

# Fast, Scalable Phrase-Based SMT Decoding

Anonymous ACL submission

## Abstract

The utilization of statistical machine translation (SMT) has grown enormously over the last decade, many using open-source software developed by the NLP community. As commercial utilization has increased, there has been a pressing need that is optimized for their requirements. Specifically, faster phrase-based decoding, and more efficient utilization of modern multicore servers.

We present in this paper a re-assessment of the major components of phrase-based decoding and decoder implementation with particular emphasis on speed and scalability to multicore machines. The result is a drop-in replacement for the Moses decoder which is up to fifteen times faster and scales almost linearly with the number of cores. Furthermore, the decoder makes less search errors than the current Moses decoder.

## 1 Introduction

SMT has been one of the outstanding success story from the NLP community in the last decade, progressing from a mostly research discipline to public useability via services such as Google Translate, Microsoft Translator Hub, as well as services and products built around offline products such as Language Weaver and the open-source Moses toolkit. The latter has spawned a cottage industry encompassing a range of organizations and services from small language service providers seeking to reduce translation cost, to large inter-governmental organizations such as the EU and the UN that require high volume, high quality translation.

For high volume users, decoding is a largest and most critical part of the translation process which needs to be fast and efficient. However, it has been noticed that the Moses decoder, amongst others, is unable to efficiently use multiple CPU cores that are now common on modern servers (reviewed paper, github discussion). That is, the time taken to decode a test set does not substantial decrease when more cores are used, in fact, decoding time may increase when more cores are added. The problem will continue to grow as the commercial use of SMT increases and the number of CPU cores increases.

There have been speculation on the causes of the inefficiency as well as potential remedies. This paper is the first we know of that seeks to tackle this problem head on. We present an phrase-based decoder that is not only significantly faster than the Moses baseline for single-threaded operation, but is able to scale run multiple threads on multicore machines with only a slightly loss in linear speed. Model scores and functionality are compatible with Moses to aid comparison and ease of transition for users. All source code will be made available under an open-source license.

### 1.1 Prior Work

There are a number of open-source SMT projects, most includes a decoder. The most well known is Moses, which supports phrase-based models, hierarchical phrase-based as well as various syntax-based models. Joshua also supports hierarchical and syntax models and has recently supported phrase-based models. Phrasal supports a number of variants of the phrase-based model. CDEC supports hierarchical and syntactic models.

A number of the decoders support multithreading whilst others use alternative methods such as Hadoop or external scripts to parallelize decoding. We shall investigate the efficiency of using

parallelizing decoding using the multi-processor approach. None of the decoder focus on multi-threads decoding.

(Recently reviewed) describes running multiple processes of the Moses decoder for increased speed.

Other prior work look to optimizing specific components of decoding. (Liang and Chiang) describes the cube-pruning and cube-growing algorithm for decoding which allows the tradeoff between speed and translation quality to the adjusted with a single parameter. (KenLM) and (DALM) describes fast, efficient datastructures for language models. (Zen) describes an implementation of a phrase-table for an SMT decoder that is loaded on demand, reducing the initial loading time and memory requirements. (CompactPT) extends this by compressing the on-disk phrase table and lexicalized re-ordering model resulting in impressive speed gains over previous work.

(mtplz) is perhaps closest in intent to this work. This takes a wholistic approach to decoding, describing a novel decoding algorithm which is focused on better decoding speed. It also describes a number of implementation details for faster decoding. However, the decoding algorithm is only able to incorporate one stateful feature function which precludes some of the useful decoding configurations which contains multiple stateful feature functions. It does not include a load-on-demand phrase table, therefore, cannot be used in a commercial environment where phrase-table has not be filtered with a know test set for any realistic size phrase-table. Neither did this paper analyze the scalability of their work to multicore servers.

The rest of the paper will be broken up into the following sections. Next, we will describe the phrase-based model and the major implementation components, with particular emphasis on decoding time shortcomings. We will then describe modifications to improve decoding speed and present results. We conclude in the last section discuss suggested improvements and future work.

## 2 Phrase-Based Model

The objective of decoding is to find the target translation with the maximum probability, given a source sentence. That is, for a source sentence  $s$ , the objective is to find a target translation  $\hat{t}$  which has the highest conditional probability

$p(t|s)$ . Mathematically, this is written as:

$$\hat{t} = \arg \max_t p(t|s) \quad (1)$$

where the *arg max* function is the search. The log-linear model generalizes Equation 1 to include more component models and weighting each model according to the contribution of each model to the total probability.

$$p(t|s) = \frac{1}{Z} \exp\left(\sum_m \lambda_m h_m(t, s)\right) \quad (2)$$

where  $\lambda_m$  is the weight, and  $h_m$  is the feature function, or ‘score’, for model  $m$ .  $Z$  is the partition function which can be ignored for optimization.

### 2.1 Beam Search

A translation of a source sentence is created by applying a series of translation rules which together translate each source word once, and only once. Each partial translation is called a *hypothesis*, which is created by applying a rule to an existing hypothesis. This process is called *hypothesis expansion* and starts with a hypothesis that has translated no source word and ends with a completed hypothesis that has translated all source words. The highest-scoring completed hypothesis, according to the model score, is returned as most probable translation,  $\hat{t}$ . Incomplete hypotheses are referred to as partial hypotheses.

Each rule translates a contiguous sequence of source words but successive translation options do not have to be adjacent on the source side, depending on the distortion limit. However, the target output is constructed strictly left-to-right from the target string of successive translation options. Therefore, successive translation options which are not adjacent and monotonic in the source causes translation reordering.

A beam search algorithm is used to create the completed hypothesis set efficiently. Partial hypotheses are organized into stacks where each stack holds a number of comparable hypotheses. Hypotheses in the same stack have the same coverage cardinality  $|C|$ , where  $C$  is the coverage set,  $C \subseteq \{1, 2, \dots |s|\}$  of the number of source words translated. Therefore,  $|s| + 1$  number of stacks are created for the decoding of a sentence  $s$ .

There are three main optimization to the search that we shall investigate. Firstly, the search creates and destroy a large number of hypothesis objects in memory which puts a heavy burden on the

operating system. We shall optimize the search algorithm to use memory pools and object pools, replacing the operating system’s general purpose memory management with our own application-aware management.

The speed of memory access is dependent on whether the data is in the CPU cache which is a constrained resource compared to memory size, typically 20MB in the latest processors. We shall seek to re-use recently accessed information to increase likelihood of the data being in the CPU cache.

In multiprocessor servers, the CPU cache is attached to each processor and each core. If a sentence is being decoded on one CPU is switched to another, the CPU cache on the new CPU must be repopulated, slowing down decoding. We will therefore investigate binding threads to specific cores.

Lastly, we shall investigate different stack configurations other than coverage cardinality to see whether they can improve speed and translation quality.

## 2.2 Feature Functions

Features functions are the  $h_m$  in Equation 2, calculating a score for each hypothesis.

The standard feature functions in the phrase-based model include:

1. log transforms translation model probabilities,  $p_{TM}(t|s)$  and  $p_{TM}(s|t)$ , and word-based translation probabilities  $p_w(t|s)$  and  $p_w(s|t)$ ,
2. log transforms of the lexicalized re-ordering probabilities,
3. log transforms of the target language model probability  $p(t)$ ,
4. a distortion penalty
5. a phrase-penalty,
6. a word penalty,
7. an unknown word penalty.

The first three feature functions frequently trained on data and require the feature to read the model from files. The other feature functions do not require model files. We shall investigate the first two feature functions for optimization.

## 2.3 Translation Model

Load-on-demand ‘binary’ phrase-tables are often used for MT deployment due to their fast loading and querying speed, and because they can be used with large phrase-tables. We therefore focus on optimizing decoding speed with these phrase-tables, specifically the Probing PT.

We shall look at the caching strategies to reduce the number of phrase-table lookups. We shall also investigate the datastructures used by the phrase-table and their impact on decoding speed.

## 2.4 Lexicalized Reordering Model

The lexicalized reordering model is trained on parallel data, usually requiring random lookups of the model file during decoding. However, the key to the lookup are the source and target phrase of each translation rule. We shall investigate the advantages of storing the model data within the translation rule.

## 3 Experimental Setup

We trained a phrase-based system using the Moses toolkit with standard settings. The training data consisted of most of the publicly available Arabic-English data from Opus (Jrg Tiedemann, 2012,) containing over 69 million parallel sentences, and tuned on a held out set. The phrase-table was then pruned, keeping only the top 100 entries per source phrase, according to  $p(t|s)$ . All models files were then binarized; the language models were binaized using KenLM (???), the phrase table using Probing PT (???), lexicalized reordering model using the compact datastructure described in ???. These binary formats were choosen for their best-in-class multithreaded performance. Table 1 gives details of the resultant sizes of the model files. For verification with a different dataset, we also occasionally used a second system trained on the French-English Europarl corpus (2m parallel sentences). For testing decoding

	ar-en	fr-en
Phrase table	17	5.8
Language model	3.1	1.8
Lex-re model	2.3	637MB

Table 1: Model sizes in GB

speed, we used a subset of the training data, Table 2. The two test scenarios have differing characteristics that we are interested in analyzing, ar-en

have short sentences with large models while fr-en have overly long sentences with smaller models. Where we need to compare model scores, we used held out test sets.

	ar-en	fr-en
For speed testing		
Set name	Subset of training data	
# sentences	800k	200k
# words	5.8m	5.9m
Avg words/sent	7.3	29.7
For model score testing		
Set name	OpenSubtitles	newstest2011
# sentences	2000	3003
# words	14,620	86,162
Avg words/sent	7.3	28.7

Table 2: Test sets

Standard Moses phrase-based configurations are used, except that we use the cube-pruning algorithm (???) with a pop-limit of 400, rather than the basic phrase-based algorithm. The cube-pruning algorithm is often employed by users who require fast decoding as it gives them the ability to trade speed with translation quality with a simple pop-limit parameter.

As a baseline, we use the latest version of the Moses decoder taken from the github repository.

For all experiments, we used a Dell PowerEdge R620 server with 16 cores, 32 hyper-threads, split over 2 physical processors (Intel Xeon E5-2650 @ 2.00GHz). The server has 380GB RAM. The operating system was Ubuntu 14.04, the code was compiled with gcc 4.8.4 and Boost library 1.59.

## 4 Results

### 4.1 Optimizing Memory

We create a dynamic memory pool which can grow as more memory is requested. The memory is not released, instead the pool can be reset in order for the memory to be re-used. We instantiate two pools for each thread, one which is never reset and another which is reset after the decoding each sentence. Objects are created in either pool according to their life cycle.

For critical objects with high churn such as the hypotheses, thread-specific LIFO queues are used to recycle objects which are no longer used. This not only reduces memory wastage but re-uses recent objects which are likely to be in the CPU cache.

Over 24% of the Moses decoder running time is spent on memory management and this increases

when more threads are used, Table 3, dampening the scalability of the decoder. By contrast, our decoder spends 11% on memory management and does not significantly increase with more cores.

	Moses		Our Work	
# threads	1	32	1	32
Memory	24%	39%	11%	13%
LM	12%	2%	47%	38%
Phrase-table	9%	5%	2%	4%
Lex RO	8%	2%	2%	2%
Search	2%	0%	14%	19%
Misc/Unknown	45%	39%	24%	29%

Table 3: Profile of %age decoding time

### 4.2 Stack Configuration

The most popular stack configuration for phrase-based model, as implemented in Pharaoh, Moses and Joshua, has been by coverage cardinality, ie. hypotheses that have translated the same number of source words are stored in the same stack. There have been research into other stack layouts such as (Ortiz-Martínez et al., 2006), and it has been noted that the decoder in (Brown et al., 1993) uses coverage stacks, as opposed to coverage cardinality.

We also note that distortion limit which constrains hypothesis extension is dependent on the hypothesis' coverage vector,  $C$  and the end position of most recent source word that has been translated,  $e$ . The distortion limit must be checked for every instance of a hypothesis and translation rule, Figure 1. However, by separating hypothe-

```

for all  $hypo$  in  $stack_{|C|}$  do
  for all translation rules do
    if can-expand( $C(hypo)$ ,  $e(hypo)$ , translation rule range) then
      expand  $hypo$  with translation rule  $\rightarrow$  new  $hypo$ 
      add new  $hypo$  to next stack
    end if
  end for
end for

```

Figure 1: Hypothesis Expansion with Cardinality Stacks

ses into set of hypotheses ('ministacks') according to coverage and end position, the distortion limit only needs to be checked for each ministack, Figure 2. Furthermore, stack pruning is done on each of these hypotheses set therefore, changing how

hypotheses are grouped can affect model scores. We therefore looked at the effects of three stack

```

for all  $ministack_{C,e}$  in  $stack_{|C|}$  do
  for all translation rules do
    if can-expand( $C$ ,  $e$ , translation rule range)
    then
      for all  $hypo$  in  $ministack_{C,e}$  do
        expand  $hypo$  with translation rule  $\rightarrow$ 
        new  $hypo$ 
        add new  $hypo$  to next  $ministack$ 
      end for
    end if
  end for
end for

```

Figure 2: Hypothesis Expansion with Coverage & End Position Stacks

configurations.

1. coverage cardinality,
2. coverage,
3. coverage and end position of most recent translated source word.

We therefore looked at the effects of three stack configurations.

1. coverage cardinality,
2. coverage,
3. coverage and end position of most recent translated source word.

Table 4 and Figure 3 present the tradeoff between decoding time and average model at various pop-limits.

Pop-limit	Cardinality		Coverage		Coverage & end pos	
	Time	Score	Time	Score	Time	Score
100	73	-8.64513	75	-8.64513	72	-8.64513
500	237	-8.59563	225	-8.59563	229	-8.59612
1,000	416	-8.58700	397	-8.58700	423	-8.58700
5,000	1930	-8.58165	1931	-8.58165	2153	-8.58098
10,000	3619	-8.58133	3630	-8.58133	4576	-8.58015
15,000	4830	-8.58130	5001	-8.58130	7156	-8.57999
20,000	5849	-8.58130	5916	-8.58130	9583	-8.57994

Table 4: Decoding time (in secs with 32 threads) and average model scores for different stack configurations

As can be seen, the model scores for all stack configurations are identical for low pop-limits parameters but grouping hypotheses into coverage & end position produces higher model scores

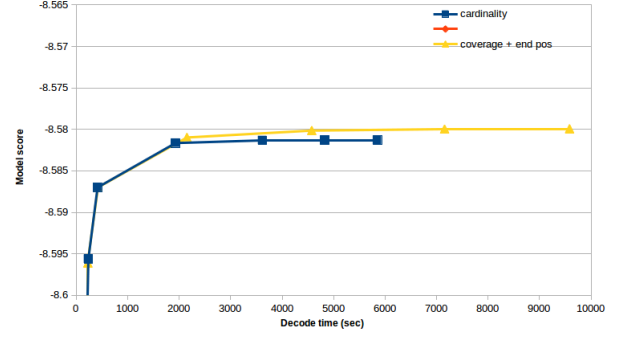


Figure 3: Trade-off between decoding time and average model scores for different stack configurations

for higher pop-limits. It is also slower but the time/quality tradeoff is better overall with this stack configuration. For lower pop-limits this configuration is slightly slower, but not by much, therefore, we shall stick with this Configuration for the remainder of the paper.

The cube-pruning algorithm contains a further priority queue which is attached to hypotheses sets which can be independent of how hypotheses are grouped. In the Moses implementation, the priority queue is also attached to the coverage cardinality, Figure 4. Again, we experiment with different

```

initialize  $queue_{|C|}$ 
for 1 to pop-limit do
  get best  $item$  in  $queue_{|C|}$ 
  create new  $hypo$  from  $item$ 
  add new  $hypo$  to new  $stack_{|C|}$ 
  create next  $items$ 
  add new  $items$  to  $queue_{|C|}$ 
end for

```

Figure 4: Cube Pruning with Unsorted Stack

queue configurations, having separate queues for each cardinality, coverage, and coverage & end position. The stack configuration remained constant (coverage & end position with pop-limit of 400). From the results in Table 5, using finer grain

Queue configuration	Time	Score
Cardinality	192	-8.59922
Coverage		-8.58635
Coverage & end position		-8.58263

Table 5: Decoding time (in secs with 32 threads) and average model scores for different queue configurations

queues results in better model scores, it is signifi-

cantly slower to decode.

### 4.3 Translation Model

### 4.4 Lexicalized Reordering Model

## 5 BLAH BLAH

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Submitted and camera-ready formatting is similar, however, the submitted paper should have:

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2. A ‘ruler’ on the left and right margins
3. Page numbers
4. A confidentiality header.

In contrast, the camera-ready **should not have** a ruler, page numbers, nor a confidentiality header. By uncommenting `\aclfinalcopy` at the top of this document, it will compile to produce an example of the camera-ready formatting; by leaving it commented out, the document will be anonymized for initial submission. Authors should place this command after the `\usepackage` declarations when preparing their camera-ready manuscript with the ACL 2016 style.

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Manuscripts must be in two-column format. Exceptions to the two-column format include the title, as well as the authors’ names and complete addresses (only in the final version, not in the version submitted for review), which must be centered at the top of the first page (see the guidelines in Subsection 6.4), and any full-width figures or tables. Type single-spaced. Do not number the pages in the camera-ready version. Start all pages directly under the top margin. See the guidelines later regarding formatting the first page.

The maximum length of a manuscript is eight (8) pages for the main conference, printed single-sided, plus two (2) pages for references (see Section 7 for additional information on the maximum number of pages).

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The ACL 2016 style defines a printed ruler which should be presented in the version submitted for review. The ruler is provided in order that reviewers may comment on particular lines in the paper without circumlocution. If you are preparing a document without the provided style files, please arrange for an equivalent ruler to appear on the final output pages. The presence or absence of the ruler should not change the appearance of any other content on the page. The camera ready copy should not contain a ruler. ( $\LaTeX$  users may uncomment the `\aclfinalcopy` command in the document preamble.)

Reviewers: note that the ruler measurements do not align well with lines in the paper — this turns out to be very difficult to do well when the paper contains many figures and equations, and, when done, looks ugly. Just use fractional references (e.g., the first line on this page is at mark 096.5), although in most cases one would expect that the approximate location will be adequate.

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ACL provides this description in  $\LaTeX$ 2e (`acl2016.tex`) and PDF format (`acl2016.pdf`), along with the  $\LaTeX$ 2e style file used to format it (`acl2016.sty`) and an ACL bibliography style (`acl2016.bst`) and example bibliography (`acl2016.bib`). These files are all available at

acl2016.org/index.php?article\_id=9. We strongly recommend the use of these style files, which have been appropriately tailored for the ACL 2016 proceedings.

### 6.3 Format of Electronic Manuscript

For the production of the electronic manuscript, you must use Adobe's Portable Document Format (PDF). This format can be generated from postscript files: on Unix systems, you can use `ps2pdf` for this purpose; under Microsoft Windows, you can use Adobe's Distiller, or if you have `cygwin` installed, you can use `dvipdf` or `ps2pdf`. Note that some word processing programs generate PDF that may not include all the necessary fonts (esp. tree diagrams, symbols). When you print or create the PDF file, there is usually an option in your printer setup to include none, all, or just non-standard fonts. Please make sure that you select the option of including ALL the fonts. *Before sending it, test your PDF by printing it from a computer different from the one where it was created.* Moreover, some word processors may generate very large postscript/PDF files, where each page is rendered as an image. Such images may reproduce poorly. In this case, try alternative ways to obtain the postscript and/or PDF. One way on some systems is to install a driver for a postscript printer, send your document to the printer specifying "Output to a file", then convert the file to PDF.

For reasons of uniformity, Adobe's **Times Roman** font should be used. In  $\text{\LaTeX}2\text{e}$  this is accomplished by putting

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```

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Print-outs of the PDF file on A4 paper should be identical to the hardcopy version. If you cannot meet the above requirements about the production of your electronic submission, please contact the publication chairs above as soon as possible.

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Center the title, author name(s) and affiliation(s) across both columns (or, in the case of initial submission, space for the names). Do not use footnotes for affiliations. Use the two-column format only when you begin the abstract.

**Title:** Place the title centered at the top of the first page, in a 15 point bold font. (For a complete guide to font sizes and styles, see Table 7.) Long titles should be typed on two lines without a blank

Command	Output	Command	Output
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<code>\^e</code>	ê	<code>\u g</code>	ğ
<code>\'i</code>	ì	<code>\l</code>	ł
<code>\.I</code>	İ	<code>\~n</code>	ñ
<code>\o</code>	ø	<code>\H o</code>	ö
<code>\'u</code>	ú	<code>\v r</code>	ř
<code>\aa</code>	å	<code>\ss</code>	ß

Table 6: Example commands for accented characters, to be used in, e.g.,  $\text{\BIBTeX}$  names.

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\bibliographystyle{acl2016}
```

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**Appendices:** Appendices, if any, directly follow the text and the references (but see above). Letter them in sequence and provide an informative title: **Appendix A. Title of Appendix.**

**Acknowledgment** sections should go as a last (unnumbered) section immediately before the references.

## 6.6 Footnotes

**Footnotes:** Put footnotes at the bottom of the page. They may be numbered or referred to by

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<sup>2</sup><http://www.abbreviations.com/jas.php>

Type of Text	Font Size	Style
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author names	12 pt	bold
author affiliation	12 pt	
the word “Abstract”	12 pt	bold
section titles	12 pt	bold
document text	11 pt	
abstract text	10 pt	
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Table 7: Font guide.

asterisks or other symbols.<sup>3</sup> Footnotes should be separated from the text by a line.<sup>4</sup> Footnotes should be in 9 point font.

## 6.7 Graphics

**Illustrations:** Place figures, tables, and photographs in the paper near where they are first discussed, rather than at the end, if possible. Wide illustrations may run across both columns and should be placed at the top of a page. Color illustrations are discouraged, unless you have verified that they will be understandable when printed in black ink.

**Captions:** Provide a caption for every illustration; number each one sequentially in the form: “**Figure 1:** Figure caption.”, “**Table 1:** Table caption.” Type the captions of the figures and tables below the body, using 9 point text. Table and Figure labels should be bold-faced.

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The ACL 2016 main conference accepts submissions of long papers and short papers. Long papers may consist of up to eight (8) pages of content,

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plus unlimited pages for references. Upon acceptance, final versions of long papers will be given one additional page (up to 9 pages with unlimited pages for references) so that reviewers' comments can be taken into account. Short papers may consist of up to four (4) pages of content, plus unlimited pages for references. Upon acceptance, short papers will be given five (5) pages in the proceedings and unlimited pages for references. For both long and short papers, all illustrations and appendices must be accommodated within these page limits, observing the formatting instructions given in the present document. Papers that do not conform to the specified length and formatting requirements are subject to be rejected without review.

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As the reviewing will be blind, the paper must not include the authors' names and affiliations. Furthermore, self-references that reveal the author's identity, e.g., "We previously showed (Smith, 1991) ..." must be avoided. Instead, use citations such as "Smith previously showed (Smith, 1991) ..." Papers that do not conform to these requirements will be rejected without review. In addition, please do not post your submissions on the web until after the review process is complete (in special cases this is permitted: see the multiple submission policy below).

We will reject without review any papers that do not follow the official style guidelines, anonymity conditions and page limits.

## 9 Multiple Submission Policy

Papers that have been or will be submitted to other meetings or publications must indicate this at submission time. Authors of papers accepted for presentation at ACL 2016 must notify the program chairs by the camera-ready deadline as to whether the paper will be presented. All accepted papers must be presented at the conference to appear in the proceedings. We will not accept for publication or presentation papers that overlap significantly in content or results with papers that will be (or have been) published elsewhere.

Preprint servers such as arXiv.org and ACL-related workshops that do not have published proceedings in the ACL Anthology are not considered archival for purposes of submission. Authors must state in the online submission form the name of the

workshop or preprint server and title of the non-archival version. The submitted version should be suitably anonymized and not contain references to the prior non-archival version. Reviewers will be told: "The author(s) have notified us that there exists a non-archival previous version of this paper with significantly overlapping text. We have approved submission under these circumstances, but to preserve the spirit of blind review, the current submission does not reference the non-archival version." Reviewers are free to do what they like with this information.

Authors submitting more than one paper to ACL must ensure that submissions do not overlap significantly ( $> 25\%$ ) with each other in content or results. Authors should not submit short and long versions of papers with substantial overlap in their original contributions.

## Acknowledgments

Do not number the acknowledgment section. This section should not be presented for the submission version.

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