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PAPER

Integration of Multiple Bilingually-Trained Segmentation Schemes into Statistical Machine Translation

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SUMMARY This paper proposes an unsupervised word segmentation algorithm that identifies word boundaries in continuous source language text in order to improve the translation quality of statistical machine translation (SMT) approaches. The method can be applied to any language pair in which the source language is unsegmented and the target language segmentation is known. In the first step, an iterative bootstrap method is applied to learn multiple segmentation schemes that are consistent with the phrasal segmentations of an SMT system trained on the resegmented bitext. In the second step, multiple segmentation schemes are integrated into a single SMT system by characterizing the source language side and merging identical translation pairs of differently segmented SMT models. Experimental results translating five Asian languages into English revealed that the proposed method of integrating multiple segmentation schemes outperforms SMT models trained on any of the learned word segmentations and performs comparably to available monolingually built segmentation tools.

key words: *statistical machine translation, word segmentation, machine learning, Asian languages*

1. Introduction

The task of *word segmentation*, i.e., identifying word boundaries in continuous text, is one of the fundamental preprocessing steps of data-driven NLP applications like *Machine Translation* (MT). In contrast to Indo-European languages like English, many Asian languages like Chinese do not use a whitespace character to separate meaningful word units. The problems of word segmentation are:

(1) *ambiguity*, e.g., for Chinese, a single character can be a word component in one context, but a word by itself in another context.
(2) *unknown words*, i.e., single words can be combined into new words such as proper nouns ("*White House*").

Purely dictionary-based approaches like [1] addressed these problems by maximum matching heuristics. Recent research on unsupervised word segmentation focuses on approaches based on probabilistic methods. For example, [2] proposed a probabilistic segmentation model based on unigram word distributions, whereas [3] used standard n-gram ($1 \leq n \leq 3$) language models. An alternative non-parametric Bayesian inference approach based on the Dirichlet process incorporating unigram and bigram word dependencies is introduced in [4].

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The focus of this paper, however, is to learn word segmentations that are *consistent with the phrasal segmentations of SMT translation models*. In the case of small translation units, e.g. single Chinese or Japanese characters, it is likely that such tokens have been seen in the training corpus, thus these tokens can be translated by an SMT engine. However, the contextual information provided by these tokens might not be enough to obtain a good translation. For example, a Japanese-English SMT engine might translate the two successive characters "白" ("white") and "鳥" ("bird") as "*white bird*", while a human would translate "白鳥" as "*swan*". Therefore, the longer the translation unit, the more context can be exploited to find a meaningful translation. On the other hand, the longer the translation unit, the less likely it is that such a token will occur in the training data due to *data sparseness* of the language resources utilized to train the statistical translation models. Therefore, a word segmentation that is "consistent with SMT models" is one that identifies translation units that are small enough to be translatable but large enough to be meaningful in the context of the given input sentence, achieving a trade-off between the *coverage* and the *translation task complexity* of the statistical models in order to improve translation quality.

The use of monolingual probabilistic models does not necessarily yield a better MT performance [5]. However, improvements have been reported for approaches taking into account not only monolingual, but also bilingual information, to derive a word segmentation suitable for SMT. Due to the availability of language resources, most recent research has focused on optimizing Chinese word segmentation (CWS) for Chinese-to-English SMT. For example, [6] proposes a Bayesian Semi-Supervised approach for CWS that builds on [4]. The generative model first segments Chinese text using an off-the-shelf segmenter and then learns new word types and word distributions suitable for SMT. Similarly, a dynamic programming-based variational Bayes approach using bilingual information to improve MT is proposed in [7]. Concerning other languages, for example, [8] extended Hidden-Markov-Models, where hidden n-gram probabilities were affected by co-occurring words in the target language part for Japanese word segmentation.

Recent research on SMT is also focusing on the usage of multiple word segmentation schemes for the source language to improve translation quality. For example, [9] combines dictionary-based and CRF-based approaches for Chinese word segmentation in order to avoid *out-of-vocabulary* (OOV) words. Moreover, the combination of different types

of morphological decomposition used in highly inflected languages like Arabic or Finnish is proposed in [10] to reduce the data sparseness problem of SMT approaches. Similarly, [11] utilizes SMT engines trained on different word segmentation schemes and combines the translation outputs using system combination techniques as a post-process to SMT decoding.

In order to integrate multiple word segmentation schemes into the SMT decoder, [12] proposed to generate word lattices covering all possible segmentations of the input sentence and to decode the lattice input. An extended version of the lattice approach that does not require the use and existence of monolingual segmentation tools was proposed in [13], where a maximum entropy model is used to assign probabilities to the segmentations of an input word to generate diverse segmentation lattices from a single automatically learned model.

The method of [14] also uses a word lattice decoding approach, but they iteratively extract multiple word segmentation schemes from the training bitext. This dictionary-based approach uses heuristics based on the maximum matching algorithm to obtain an agglomeration of segments that are covered by the dictionary. It uses all possible source segmentations that are consistent with the extracted dictionary to create a word lattice for decoding.

The method proposed in this paper differs from previous approaches in the following ways:

- it works for any language pair in which the source language is unsegmented and the target language segmentation is known.
- it can be applied for the translation of a source language where no linguistically motivated word segmentation tools are available.
- it applies machine learning techniques to identify segmentation schemes that improve the translation quality for a given language pair.
- it decodes directly from unsegmented text using segmentation information implicit in the phrase-table to generate the target and thus avoids issues of consistency between phrase-table and input representation.
- it uses segmentations at all iterative levels of the bootstrap process, rather than only those from the final iteration, which allows for consideration of segmentation from many levels of granularity.

Word segmentations are learned using a parallel corpus by aligning character-wise source language sentences to word units separated by a whitespace in the target language. Successive characters aligned to the same target words are merged into a larger source language unit. Therefore, the granularity of the translation unit is defined in the given bitext context. In order to minimize the side effects of alignment errors and to achieve segmentation consistency, a Maximum-Entropy (ME) algorithm is applied to learn a source language word segmentation that is consistent with the translation model of an SMT system trained on the resegmented bitext. The process is iterated until no further improvement in translation quality is achieved. In order to integrate multiple word segmentation into a single SMT system, the statistical translation models trained on differently segmented source language corpora are merged by characterizing the source side of each translation model, summing up the probabilities of identical phrase translation pairs, and rescoring the merged translation model (see Sect. 2).

The proposed segmentation method is applied to the translation of five Asian languages, i.e., Japanese, Korean, Thai, and two Chinese dialects (Chinese Mandarin and Taiwanese Mandarin), into English. The utilized language resources and the outline of the experiments are summarized in Sect. 3. The experimental results revealed that the proposed method outperforms not only a baseline system that translates characterized source language sentences, but also all SMT models trained on any of the learned word segmentations. In addition, the proposed method achieves translation results comparable to SMT models trained on linguistically segmented bitext.

2. Word Segmentation

The word segmentation method proposed in this paper is an unsupervised, language-independent approach that treats the task of word segmentation as a *phrase-boundary tagging* task. This method uses a parallel text corpus consisting of initially unigram segmented source language character sequences and whitespace-separated target language words. The initial bitext is used to train a standard phrase-based SMT system (SMT_{chr}). The character-to-word alignment results of the SMT training procedure[†] are exploited to identify successive source language characters aligned to the same target language word in the respective bitext and to merge these characters into larger translation units, defining its granularity in the given bitext context. Unaligned source language characters are treated as a single translation unit.

The obtained translation units are then used to learn the word segmentation that is most consistent with the phrase alignments of the given SMT system. First, each character of the source language text is annotated with a word-boundary indicator where only two tags are used, i.e, *"WB"* (word boundary) if the given source language character is the last one of a merge character sequence aligned to a target language word, and *"NB"* (no boundary), otherwise. Using these alignment-based word boundary annotations, a Maximum-Entropy (ME) method is applied to learn the most consistent word segmentation (see Sect. 2.1), to resegment the original source language corpus, and to re-train a phrase-based SMT engine that will hopefully achieve a better translation performance than the initial SMT engine. This process should be repeated as long as an improvement in translation quality is achieved. Eventually, the concate-

[†]For the experiments presented in Sect. 3, the GIZA++ toolkit was used.

nation of succeeding translation units will result in overfitting, i.e., the newly created token can only be translated in the context of rare training data examples. Therefore, a lower translation quality due to an increase of untranslatable source language phrases is to be expected (see Sect. 2.2).

However, in order to increase the *coverage* and to reduce the *translation task complexity* of the statistical models, the proposed method integrates multiple segmentation schemes into the statistical translation models of a single SMT engine so that longer translation units are preferred for translation, if available, and smaller translation units can be used otherwise (see Sect. 2.3).

2.1 Maximum-Entropy Tagging Model

ME models provide a general purpose machine learning technique for classification and prediction. They are versatile tools that can handle large numbers of features, and have shown themselves to be highly effective in a broad range of NLP tasks including sentence boundary detection or part-of-speech tagging [15].

A *maximum entropy classifier* is an exponential model consisting of a number of binary feature functions and their weights [16]. The model is trained by adjusting the weights to maximize the entropy of the probabilistic model given constraints imposed by the training data. In our experiments, we use a *conditional maximum entropy* model, where the conditional probability of the outcome given the set of features is modeled [17]. The model has the following form:

$$p(t,c) = \gamma \prod_{k=0}^{K} \alpha_k^{f_k(c,t)} \cdot p_0$$

where:

- t is the tag being predicted;
- c is the context of t;
- γ is a normalization coefficient;
- K is the number of features in the model;
- f_k are binary feature functions;
- a_k is the weight of feature function f_k;
- p_0 is the default model.

The feature set is given in Table 1. The *lexical context features* consist of target words annotated with a tag t. w_0 denotes the word being tagged and $w_{-2}, \ldots, w_{+2}$ the surrounding words. t_0 denotes the current tag, t_{-1} the previous tag, etc. The *tag context features* supply information about the context of previous tag sequences. This conditional model can be used as a classifier. The model is trained iteratively, and we used the improved iterative scaling algorithm (IIS) [15] for the experiments presented in Sect. 3.

Table 1 Feature set of ME tagging model.

Lexical Context Features	$< t_0, w_{-2} >$ $< t_0, w_{-1} >$ $< t_0, w_0 >$ $< t_0, w_{+1} >$ $< t_0, w_{+2} >$
Tag Context Features	$< t_0, t_{-1} >$ $< t_0, t_{-1}, t_{-2} >$

2.2 Iterative Bootstrap Method

The proposed iterative bootstrap method to learn the word segmentation that is consistent with an SMT engine is summarized in Fig. 1. After the ME tagging model is learned from the initial character-to-word alignments of the respective bitext ((1)-(4)), the obtained ME tagger is applied to resegment the source language side of the unsegmented parallel text corpus ((5)). This results in a resegmented bitext that can be used to retrain and reevaluate another engine SMT_1 ((6)), achieving what is hoped to be a better translation performance than the initial SMT engine (SMT_{chr}).

The unsupervised ME tagging method can also be applied to the token-to-word alignments extracted during the training of the SMT_1 engine to obtain an ME tagging model ME_1 capable of handling longer translation units ((7)-(8)). Such a bootstrap method iteratively creates a sequence of SMT engines SMT_i ((9)-(J)), each of which reduces the translation complexity, because larger chunks can be translated in a single step leading to fewer word order or word disambiguation errors. However, at some point, the increased length of translation units learned from the training corpus will lead to overfitting, resulting in reduced translation performance when translating unseen sentences. Therefore, the bootstrap method stops when the J^{th} resegmentation of the training corpus results in a lower automatic evaluation score for the unseen sentences than the one for the previous iteration. The ME tagging model ME_{J-1} that achieved the highest automatic translation scores is then selected as the best single-iteration word segmenter.

2.3 Integration of Multiple Segmentation Schemes

The integration of multiple word segmentation schemes is carried out by merging the translation models of the SMT engines trained on the characterized and iteratively learned segmentation schemes. This process is performed by linearly interpolating the model probabilities of each of the

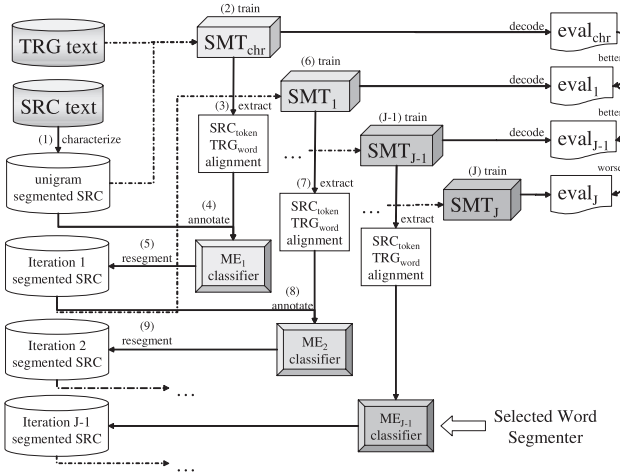


Fig. 1 Iterative bootstrap method.

models. In our experiments, equal weights were used; however, it might be interesting to investigate varying the weights according to iteration number, as the latter iterations may contain more useful segmentations.

In addition to the model interpolation, we also remove the internal segmentation of the source phrases by splitting them into characters. The advantages are twofold. Primarily it allows decoding directly from unsegmented text. Moreover, the segmentation of the source phrase can differ between models at differing iterations; removing the source segmentation at this stage makes the phrase pairs in the translations models at various stages in the iterative process consistent with one another. Consequently, duplicate bilingual phrase pairs appear in the phrase table. These duplicates are combined by summing their model probabilities prior to model interpolation.

The rescored translation model covers all translation pairs that were learned by any of the iterative models. Therefore, the selection of longer translation units during decoding can reduce the complexity of the translation task. On the other hand, overfitting problems of single-iteration models can be avoided because multiple smaller source language translation units can be exploited to cover the given source language input parts and to generate translation hypotheses based on the concatenation of associated target phrase expressions. Moreover, the merging process increases the translation probabilities of the source/target translation parts that cover the same surface string but differ only in the segmentation of the source language phrase. Therefore, the more often such a translation pair is learned by different iterative models, the more often the respective target language expression will be exploited by the SMT decoder.

The translation of unseen data using the merged translation models is carried out by (1) characterizing the input text and (2) applying the SMT decoding in a standard way.

3. Experiments

The effects of using different word segmentations and integrating them into an SMT engine are investigated using the multilingual *Basic Travel Expressions Corpus* (BTEC), which is a collection of sentences that bilingual travel experts consider useful for people going to or coming from other countries [18]. For the word segmentation experiments, we selected five Asian languages that do not naturally separate word units, i.e., Japanese (ja), Korean (ko), Thai (th), and two dialects of Chinese (Chinese Mandarin (zh) and Taiwanese Mandarin (tw)).

Table 2 summarizes the characteristics of the BTEC corpus used for the training (*train*) of the SMT models, the tuning of model weights and the stop conditions of the iterative bootstrap method (*dev*), and the evaluation of translation quality (*eval*). Besides the number of sentences (*sen*) and the vocabulary (*voc*), the sentence length (*len*) is also given as the average number of words per sentence. The given statistics are obtained using commonly-used linguistic segmentation tools available for the respective language,

Table 2 Language resources.

BTEC		train set	dev set	eval set
# of sen		160,000	1,000	1,000
en	voc	15,390	1,262	1,292
	len	7.5	7.1	7.2
ja	voc	17,168	1,407	1,408
	len	8.5	8.2	8.2
ko	voc	17,246	1,366	1,365
	len	8.0	7.7	7.8
th	voc	7,354	1,081	1,053
	len	7.8	7.3	7.4
zh	voc	11,084	1,312	1,301
	len	7.1	6.4	6.5

i.e., CHASEN[†] (ja), WORDCUT[††] (th), ICTCLAS[†††] (zh), HanTagger[††††] (ko). No segmentation was available for Taiwanese Mandarin and therefore no meaningful statistics could be obtained.

For the training of the SMT models, standard word alignment [19] and language modeling [20] tools were used. Minimum error rate training (MERT) was used to tune the decoder's parameters and performed on the *dev* set using the technique proposed in [19]. For the translation, a multi-stack phrase-based decoder [21] was used.

For the evaluation of translation quality, we applied standard automatic evaluation metrics, i.e., BLEU [22] and METEOR [23]. We have tested the statistical signifcance of our results[†††††] using the bootstrap method reported in [24] that (1) performs a random sampling with replacement from the evaluation data set, (2) calculates the evaluation metric score of each engine for the sampled test sentences and the difference between the two MT system scores, (3) repeats the sampling/scoring step iteratively, and (4) applies the *Student's t-test* at a significance level of 95% confidence to test whether the score differences are significant.

In addition, human assessment of translation quality was carried out using the *Ranking* metrics. For the *Ranking* evaluation, a human grader was asked to *"rank each whole sentence translation from Best to Worst relative to the other choices (ties are allowed)"* [25]. The *Ranking* scores were obtained as the average number of times that a system was judged better than any other system and the normalized ranks (*NormRank*) were calculated on a per-judge basis for each translation task using the method of [26].

Section 3.1 compares the proposed method to the baseline system that translates characterized source language sentences and to the SMT engines that are trained on iteratively learned as well as language-dependent linguistic word segmentations. The effects of the iterative learning method are summarized in Sect. 3.2.

[†]http://chasen.naist.jp/hiki/ChaSen/.
[††]http://sourceforge.net/projects/thaiwordseg/files/.
[†††]http://www.nlp.org.cn/.
[††††]Inhouse Korean word segmenter.
[†††††]2000 iterations were used for the analysis of the automatic evaluation results in this paper. All reported differences in evaluation scores are statistically significant.

Table 3 Automatic evaluation (BTEC).

BLEU

source language	word segmentation			
	character	single-best	proposed	linguistic
ja	36.93	39.65	41.25	**41.46**
ko	34.72	37.32	**38.51**	37.19
th	41.42	50.16	50.53	**56.68**
zh	36.59	37.02	**38.61**	38.13
tw	45.71	50.95	**52.21**	–

METEOR

source language	word segmentation			
	character	single-best	proposed	linguistic
ja	59.78	60.95	65.45	**66.03**
ko	58.45	60.06	**64.31**	63.04
th	67.22	71.22	72.58	**79.02**
zh	61.77	62.38	**63.80**	62.72
tw	70.14	73.64	**74.38**	–

3.1 Effects of Word Segmentation

The automatic evaluation scores of the SMT engines trained on the differently segmented source language resources are given in Table 3, where "*character*" refers to the baseline system of using character-segmented source text; "*single-best*"[†] is the SMT engine that is trained on the corpus segmented by the best-performing iteration of the bootstrap approach; "*proposed*" is the SMT engine whose models integrate multiple word segmentation schemes; and "*linguistic*" uses language-dependent linguistically motivated word segmentation tools. The reported scores are calculated as the mean score of all metric scores obtained for the iterative sampling method used for statistical significance testing and listed as percentage figures.

The results show that the proposed method outperforms the *character* (*single-best*) system for each of the involved languages for both evaluation metrics achieving gains of 2.0~9.1 (0.4~1.6) BLEU points and 2.0~5.9 (0.7~4.6) METEOR points, respectively. However, the improvements depend on the respective source language and its characteristics. For example, the smallest gains were obtained for Chinese Mandarin, because single characters frequently form words of their own, thus resulting in more ambiguity than Japanese, where consecutive *hiragana* or *katakana* characters can form larger meaningful units.

Comparing the proposed method towards linguistically motivated segmenters, the results show that the proposed method achieves higher automatic evaluation scores than the SMT engines using linguistic segmentation tools for tasks such as translating Korean and Chinese Mandarin into English. Slightly lower evaluation scores were achieved for the automatically learned word segmentation for Japanese, although the results of the proposed method are quite similar. This is a suprisingly strong result, given the maturity of the linguistically motivated segmenters, and given that our segmenters use only the bilingual corpus used to train the SMT systems.

Table 4 Subjective evaluation (BTEC).

NormRank

source language	word segmentation			
	character	single-best	proposed	linguistic
ja	2.76	2.85	**3.18**	3.12
ko	2.68	2.90	**3.17**	3.09
th	2.65	2.95	3.05	**3.43**
zh	2.87	3.01	**3.07**	3.04
tw	2.83	2.86	**3.24**	–

The Thai-English experiments expose some issues that are related to the definition of what a "character" is. Our segmentation schemes are learned directly from the bitext without any language-specific information, and can cope well with most languages. However, Thai seems to be an exceptional case in our experiments, because (1) the Thai script is a segmental writing system which is based on consonants but in which vowel notation is obligatory, so that the characterization of the baseline system affects vowel dependencies, (2) it uses tone markers that are placed above the consonant, but are treated as a single character in our approach, and (3) vowels sounding after a consonant are non-sequential and can occur before, after, above, or below a consonant increasing the number of word form variations in the training corpus and reducing the accuracy of the learned ME tagging models. This is an interesting result that motivates further study on how to incorporate features on language scripts into our machine learning framework. For example, Japanese is written in three different scripts (*kanji*, *hiragana*, *katakana*). Therefore, the script class of each character could be used as an additional feature to obtain the initial segmentation of the training corpus.

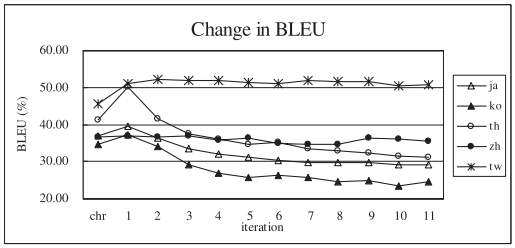
Finally, the results for Taiwanese Mandarin, where no linguistic tool was available to segment the source language text, shows that the proposed method can be applied successfully for the translation of any language where no linguistically-motivated segmentation tools are available.

Table 4 summarizes the subjective evaluation results which were carried out by a paid evaluation expert who is a native speaker of English. The *NormRank* results confirm the findings of the automatic evaluation. In addition, for Japanese, the translation outputs of the proposed method were judged better than those of the linguistically segmented SMT model.

3.2 Effects of Bootstrap Iteration

In order to get an idea of the robustness of the proposed method, the changes in system performance for each source language during the iterative bootstrap method is given in Fig. 2. The results for BLEU and METEOR show that all languages reach their best performance after the first or second iteration and then slightly, but consistently decrease with the increased number of iterations. The reason for this is the

[†]This approximates the approach of [14] and is given as a way of showing the effect of segmentation at multiple levels of granularity.



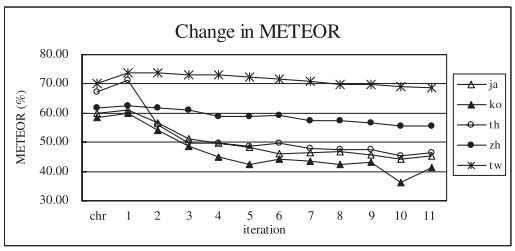
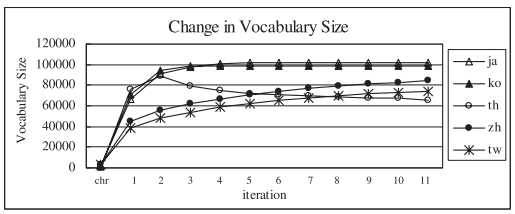


Fig. 2 Change in system performance.



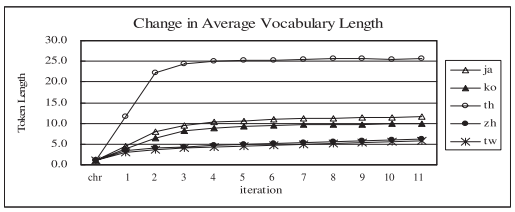


Fig. 3 Change in vocabulary size and length.

effect of overfitting caused by the concatenation of source tokens that are aligned to longer target phrases, resulting in the segmentation of longer translation units.

The changes in the vocabulary size and the word length are summarized in Fig. 3. The amount of words extracted by the proposed method is much larger than the one of the baseline system, increasing the vocabulary size by a factor of 10 for Chinese Mandarin and Taiwanese Mandarin, 30 for Japanese and Korean, and 100 for Thai. It is also larger than the vocabulary obtained for the linguistic tools by a factor of 1.5∼2.5 for all investigated languages. The average vocabulary length also increased for each iteration whereby the length of the translation units learned after 10 iterations almost doubles the word size of the initial iteration.

The overfitting problem of the iterative bootstrap method is illustrated in the increase of *out-of-vocabulary* words, i.e. source language words contained in the unseen evaluation data set that cannot be translated by the respective SMT. The results given in Fig. 4 show a large increase in OOV for the first three iterations, resulting in lower translation qualities as listed in Fig. 2.

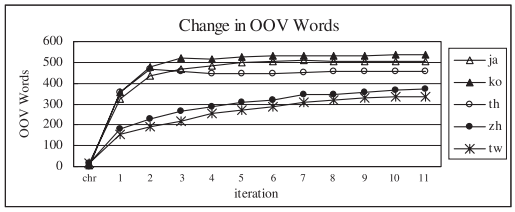


Fig. 4 Change in out-of-vocabulary size.

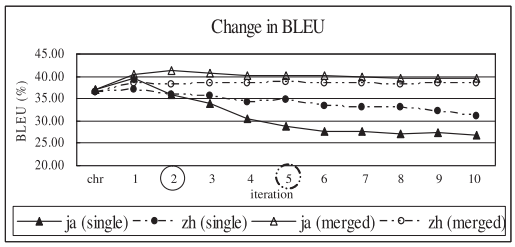


Fig. 5 Gain of integrating multiple segmentation schemes.

Table 5 Number of integrated segmentation schemes.

inter-polation	source language				
	ja	ko	th	zh	tw
#systems	2	5	3	5	3

3.3 Effects of Integrating Multiple Segmentation Schemes

Figure 5 illustrates the effects of integrating multiple SMT phrase-tables based on different word segmentation schemes for the Chinese Mandarin (zh) and Japanese (ja) to English BTEC translation tasks. Initially, the character-based and the first-iteration phrase-tables are linearily interpolated as described in Sect. 2.3. For each iteration, the newly learned phrase-table is interpolated with the previous integrated one. After each interpolation step, the BLEU scores are recalculated using the extended phrase-table. The results show that the system performance of the proposed method initially increases, then decreases slightly after a certain number of iterations. Table 5 summarizes the number of systems based on iteratively learned word segmentation schemes that are interpolated with the character-based system to obtain the highest BLEU scores reported in Table 3.

Table 6 illustrates translation examples using different segmentation schemes for the Japanese-English BTEC translation task. The SMT engines that output the best translations are marked with an asterisk. In the first example, the concatenation of “もう真夜中” (*already midnight*) by the *single-best* segmentation scheme leads to an OOV word, thus only a partial translation can be achieved. However, the problem can be resolved using the proposed method. The second example is best translated using the *single-best* word segmentation that correctly handles the sentence coordination. The baseline system omits the sentence coordination information, resulting in an unacceptable translation. The third examples illustrates that longer tokens reduce the

Table 6 Sample translations (BTEC).

linguistic	*seg:* ええ/。/えーと/、/もう/真夜中/です/ね 。 *trans:* Yes. Let's see. It's midnight.
character*	*seg:* え/え/。/え/ー/と/、/も/う/真/夜/中/で/す/ね/。 *trans:* Yes. Well, it's already midnight.
single-best	*seg:* ええ。/えーと/、/もう真夜中/で/すね。 *trans:* Yes. Let 's see.
proposed*	*seg:* え/え/。/え/ー/と/、/も/う/真/夜/中/で/す/ね/。 *trans:* Yes. Well, it's already midnight.
linguistic	*seg:* ジーンズ/が/欲しい/の/です/が/、/いい/店/を/教え/て/ください/。 *trans:* I'd like a pair of jeans. Could you recommend a good shop?
character	*seg:* ジ/ー/ン/ズ/が/欲/し/い/の/で/す/が/、/い/い/店/を/教/え/て/く/だ/さ/い/。 *trans:* Could you recommend a good 'd like a pair of jeans.
single-best*	*seg:* ジーンズ/が欲し/い/のですが、/いい/店/を教え/てください/。 *trans:* I'd like some jeans. Could you recommend a good shop?
proposed	*seg:* ジ/ー/ン/ズ/が/欲/し/い/の/で/す/が/、/い/い/店/を/教/え/て/く/だ/さ/い/。 *trans:* I 'd like a pair of jeans and could you recommend a good shop?
linguistic	*seg:* 今日/の/午後/まで/に/でき/ます/か/。 *trans:* Will it be ready by this afternoon?
character	*seg:* 今/日/の/午/後/ま/で/に/で/き/ま/す/か/。 *trans:* It'll be ready by this afternoon?
single-best	*seg:* 今日の/午後まで/に/できま/すか。 *trans:* Will it be ready by this afternoon?
proposed*	*seg:* 今/日/の/午/後/ま/で/に/で/き/ま/す/か/。 *trans:* Can you have these ready by this afternoon?

translation complexity and thus can be translated better than the other segmentation that cause more ambiguities.

3.4 Effects of Incorporating Linguistic Segmentations

In order to investigate the effects of integrating language-dependent segmentation information, we also interpolated the phrase-table of the linguistically-based SMT system with the iteratively learned ones. The experimental results summarized in Table 7 show that the proposed method can even improve a state-of-the-art baseline SMT system that is trained using a linguistically motivated word segmentation scheme by integrating linguistically, character-based, and learned word segmentation schemes.

3.5 Domain Dependency

In addition to the travel data sets, we also applied the proposed method to the task of translating scientific paper abstracts. The *JST* corpus is a collection of 1M Japanese-English sentence pairs (avg. 34 words/sentence) comprised of abstracts from scientific papers covering topics including medicine (28.4%), physics (9.4%), biology (8.9%), electrical engineering (7.6%), agriculture (6.3%), computer science (6.0%), and 20 additional areas (33.0%). The data was extracted from a larger set of scientific abstracts from the Japan Science and Technology Agency using the sentence alignment method proposed in [27]. The experimental results are summarized in Table 8. The results show the same tendency as the Japanese-English BTEC task, i.e. the proposed method outperforms the character-based and single-best systems and achieves scores similar to an SMT system trained on linguistically segmented data sets.

Table 7 Integration of linguistic and learned segmentations (BTEC).

BLEU

	word segmentation: linguistic only	word segmentation: proposed +linguistic
ja	41.46	**42.65**
ko	37.19	**38.35**
th	56.68	**56.88**
zh	38.13	**38.92**

METEOR

	word segmentation: linguistic only	word segmentation: proposed +linguistic
ja	66.03	**66.46**
ko	63.04	**63.10**
th	**79.02**	78.62
zh	62.72	**63.65**

Table 8 Automatic evaluation (JST).

source (ja)	word segmentation: character	single-best	proposed	linguistic
BLEU	12.72	13.28	13.82	**14.20**
METEOR	50.30	51.74	53.00	**53.43**

4. Conclusions

This paper proposes a new language-independent method to segment languages that do not use whitespace characters to separate meaningful word units in an unsupervised manner in order to improve the performance of a state-of-the-art SMT system. The proposed method does not need any linguistic information about the source language which is important when building SMT systems for the translation of relatively resource-poor languages which frequently lack morphological analysis tools. In addition, the development costs are far less than those for developing linguistic word segmentation tools or even paying humans to segment the data sets manually, since only the bilingual corpus used to train the SMT system is needed to train the segmenter.

The effectiveness of the proposed method was investigated for the translation of Japanese, Korean, Thai, Chinese Mandarin and Taiwanese Mandarin into English for the domain of travel conversations. The automatic evaluation of the translation results showed consistent improvements of 2.0~9.1 BLEU points and 2.0~5.9 METEOR points compared to a baseline system that translates characterized input. Moreover, it improves the best performing SMT engine of the iterative learning procedure by 0.4~1.6 BLEU points and 0.7~4.6 METEOR points.

In addition, the proposed method achieved translation

results similar to SMT models trained on bitext segmented with linguistically motivated tools according to human evaluations, even though no external information and only the given bitext was used to train the segmentation models. The integration of linguistically motivated and iteratively learned word segmentations schemes improved the overall system performance further.

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References

[1] K.S. Cheng, G. Young, and K.F. Wong, "A study on word-based and integrat-bit Chinese text compression algorithms," American Society of Information Science, vol.50, no.3, pp.218–228, 1999.
[2] M. Brent, "An efficient, probabilistically sound algorithm for segmentation and word discovery," Mach. Learn., vol.34, pp.71–105, 1999.
[3] A. Venkataraman, "A statistical model for word discovery in transcribed speech," Computational Linguistics, vol.27, no.3, pp.351–372, 2001.
[4] S. Goldwater, T. Griffith, and M. Johnson, "Contextual dependencies in unsupervised word segmentation," Proc. ACL, pp.673–680, Sydney, Australia, 2006.
[5] P.C. Chang, M. Galley, and C. Manning, "Optimizing Chinese word segmentation for machine translation performance," Proc. 3rd Workshop on SMT, pp.224–232, Columbus, USA, 2008.
[6] J. Xu, J. Gao, K. Toutanova, and H. Ney, "Bayesian semi-supervised Chinese word segmentation for SMT," Proc. COLING, pp.1017–1024, Manchester, UK, 2008.
[7] T. Chung and D. Gildea, "Unsupervised tokenization for machine translation," Proc. EMNLP, pp.718–726, Singapore, 2009.
[8] G. Kikui and H. Yamamoto, "Finding translation pairs from English-Japanese untokenized aligned corpora," Proc. Workshop on Speech-to-Speech Translation, pp.23–30, Philadephia, USA, 2002.
[9] R. Zhang, K. Yasuda, and E. Sumita, "Improved statistical machine translation by multiple Chinese word segmentation," Proc. 3rd Workshop on SMT, pp.216–223, Columbus, USA, 2008.
[10] A. de Gispert, S. Virpioja, M. Kurimo, and W. Byrne, "Minimum bayes risk combination of translation hypotheses from alternative morphological decompositions," Proc. HLT/NAACL, Companion Volume, pp.73–76, Boulder, USA, 2009.
[11] P. Nakov, C. Liu, W. Lu, and H.T. Ng, "The NUS SMT system for IWSLT 2009," Proc. IWSLT, pp.91–98, Tokyo, Japan, 2009.
[12] C. Dyer, S. Muresan, and P. Resnik, "Generalizing word lattice translation," Proc. ACL, pp.1012–1020, Columbus, USA, 2008.
[13] C. Dyer, "Using a maximum entropy model to build segmentation lattices for MT," Proc. HLT, pp.406–414, Boulder, USA, 2009.
[14] Y. Ma and A. Way, "Bilingually motivated domain-adapted word segmentation for statistical machine translation," Proc. 12th EACL, pp.549–557, Athens, Greece, 2009.
[15] A. Berger, S.D. Pietra, and V.D. Pietra, "A maximum entropy approach to NLP," Computational Linguistics, vol.22, no.1, pp.39–71, 1996.
[16] S.D. Pietra, V.D. Pietra, and J. Lafferty, "Inducing features of random fields," IEEE Trans. Pattern Anal. Mach. Intell., vol.19, no.4, pp.380–393, 1997.
[17] A. Ratnaparkhi, "A maximum entropy model for part-of-speech tagging," Proc. EMNLP, pp.133–142, Pennsylvania, USA, 1996.
[18] G. Kikui, S. Yamamoto, T. Takezawa, and E. Sumita, "Comparative study on corpora for speech translation," IEEE Trans. Audio, Speech and Language, vol.14, no.5, pp.1674–1682, 2006.
[19] F.J. Och and H. Ney, "A systematic comparison of statistical alignment models," Computational Linguistics, vol.29, no.1, pp.19–51, 2003.
[20] A. Stolcke, "SRILM an extensible language modeling toolkit," Proc. ICSLP, pp.901–904, Denver, USA, 2002.
[21] A. Finch, E. Denoual, H. Okuma, M. Paul, H. Yamamoto, K. Yasuda, R. Zhang, and E. Sumita, "The NICT/ATR speech translation system," Proc. IWSLT, pp.103–110, Trento, Italy, 2007.
[22] K. Papineni, S. Roukos, T. Ward, and W.J. Zhu, "BLEU: A method for automatic evaluation of machine translation," Proc. 40th ACL, pp.311–318, Philadelphia, USA, 2002.
[23] A. Lavie and A. Agarwal, "METEOR: An automatic metric for MT evaluation with high levels of correlation with human judgments," Proc. 2nd Workshop on SMT, pp.228–231, Prague, Czech Republic, 2007.
[24] Y. Zhang, S. Vogel, and A. Waibel, "Interpreting Bleu/NIST scores: How much improvement do we need to have a better system?," Proc. LREC, pp.2051–2054, Lisbon, Portugal, 2004.
[25] C. Callison-Burch, C. Fordyce, P. Koehn, C. Monz, and J. Schroeder, "(Meta-) Evaluation of machine translation," Proc. 2nd Workshop on SMT, pp.136–158, Prague, Czech Republic, 2007.
[26] J. Blatz, E. Fitzgerald, G. Foster, S. Gandrabur, C. Goutte, A. Kulesza, A. Sanchis, and N. Ueffing, "Confidence estimation for statistical machine translation," Final Report of the JHU Summer Workshop, 2003.
[27] M. Utiyama and H. Isahara, "A Japanese-English patent parallel corpus," Proc. MT Summit XI, pp.475–482, Copenhagen, Denmark, 2007.

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