

# Two Knives Cut Better Than One: Chinese Word Segmentation with Dual Decomposition

## Abstract

There are two dominant approaches to the Chinese word segmentation problem: word-based and character-based models, each with respective strengths. Prior work has shown that gains in segmentation performance can be achieved from combining these two types of models; however, past efforts have not provided a practical technique to allow mainstream adoption. We propose a method that effectively combines the strength of both segmentation schemes using an efficient dual-decomposition algorithm for joint inference. Our method is simple and easy to implement. Experiments on SIGHAN 2003 and 2005 evaluation datasets show that our method achieves the best reported results to date on 6 out of 7 datasets.

## 1 Introduction

Chinese text is written without delimiters between words; as a result, Chinese word segmentation (CWS) is an essential foundational step for many tasks in Chinese natural language processing. As demonstrated by (Shi and Wang, 2007; Bai et al., 2008; Chang et al., 2008; Kummerfeld et al., 2013), the quality and consistency of segmentation has important downstream impacts on system performance in machine translation, POS tagging and parsing.

State-of-the-art performance in CWS is high, with F-scores in the upper 90s. Still, challenges remain. Unknown words, also known as out-of-vocabulary (OOV) words, lead to difficulties for word- or dictionary-based approaches. Ambiguity can cause errors when the appropriate segmentation is determined contextually, such as 才能 (“talent”) and 才 / 能 (“just able”) (Gao et al., 2003).

There are two primary classes of models: character-based (Xue, 2003; Tseng et al., 2005; Zhang et al., 2006; Wang et al., 2010) and word-based (Andrew, 2006; Zhang and Clark, 2007),

with corresponding advantages and disadvantages. Sun (2010) details their theoretical distinctions: character-based approaches better model the internal compositional structure of words and are therefore more effective at inducing new OOV words; word-based approaches are better at reproducing the words of the training lexicon and can capture information from significantly larger contextual spans. Prior work has shown performance gains from combining these two types of models to exploit their respective strengths, but such approaches are often complex to implement and computationally expensive.

In this work, we propose a simple and principled joint decoding method for combining character-based and word-based segmenters based on dual decomposition. This method has strong optimality guarantees and works very well empirically. It is easy to implement and does not require retraining of existing character- and word-based segmenters. Experimental results on standard SIGHAN 2003 and 2005 bake-off evaluations show that our model outperforms the character and word baselines by a significant margin. In particular, it improves OOV recall rates and segmentation consistency, and gives the best reported results to date on 6 out of 7 datasets.

## 2 Models for CWS

In this section, we describe the character-based and word-based models we use as baselines, and review existing approaches to combine these models.

### 2.1 Character-based Models

In the most commonly used contemporary approach to character-based segmentation, first proposed by (Xue, 2003), CWS is seen as a character sequence tagging task, where each character is tagged on whether it is at the beginning, middle, or end of a word. Conditional random field (CRF) (Lafferty et

al., 2001) is widely adopted for this task, and gives state-of-the-art results (Tseng et al., 2005). In a first-order linear-chain CRF model, the conditional probability of a label sequence  $\mathbf{y}$  given a word sequence  $\mathbf{x}$  is defined as:

$$P(\mathbf{y}|\mathbf{x}) = \frac{1}{Z} \sum_{t=1}^{|\mathbf{y}|} \exp(\theta \cdot f(x, y_t, y_{t+1}))$$

$f(x, y_t, y_{t+1})$  are features functions that typically include surrounding n-gram and morphological suffix/prefix features. These types of features capture the compositional properties of characters and are likely to generalize well to unknown words. But the Markov assumption in CRF limits the context of such features; it is difficult to capture long-range word features in this model.

## 2.2 Word-based Models

Word-based models searches through lists of word candidates using scoring functions that directly assign scores to word candidates. Early word-based segmentation work employed simple heuristics like dictionary-lookup maximum matching (Chen and Liu, 1992). Zhang and Clark (2007) reported more recent success using a linear model trained with the average perceptron algorithm (Collins, 2002). Formally, given input  $\mathbf{x}$ , their models seeks for a segmentation  $F(\mathbf{x})$  such that:

$$F(\mathbf{y}|\mathbf{x}) = \operatorname{argmax}_{\mathbf{y} \in \text{GEN}(\mathbf{x})} (\alpha \cdot \phi(\mathbf{y}))$$

Searching through the entire  $\text{GEN}(\mathbf{x})$  space is intractable even with a local model. A beam-search algorithm is therefore employed. The search algorithm consumes one character input token at a time, and iterate through the existing beams to score two new alternative hypotheses by either appending the new character to the last word in the beam, or start a new word at current position.

## 2.3 Combine Models with Dual Decomposition

Various mixing approaches have been proposed to combine the above two approaches (Wang et al., 2006; Lin, 2009; Sun et al., 2009; Sun, 2010; Wang et al., 2010). These mixing models perform well on standard datasets, but are not in wide use because of

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### Algorithm 1 DD inference algorithm, modified Viterbi and beam-search.

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 $\forall i \in \{1 \text{ to } |\mathbf{x}|\} : \forall k \in \{0, 1\} : u_i(k) = 0$ 
for  $t \leftarrow 1$  to  $T$  do
   $\mathbf{y}^{c*} = \operatorname{argmax}_{\mathbf{y}} P(\mathbf{y}^c|\mathbf{x}) + \sum_{i \in |\mathbf{x}|} u_i(y_i^c)$ 
   $\mathbf{y}^{w*} = \operatorname{argmax}_{\mathbf{y} \in \text{GEN}(\mathbf{x})} F(\mathbf{y}^w|\mathbf{x}) - \sum_{i \in |\mathbf{x}|} u_i(y_j^w)$ 
  if  $\mathbf{y}^{c*} = \mathbf{y}^{w*}$  then
    return  $(\mathbf{y}^{c*}, \mathbf{y}^{w*})$ 
  end if
  for all  $i \in \{1 \text{ to } |\mathbf{x}|\}$  do
     $\forall k \in \{0, 1\} : u_i(k) = u_i(k) + \alpha_t(2k-1)(y_i^{w*} - y_i^{c*})$ 
  end for
end for
return  $(\mathbf{y}^{c*}, \mathbf{y}^{w*})$ 

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Viterbi:

$$V_1(1) = 1, V_1(0) = 0$$

**for**  $i = 2$  **to**  $|\mathbf{x}|$  **do**

$$\forall k \in \{0, 1\} : V_i(k) = \operatorname{argmax}_{k'} P_i(k|k') V_{i-1}k' + u_i(k)$$

**end for**

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Beam-Search:

**for**  $i = 1$  **to**  $|\mathbf{x}|$  **do**

**for** item  $v = \{w_0, \dots, w_j\}$  in  $\text{beam}(i)$  **do**

append  $x_i$  to  $w_j$ ,  $\text{score}(v) \stackrel{\pm}{=} u_i(0)$

$v = \{w_0, \dots, w_j, x_i\}$ ,  $\text{score}(v) \stackrel{\pm}{=} u_i(1)$

**end for**

**end for**

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their high computational costs and difficulty of implementation.

Dual decomposition (DD) (Rush et al., 2010) offers an attractive framework for combining these two types of models without incurring high cost in model complexity (in contrast to (Sun et al., 2009)) or decoding efficiency (in contrast to bagging in (Wang et al., 2006; Sun, 2010)). DD has been successfully applied to similar situations where we want to combine local model with global models, for example, in dependency parsing (Koo et al., 2010), bilingual sequence tagging (Wang et al., 2013) and word alignment (DeNero and Macherey, 2011).

The idea is that jointly model both character-sequence and word information can be computationally challenging, instead we could try to find outputs that the two models are most likely to agree on. Formally, the objective of DD is:

$$\max_{\mathbf{y}^c, \mathbf{y}^w} P(\mathbf{y}^c|\mathbf{x}) + F(\mathbf{y}^w|\mathbf{x}) \ni \mathbf{y}^c = \mathbf{y}^w$$

where  $\mathbf{y}^c$  is the output of character-based CRF and  $\mathbf{y}^w$  is the output of word-based perceptron.

	AS					PU				
	R	P	F <sub>1</sub>	R <sub>oov</sub>	C <sub>const</sub>	R	P	F <sub>1</sub>	R <sub>oov</sub>	C <sub>const</sub>
Char-based CRF	95.2	93.6	94.4	58.9	0.064	94.6	95.3	94.9	77.8	0.089
Word-based Perceptron	95.8	95.0	95.4	69.5	0.060	94.1	95.5	94.8	76.7	0.099
Dual-decomp	95.9	94.9	95.4	67.7	0.055	94.8	95.7	95.3	78.7	0.086
	CU					MSR				
	R	P	F <sub>1</sub>	R <sub>oov</sub>	C <sub>const</sub>	R	P	F <sub>1</sub>	R <sub>oov</sub>	C <sub>const</sub>
Char-based CRF	94.7	94.0	94.3	76.1	0.065	96.4	96.6	96.5	71.3	0.074
Word-based Perceptron	94.3	94.0	94.2	71.7	0.073	97.0	97.2	97.1	74.6	0.063
Dual-decomp	95.0	94.4	94.7	75.3	0.062	97.3	97.4	97.4	76.0	0.055

Table 1: Results on SIGHAN 2005 datasets. R<sub>oov</sub> denotes OOV recall, and C<sub>const</sub> denotes segmentation consistency.

The DD algorithm is an iterative procedure: in each iteration, if the best segmentations provided by the two models do not agree, then the two models will receive penalties for the decisions they made that differ from the other. This penalty exchange is similar to message passing, and as the penalty accumulate over the iterations, the two models are pushed towards agreeing with each other. We give an updated Viterbi decoding algorithm for CRF and a modified beam-search algorithm for perceptron, as well as pseudo-code for DD algorithm in Algo. 1<sup>1</sup>.

### 3 Experiments

We conduct experiments on the SIGHAN 2003 (Sproat and Emerson, 2003) and 2005 (Emerson, 2005) bake-off datasets to evaluate the effectiveness of the proposed dual decomposition algorithm. We take the publicly available Stanford CRF segmenter (Tseng et al., 2005)<sup>2</sup> as our character-based baseline model, and reproduce the perceptron-based segmenter from Zhang and Clark (2007) as our word-based baseline model. We adopted the development setting from (Zhang and Clark, 2007), and used CTB sections 1-270 for training, and sections 400-931 for development. The optimized hyper-parameters used are:  $\ell_2$  regularization parameter  $\lambda$  in CRF is set to 3; perceptron is trained for 10 iterations with beam size 200; dual decomposition is run to max iteration ( $T$  in Algo. 1) of 100 with step size ( $\alpha_t$  in Algo. 1) 0.1. Other than the standard precision (P), recall (R) and F<sub>1</sub> scores, we also evaluate segmentation consistency as proposed by (Chang et al., 2008).

<sup>1</sup>Due to space limitation, we defer to the tutorial of Rush and Collins (2012) for a full introduction of DD.

<sup>2</sup><http://nlp.stanford.edu/software/segmenter.shtml>

They have shown that increased segmentation consistency is correlated with better machine translation performance. The consistency measure calculates the entropy of segmentation variations — the lower the score the better. Statistical significance tests are done using the paired bootstrap resampling method (Efron and Tibshirani, 1993).

### 4 Results

Table 1 shows our empirical results on SIGHAN 2005 dataset. Our dual decomposition method outperforms both the word-based and character-based baselines consistently across all four subsets in both F<sub>1</sub> and OOV recall (R<sub>oov</sub>). Our method demonstrating a robustness across domains and segmentation standards regardless of which baseline model was stronger. Of particular note is DD’s significant improvement in R<sub>oov</sub>, which is particularly important for downstream applications such as entity recognition. The DD algorithm is also more consistent (as measured by C<sub>const</sub>), which would likely to lead to improvements in applications such as machine translation (Chang et al., 2008).

In addition, we also test our results on the earlier SIGHAN 2003 dataset. The improvement over word and char-based baselines remains. Table 2 puts our method in the context of earlier systems for CWS. Our method achieves the best reported score on 6 out of 7 datasets.

### 5 Discussion and Error Analysis

On the whole, dual decomposition produces state-of-the-art segmentations that are more accurate, more consistent, and more successful at inducing OOV words than the baseline systems that it com-

SIGHAN 2005				
	AS	PU	CU	MSR
<i>Best 05</i>	95.2	95.0	94.3	96.4
<i>Zhang et al. 06</i>	94.7	94.5	94.6	96.4
<i>Z&amp;C 07</i>	94.6	94.5	95.1	97.2
<i>Sun et al. 09</i>	-	95.2	94.6	97.3
<i>Sun 10</i>	95.2	95.2	<b>95.6</b>	96.9
Dual Decomp	<b>95.4</b>	<b>95.3</b>	94.7	<b>97.4</b>

SIGHAN 2003			
	AS	PU	CU
<i>Best 03</i>	96.1	95.1	94.0
<i>Peng et al. 04</i>	95.6	94.1	92.8
<i>Z&amp;C 07</i>	96.5	94.0	94.6
Dual Decomp	<b>97.1</b>	<b>95.4</b>	<b>94.9</b>

Table 2: Performance of dual decomposition in comparison to past published results on SIGHAN 2003 and 2005 datasets. Best reported F<sub>1</sub> score for each dataset is highlighted in bold. *Z&C 07* refers to Zhang and Clark (2007). *Best 03, 05* are results of the winning systems for each dataset in the respective shared tasks.

bins. On the SIGHAN 2005 test set, over 99.1% cases the DD algorithm converged within 100 iterations which gives optimality guarantee. In 77.4% of the cases, DD converged in the first iteration. The number of iterations to convergence histogram is plotted in Figure 1.

**Error analysis** Since dual decomposition is a method of joint decoding, it is liable to reproduce errors made by the constituent systems. In the example below, dual decomposition output follows the incorrect segmentation of the character-based CRF in oversegmenting the compound "sea, land, and air."

*Gloss* Large-scale / sea, land, and air / joint / military exercises  
*Gold* 大规模 / 海陆空 / 联合 / 军演  
*CRF* 大规模 / 海 / 陆空 / 联合 / 军演  
*PCPT* 大规模 / 海陆空 / 联合 / 军演  
*DD* 大规模 / 海 / 陆空 / 联合 / 军演

Nevertheless, in many cases the relative confidence of each model means that dual decomposition is capable of using information from both sources to generate a series of correct segmentations better than either baseline model alone. The example below shows a difficult-to-segment proper name comprised of common characters, which results in undersegmentation by the character-based CRF and oversegmentation by the word-based Perceptron, but our method achieves the correct middle ground.

*Gloss* Tian Yage / 's / creations

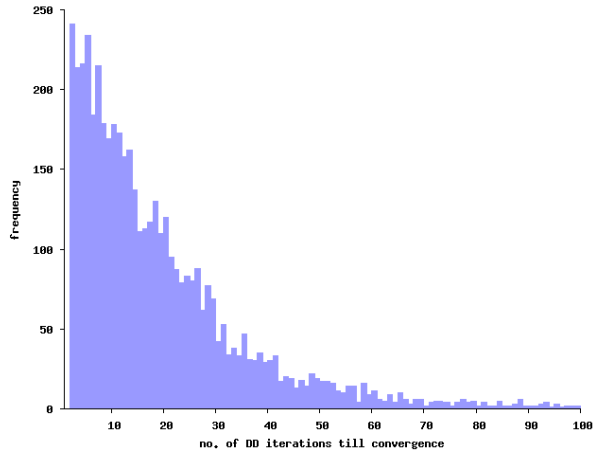


Figure 1: No. of iterations till DD convergence.

*Gold* 田雅各 / 的 / 创作  
*CRF* 田雅各的 / 创作  
*PCPT* 田雅 / 各 / 的 / 创作  
*DD* 田雅各 / 的 / 创作

A powerful feature of the dual decomposition approach is that it can generate correct segmentation decisions in cases where a voting or product-of-experts model could not, since joint decoding allows the sharing of information at decoding time. In the following example, both baseline models miss the contextually clear grammatical role of 上 ("above") and instead produce the otherwise common compound 上去 ("go up"); dual decomposition allows the model to generate the correct segmentation.

*English* Enjoy / a bit of / snack food / , ...  
*Gold* 享受 / 一点 / 点心 / ,  
*CRF* 享受 / 一点点 / 心 / ,  
*PCPT* 享受 / 一点点 / 心 / ,  
*DD* 享受 / 一点 / 点心 / ,

We found more than 400 such surprisingly accurate instances in our dual decomposition output.

## 6 Conclusion

In this paper we presented an approach to Chinese word segmentation using dual decomposition for system combination. We demonstrated that this method allows for joint decoding of existing CWS systems that are more accurate and consistent than either system alone, and further achieves the best performance reported to date on standard datasets for the task. Perhaps most importantly, our approach

is straightforward to implement and does not require retraining of the underlying segmentation models used. This suggests its potential for broader applicability in real-world settings than existing approaches to combining character-based and word-based models for Chinese word segmentation.

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