  $\theta$  to identify the correct VP members excluding “How” and “referred.” The interplay loss and the decoding process gave this parse a chance for perfection.

In Figure 14 for German, **DB** achieved a long distant constituent in a more subtle way. The word “zwar” joins “registriert” as an  $\emptyset$ -subtree when the formation of intermediate NP shortens their distance and prevents a travel through. “Gegenwärtig” follows and forms a VP. However, **DM** failed.

**The  $\rho_\emptyset > 0$  matters.** The above failure explains why **DM** is inferior to **DB** with  $\rho_\emptyset = 0$ . **DB**’s orientation system allows some free travel before joining with correct mates. The constituent formation through steps of accumulation creates



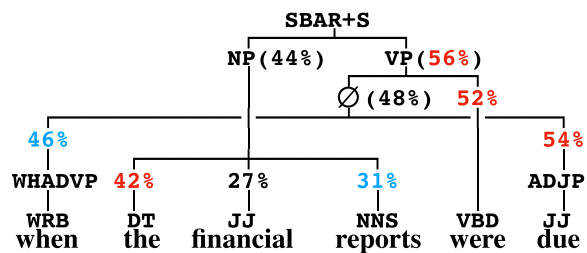


Figure 15: A semantic  $\emptyset$ -subtree by **DM** with  $\rho_{\emptyset} > 0$ . Copula “were” has less *affinity* than “when” and “due.”

a more stable context. However, **DM**’s group action happens all at once. An incorrect composition might create a quite different context, which leads to unseen reaction chains. The strange unsupervised headedness weights reflect the issue. On the other side, with  $\rho_{\emptyset} > 0$ , **DM** can also gradually build and discover some semantic substructures, as shown in Figure 15. In contrast, **DB** is not sensitive to  $\rho_{\emptyset}$  because of its nature, in agreement with Table 6.

## 7 Conclusion

We proposed a pair of efficient and effective discontinuous combinatory constituency parsers and extended the neural combinator family of **NCCP**. A binary combinator **DB** is based on orientation extended into a joint-swap system. A multi-branching combinator **DM** leverages bi-affine attention adapted for constituency. Our models (as in Table 2) achieved state-of-the-art discontinuous F1 scores with a significant advantage in speed.

In the future, we will aim to extend **DCCP** into a multilingual tool for directed acyclic graph (DAG) parsing with function tag prediction for predicate-argument structure.

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