

Analyzing Uncertainty in Neural Machine Translation

Myle Ott Michael Auli David Grangier Marc'Aurelio Ranzato
Facebook AI Research

Abstract

Machine translation is a popular test bed for research in neural sequence-to-sequence models but despite much recent research, there is still a lack of understanding of these models. Practitioners report performance degradation with large beams, the under-estimation of rare words and a lack of diversity in the final translations. Our study relates some of these issues to the inherent uncertainty of the task, due to the existence of multiple valid translations for a single source sentence, and to the extrinsic uncertainty caused by noisy training data. We propose tools and metrics to assess how uncertainty in the data is captured by the model distribution and how it affects search strategies that generate translations. Our results show that search works remarkably well but that the models tend to spread too much probability mass over the hypothesis space. Next, we propose tools to assess model calibration and show how to easily fix some shortcomings of current models. We release both code and multiple human reference translations for two popular benchmarks.

1 Introduction

Machine translation (MT) is an interesting task not only for its practical applications but also for the formidable learning challenges it poses, from how to transduce variable length sequences, to searching for likely sequences in an intractably large hypothesis space, to dealing with the multi-modal nature of the prediction task, since typically there are several correct ways to translate a given sentence.

The research community has made great advances on this task, recently focusing the effort on the exploration of several variants of neural models (Bahdanau et al., 2014; Luong et al., 2015; Gehring et al., 2017; Vaswani et al., 2017) that have greatly improved the state of the art performance on public benchmarks. However, several open questions remain (Koehn & Knowles, 2017). In this work, we analyze top-performing trained models in order to answer some of these open questions. We target better understanding to help prioritize future exploration towards the most critical aspects of the problem and therefore speed up progress.

For instance, according to conventional wisdom neural machine translation (NMT) systems under-estimate rare words (Koehn & Knowles, 2017), why is that? Is the model poorly calibrated? Is this due to exposure bias (Ranzato et al., 2016), i.e., the mismatch between the distribution of words observed at training and test

time? Or is this due to the combination of uncertainty in the prediction of the next word and inference being an arg max selection process, which always picks the most likely/frequent word? Similarly, it has been observed in several studies (Koehn & Knowles, 2017) that performance degrades with large beams. Is this due to poor fitting of the model which assigns large probability mass to bad sequences? Or is this due to the heuristic nature of this search procedure which fails to work for large beam values? In this paper we will provide answers and solutions to these and other related questions.

The underlying theme of all these questions is *uncertainty*, i.e. the one-to-many nature of the learning task. In other words, for a given source sentence there are several target sequences that have non negligible probability mass. Since the model only observes one or very few realizations from the data distribution, it is natural to ask the extent to which an NMT model trained with token-level cross-entropy is able to capture such a rich distribution, and whether the model is calibrated. Also, it is equally important to understand the effect that uncertainty has on search and whether there are better and more efficient search strategies.

Unfortunately, NMT models have hundreds of millions of parameters, the search space is exponentially large and we typically observe only one reference for a given source sentence. Therefore, measuring fitness of a NMT model to the data distribution is a challenging scientific endeavor, which we tackle by borrowing and combining tools from the machine learning and statistics literature (Kuleshov & Liang, 2015; Guo et al., 2017). With these tools, we show that search works surprisingly well, yielding highly likely sequences even with relatively narrow beams. Even if we consider samples from the model that have similar likelihood, beam hypotheses yield higher BLEU on average. Our analysis also demonstrates that although NMT is very well calibrated at the token and set level, it generally spreads too much probability mass over the space of sequences. This often results in individual hypotheses being underestimated, and overall, poor quality of samples drawn from the model. Interestingly, systematic mistakes in the data collection process can also contribute to uncertainty, and it turns out that a particular kind of noise, the target sentence being replaced by a copy of the corresponding source sentence, is responsible for much of the degradation observed when using wide beams.

This analysis – the first one of its kind – introduces tools and metrics to assess fitting of the model to the data distribution, and shows areas of improvement for

NMT. It also suggests easy fixes for some of the issues reported by practitioners. We will also open source the code to reproduce this analysis and release the data we collected for our evaluation, which consists of ten human translations for 500 sentences taken from the WMT’14 En-Fr and En-De test sets¹.

2 Related Work

In their seminal work, Zoph et al. (2015) frame translation as a compression game and measure the amount of information added by translators. While this work precisely quantifies the amount of uncertainty, it does not investigate its effect on modeling and search. In another context, uncertainty has been considered for the design of better evaluation metrics (Dreyer & Marcu, 2012; Galley et al., 2015), in order not to penalize a model for producing a valid translation which is different from the provided reference.

Most work in NMT has focused on improving accuracy without much consideration for the intrinsic uncertainty of the translation task itself (Bahdanau et al., 2014; Luong et al., 2015; Gehring et al., 2017; Vaswani et al., 2017) (§3). Notable exceptions are latent variable models (Blunsom et al., 2008; Zhang et al., 2016) which explicitly attempt to model multiple modes in the data distribution, or decoding strategies which attempt to predict diverse outputs while leaving the model unchanged (Gimpel et al., 2013; Vijayakumar et al., 2016; Li & Jurafsky, 2016; Cho, 2016). However, none of these works check for improvements in the match between the model and the data distribution.

Recent work on analyzing machine translation has focused on topics such as comparing neural translation to phrase-based models (Bentivogli et al., 2016; Toral & Sanchez-Cartagena, 2017). Koehn & Knowles (2017) presented several challenges for NMT, including the deterioration of accuracy for large beam widths and the under-estimation of rare words, which we address in this paper. Isabelle et al. (2017) propose a new evaluation benchmark to test whether models can capture important linguistic properties. Finally, Niehues et al. (2017) focus on search and argue in favor of better translation modeling instead of improving search.

3 Data Uncertainty

Uncertainty is a core challenge in translation, as there are several ways to correctly translate a sentence; but what are typical sources of uncertainty found in modern benchmark datasets? Are they all due to different ways to paraphrase a sentence? In the following sections, we answer these questions, distinguishing uncertainty inherent to the task itself (§3.1), and uncertainty due to spurious artifacts caused by the data collection process (§3.2).

¹Code and new reference translations can be obtained at: URL coming soon.

3.1 Intrinsic Uncertainty

One major source of uncertainty is due to the existence of several *semantically equivalent* translations of the same source sentence. This has been extensively studied in the literature (Dreyer & Marcu, 2012). Translations can be more or less literal, and even if literal there are many ways to express the same meaning. Some sentences can be in the active or passive form and for some languages determiners and prepositions such as ‘the’, ‘of’, or ‘their’ can be optional.

Besides uncertainty due to the existence of distinct, yet semantically equivalent translations, there are also sources of uncertainty due to *under-specification* when translating into a target language more inflected than the source language. Without additional context, it is often impossible to predict the missing gender, tense, or number, and therefore, there are multiple plausible translations of the same source sentence. Simplification or addition of cultural context are also common sources of uncertainty (Venuti, 2008).

3.2 Extrinsic Uncertainty

Statistical machine translation systems, and in particular NMT models, require lots of training data to perform well. To save time and effort, it is common to augment high quality human translated corpora with lower quality web crawled data (Smith et al., 2013). This process is error prone and responsible for introducing additional uncertainty in the data distribution. Target sentences may only be partial translations of the source, or the target may contain information not present in the source. A lesser-known example are target sentences which are entirely in the source language, or which are primarily *copies of the corresponding source*. For instance, we found that between 1.1% to 2.0% of training examples in the WMT’14 En-De and WMT’14 En-Fr datasets (§4.2) are “copies” of the source sentences.² Source copying is particularly interesting since we show that, even in small quantities, it can significantly affect the model output (§5.3).

4 Experimental Setup

This section describes the models and the datasets used in our analysis.

4.1 Sequence to Sequence Model

Our experiments rely on the publicly available pre-trained models of the *fairseq-py* toolkit (Gehring et al., 2017).³ These models achieve competitive performance on the datasets we consider.⁴ Formally, let \mathbf{x} be an input sentence with m words $\{x_1, \dots, x_m\}$, and

²A target sentence is labeled a “copy” if at least 50% of the unigrams overlap with the source; overlap is computed as the unigram Intersection over Union, excluding punctuation and numbers.

³github.com/facebookresearch/fairseq-py

⁴Preliminary experiments with other architectures, like RNNs, confirmed the generality of our findings.

\mathbf{t} be the ground truth target sentence with n words $\{t_1, \dots, t_n\}$. The model is composed of an *encoder* and a *decoder*. The encoder takes \mathbf{x} through several convolutional layers to produce a sequence of hidden states, $\mathbf{z} = \{z_1, \dots, z_m\}$, one per input word. At time step k , the decoder takes a window of words produced so far (or the ground truth words at training time), $\{t_{k-1}, \dots, t_{k-i}\}$, the set of encoder hidden states \mathbf{z} and produces a distribution over the current word: $p(t_k | t_{k-1}, \dots, t_{k-i}, \mathbf{z})$. More precisely, at each time step, an *attention* module (Bahdanau et al., 2014) summarizes the sequence \mathbf{z} with a single vector through a weighted sum of $\{z_1, \dots, z_m\}$. The weights depend on the source sequence \mathbf{x} and the decoder hidden state, h_k , which is the output of several convolutional layers taking as input $\{t_{k-1}, \dots, t_{k-i}\}$. From the source attention vector, the hidden state of the decoder is computed and the model emits a distribution over the current word as in: $p(t_k | h_k) = \text{softmax}(Wh_k + b)$. Gehring et al. (2017) provides further details. To train the translation model, we minimize the cross-entropy loss: $\mathcal{L} = -\sum_{i=1}^n \log p(t_i | t_{i-1}, \dots, t_1, \mathbf{x})$, using Nesterov’s momentum (Sutskever et al., 2013).

At test time, we aim to output the most likely translation given the source sentence, according to the model estimate. We approximate such an output via *beam search*. Unless otherwise stated, we use beam width $k = 5$, where hypotheses are compared to one another in terms of length-normalized log-likelihood. Some experiments consider *sampling* from the model conditional distribution $p(t_i | t_{i-1}, \mathbf{h}_{i-1}, \mathbf{x})$, one token at a time, until the special end of sentence symbol is sampled.

4.2 Datasets and Evaluation

We consider the following datasets:

WMT’14 English-German (En-De): We use the same setup as Luong et al. (2015) which comprises 4.5M sentence pairs for training and we test on newstest2014.⁵

We build a validation set by removing 44k random sentence-pairs from the training data. As vocabulary we use 40k sub-word types based on a joint source and target byte pair encoding (BPE; Sennrich et al., 2016).

WMT’17 English-German (En-De): The above pre-processed version of WMT’14 En-De did not provide a split into sub-corpora which we required for some experiments. We therefore also experiment on the 2017 data where we test on newstest2017. The full version of the dataset (*original*) comprises 5.9M sentence pairs after length filtering to 175 tokens. We then consider the news-commentary portion with 270K sentences (*clean*), and a *filtered* version comprising 4M examples after removing low scoring sentence-pairs according to a model trained on the cleaner news-commentary portion.

WMT’14 English-French (En-Fr): We remove sentences longer than 175 words and pairs with a source/target length ratio exceeding 1.5 resulting in 35.5M sentence pairs for training. The source and target vocabulary is based on 40k BPE types. Results

	En-Fr	En-De
Automatic evaluation		
train PPL	2.54	5.14
valid PPL	2.56	6.36
test BLEU	41.03	24.78
Human evaluation (pairwise)		
Ref > Sys	42.0%	80.0%
Ref = Sys	11.6%	5.6%
Ref < Sys	46.4%	14.4%

Table 1: Automatic and human evaluation on a 500 sentence subset of the WMT’14 En-Fr and En-De test sets. Models generalize well in terms of perplexity and BLEU. Our human evaluation compares (reference, system) pairs for beam 5.

are reported on both newstest2014 and a validation set held-out from the training data comprising 26k sentence pairs.

We evaluate with tokenized BLEU (Papineni et al., 2002) on the corpus-level and the sentence-level, after removing BPE splitting. Sentence-level BLEU is computed similarly to corpus BLEU, but with smoothed n -gram counts (+1) for $n > 1$ (Lin & Och, 2004).

5 Uncertainty and Search

In this section we start by showing that the models under consideration are well trained (§5.1). Next, we quantify the amount of uncertainty in the model’s output and compare two search strategies: beam search and sampling (§5.2). Finally we investigate the influence of a particular kind of extrinsic uncertainty in the data on beam search, and provide an explanation for the performance degradation observed with wide beams (§5.3).

5.1 Preliminary: Models Are Well Trained

We start our analysis by confirming that the models under consideration are well trained. Table 1 shows that the models, and particularly the En-Fr model, achieve low perplexity and high BLEU scores.

To further assess the quality of these models, we conducted a human evaluation with three professional translators. Annotators were shown the source sentence, reference translation, and a translation produced by our model through *beam search*—a breadth-first search that retains only the k most likely candidates at each step. Here, we consider a relatively narrow beam of size $k = 5$. The reference and model translations were shown in random order and annotators were blind to their identity. We find that model translations roughly match human translations for the En-Fr dataset, while for the En-De dataset humans prefer the reference over the model output 80% of the time. Overall, the **models are well trained**—particularly the En-Fr model—and

⁵<http://nlp.stanford.edu/projects/nmt>

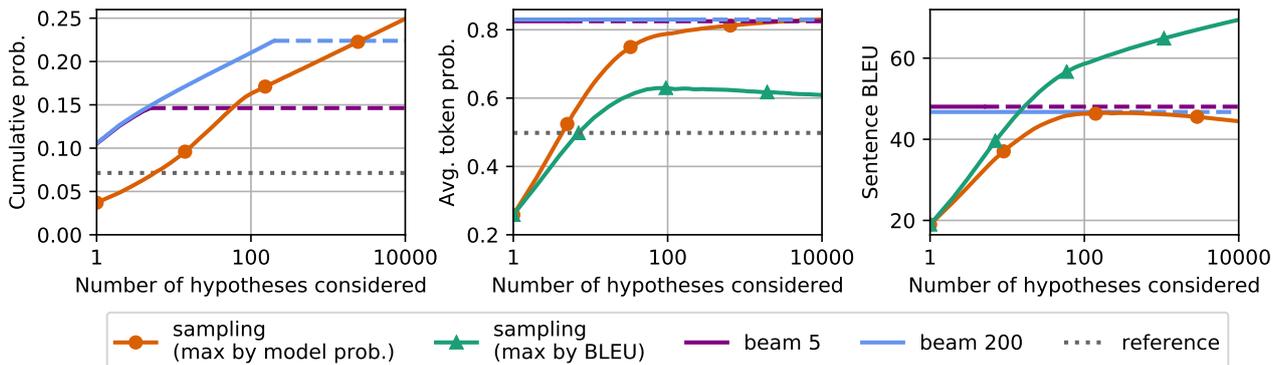


Figure 1: *Left*: Cumulative sequence probability of hypotheses obtained by beam search and sampling on the WMT’14 En-Fr valid set; *Center*: same, but showing the average per-token probability as we increase the number of considered hypotheses, selecting hypotheses either by probability or sentence BLEU; *Right*: same, but showing sentence BLEU as we increase the number of hypotheses.

beam search can find outputs that are highly rated by human translators.

5.2 Model Output Distribution Is Highly Uncertain

How much uncertainty is there in the model’s output distribution? What search strategies are the most *effective* (i.e., produce the highest scoring hypotheses) and *efficient* (i.e., require generating the fewest candidate hypotheses)? To answer these questions we sample 10k translations and compare the hypotheses to those produced by beam search with $k = 5$ and $k = 200$.

Figure 1 (*Left*) shows that **the model’s output distribution is highly uncertain**: even after drawing 10k samples we cover only 24.9% of the sequence-level probability mass. And while beam search is much more efficient at searching this space, covering 14.6% of the output probability mass with $k = 5$ and 22.4% of the probability mass with $k = 200$, these findings suggest that most of the probability mass is spread elsewhere in the space.

Figure 1 also compares the average sentence-level BLEU and model scores of hypotheses produced by sampling and beam search. Sampling results for varying sample size $n = 1, \dots, 10k$ are on two curves: orange reports probability (*Center*) and sentence BLEU (*Right*) for the sentence with the highest probability within n samples, while green does the same for the sentence with the highest sentence BLEU in the same set. We find that sampling produces hypotheses with similar probabilities as beam search (*Center*), however, for the same likelihood beam hypotheses have higher BLEU scores (*Right*). We also note that **BLEU and model probability are imperfectly correlated**: while we find more likely translations as we sample more candidates, BLEU over those samples eventually decreases (*Right*, orange curve). Vice versa, hypotheses selected by BLEU have lower likelihood score beyond 80 samples (*Center*, green curve). We revisit this surprising finding in §5.3.

Finally, we observe that the model on average assigns much lower scores to the reference translation compared

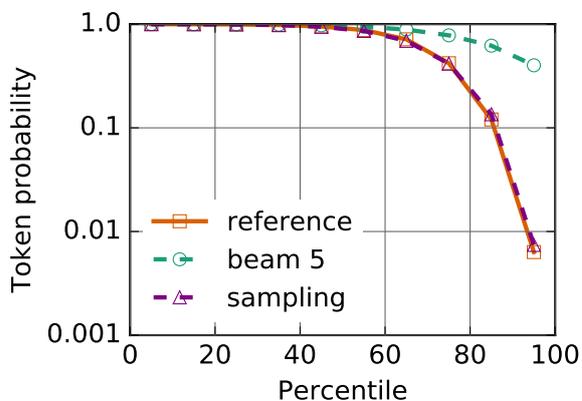


Figure 2: Probability quantiles for tokens in the reference, beam search hypotheses ($k = 5$), and sampled hypotheses for the WMT’14 En-Fr validation set.

to beam hypotheses (Figure 1, *Center*). To better understand this, in Figure 2 we compare the token-level model probabilities of the reference translation, to those of outputs from beam search and sampling. We observe once again that **beam search is a very effective search strategy**, finding hypotheses with very high average token probabilities and rarely leaving high likelihood regions; indeed only 20% of beam tokens have probabilities below 0.7. In contrast, the probabilities for sampling and the human references are much lower. The high confidence of beam is somewhat surprising if we take into account the exposure bias (Ranzato et al., 2016) of these models, which have only seen gold translations at training time. We refer the reader to §6.2 for discussion about how well the model actually fits the data distribution.

5.3 Uncertainty Causes Large Beam Degradation

In the previous section we observed that repeated sampling from the model can have a negative impact on BLEU, even as we find increasingly likely hypotheses. Similarly, we observe lower BLEU scores for beam 200 compared to beam 5, consistent with past ob-

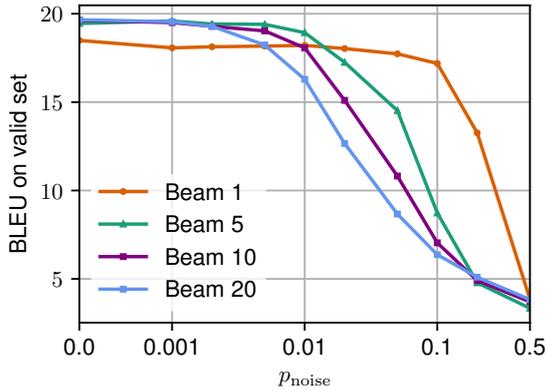


Figure 3: Accuracy of models trained on WMT’17 English-German news-commentary data with added synthetic copy noise in the training data (x-axis) tested with various beam sizes on the validation set.

servations about performance degradation with large beams (Koehn & Knowles, 2017).

Why does the BLEU accuracy of translations found by larger beams deteriorate rather than improve despite these sequences having higher likelihood? To answer this question we return to the issue of extrinsic uncertainty in the training data (§3.2) and its impact on the model and search. One particularly interesting case of noise is when target sentences in the training set are simply a copy of the source.

In the WMT’14 En-De and En-Fr dataset between 1.1% and 2.0% of the training sentence pairs are “copies” (§3.2). How does the model represent these training examples and does beam search find them? It turns out that **copies are over-represented in the output of beam search**. On WMT’14 En-Fr, beam search outputs copies at the following rates: 2.6% (beam=1), 2.9% (beam=5), 3.2% (beam=10) and 3.5% (beam=20).

To better understand this issue, we trained models on the news-commentary portion of WMT’17 English-German which does not contain copies. We added synthetic copy noise by randomly replacing the true target by a copy of the source with probability p_{noise} . Figure 3 shows that larger beams are much more affected by copy noise. Even just 1% of copy noise can lead to a drop of 3.3 BLEU for a beam of $k = 20$ compared to a model with no added noise. For a 10% noise level, all but greedy search have their accuracy more than halved.

Next, we examine model probabilities at the token-level. Specifically, we plot the average per position log-probability assigned by the En-Fr model to each token of: (i) the reference translation, (ii) the beam search output with $k = 5$, and (iii) a synthetic output which is a copy of the source sentence. Figure 4 shows that the probability of copying the first source token is very unlikely according to the model (and actually matches the ground truth rate of copy noise). However, after three tokens the model switches to almost deterministic transitions. Because beam search proceeds in strict left-to-right manner, the copy mode is only reachable if the beam is wide enough to consider the first source

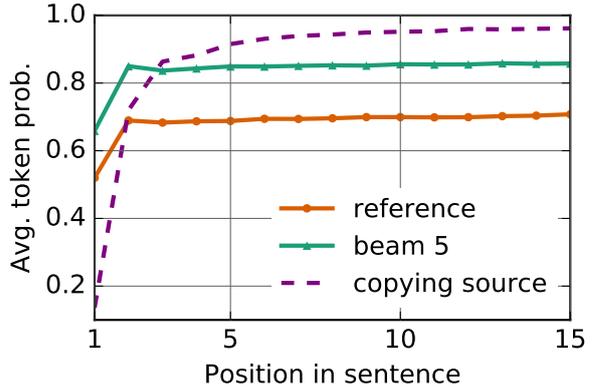


Figure 4: Average probability at each position of the output sequence on the WMT’14 En-Fr validation set, comparing the reference translation, beam search hypothesis ($k = 5$), and copying the source sentence.

word which has low probability. However, once in the beam, the copy mode quickly takes over. This explains why large beam settings in Figure 3 are more susceptible to copy noise compared to smaller settings. Thus, while larger beam widths are effective in finding higher likelihood outputs, such sequences may correspond to copies of the source sentence, which explains the drop in BLEU score for larger beams. Deteriorating accuracy of larger beams has been previously observed (Koehn & Knowles, 2017), however, it has not until now been linked to the presence of copies in the training data or model outputs.

Note that this finding does not necessarily imply a failure of beam nor a failure of the model to match the data distribution. Larger beams do find more likely hypotheses. It could very well be that the true data distribution is such that no good translation individually get a probability higher than the rate of copy. In that case, even a model perfectly matching the data distribution will return a copy of the source. We refer the reader to §6.2 for further analysis on this subject. The only conclusion thus far is that **extrinsic uncertainty is (at least partially) responsible for the degradation of performance of large beams**.

Finally, we present two simple methods to mitigate this issue. First, we pre-process the training data by removing low scoring sentence-pairs according to a model trained on the news-commentary portion of the WMT’17 English-German data (*filtered*; §4.2). Second, we apply an inference constraint that prunes completed beam search hypotheses which overlap by 50% or more with the source (*no copy*). Figure 5 shows that BLEU improves as beam gets wider on the clean portion of the dataset. Also, the performance degradation is greatly mitigated by both filtering the data and by constraining inference, with the best result obtained by combining both techniques, yielding an overall improvement of 0.5 BLEU over the *original* model. Appendix A describes how we first discovered the copy noise issue.

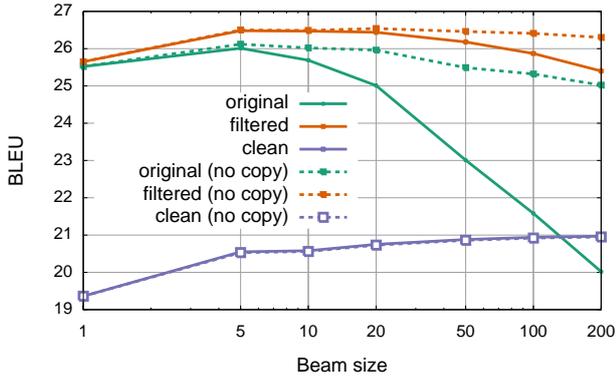


Figure 5: BLEU on newstest2017 as a function of beam width for models trained on all of the WMT’17 En-De training data (*original*), a filtered version of the training data (*filtered*) and a small but clean subset of the training data (*clean*). We also show results when excluding copies as a post-processing step (*no copy*).

6 Model Fitting and Uncertainty

The previous section analyzed the most likely hypotheses according to the model distribution. This section takes a more holistic view and compares the estimated distribution to the true data distribution. Since exact comparison is intractable and we can only have access to few samples from the data distribution, we propose several necessary conditions for the two distributions to match. First, we inspect the match for unigram statistics. Second, we move to analyze calibration at the set level and design control experiments to assess probability estimates of sentences. Finally, we compare in various ways samples from the model with human references. We find uncontroversial evidence that the model spreads too much probability mass in the hypothesis space compared to the data distribution, often under-estimating the actual probability of individual hypothesis. Appendix B outlines another condition.

6.1 Matching Conditions at the Token Level

If the model and the data distribution match, then unigram statistics of samples drawn from the two distributions should also match (not necessarily vice versa). This is a particularly interesting condition to check since NMT models are well known to under-estimate rare words (Koehn & Knowles, 2017); is the actual model poorly estimating word frequencies or is this just an artifact of beam search? Figure 6 shows that samples from the model have roughly a similar word frequency distribution as references in the training data, except for extremely rare words; note that in the 10 percent quantile bin, the median occurrence of words is only 12 (see Appendix C for more analysis of this issue). On the other hand, beam search over-represents frequent words and under-represents more rare words, which is expected since high probability sequences should con-

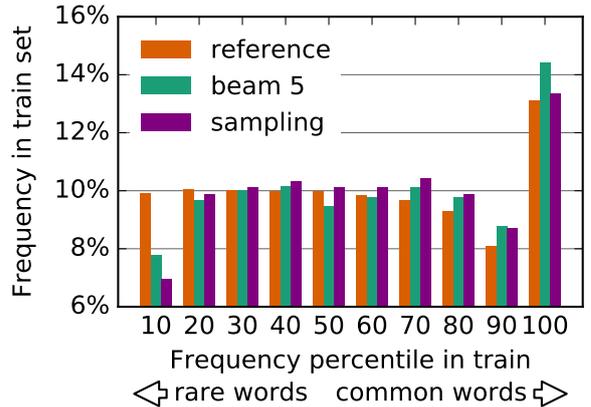


Figure 6: Unigram word frequency over the human references, the output of beam search ($k = 5$) and sampling on the news-commentary portion of the WMT’17 En-De training set.

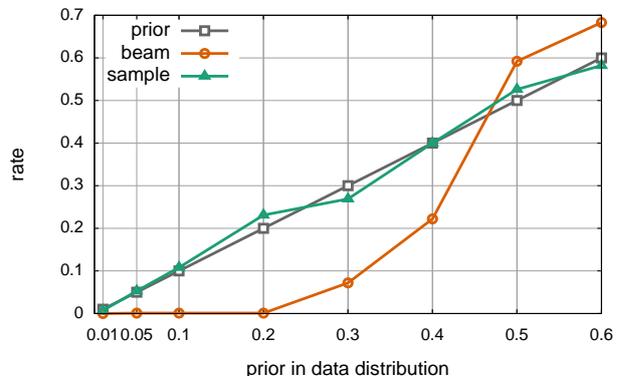


Figure 7: Comparison of how often a word type is output by the model with beam search or sampling compared to the data distribution; prior is the data distribution. Values below prior underestimate the data distribution and vice versa.

tain more frequent words.

Digging deeper, we perform a synthetic experiment where we select 10 target word types $w \in W$ and replace each w in the training set with either w_1 or w_2 at a given replacement rate $p(w_1|w)$.⁶ We train a new model on this modified data and verify whether the model can estimate the original replacement rate that determines the frequency of w_1 and w_2 . Figure 7 compares the replacement rate in the data (prior) to the rate measured over the output of either beam search or sampling. Sampling closely matches the data distribution for all replacement rates but beam greatly overestimates the majority class: it either falls below the prior for rates of 0.5 or less, or exceeds the prior for rates larger than 0.5. These observations confirm that the **model closely matches unigram statistics except for very rare words, while beam prefers common alternatives to rarer ones.**

⁶Each type has a token count between 3k-7k and the total token count of W is 50k. To relate this experiment to the one in fig. 6, we operate in bin 20 when $p(w_1|w) = 0.01$.

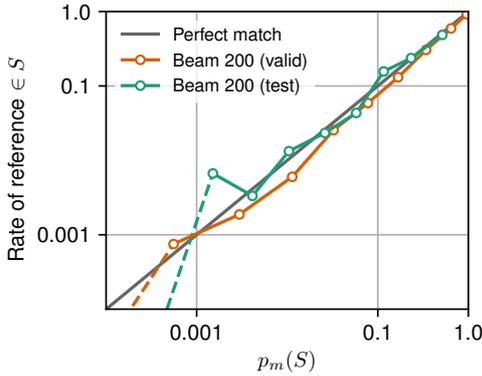


Figure 8: Matching distributions at the set level using 200 beam search hypotheses on the WMT’14 En-Fr valid and test set. Points are binned so that each represents 10% of sentences. The lowest probability bin (not shown) has value 0 (reference never in S).

6.2 Matching Conditions at the Sequence Level

In this section, we further analyze how well the model captures uncertainty in the data distribution via a sequence of necessary conditions operating at the sequence level.

Set-Level Calibration. Calibration (Guo et al., 2017; Kuleshov & Liang, 2015) verifies whether the model probability estimates p_m match the true data probabilities p_d . If p_d and p_m match, then for any set S , we observe:

$$\mathbb{E}_{x \sim p_d} [\mathbb{I}\{x \in S\}] = p_m(S).$$

The left hand side counts the expected number of times we observe a sample in S , when sampling from the data distribution; the right hand side sums the model probability estimates over S .

In Figure 8, we plot the left hand side against the right hand side where S is a set of 200 beam search hypotheses on the WMT’14 En-Fr validation set, covering an average of 22.4% of the model’s probability mass. Points are binned so that each point represents 10% of sentences in the validation or test set (Nguyen & O’Connor, 2015). For instance, the rightmost point in the figure corresponds to sentences for which beam collects nearly the entire probability mass, typically very short sentences. This experiment shows that the **model matches the data distribution remarkably well at the set level** on both the validation and test set.

Control Experiment. To assess the fit to the data distribution further, we re-consider the models trained with varying levels of copy noise (p_{noise} , cf. §5.3) and check whether we reproduce the correct amount of copying (evaluated at the sequence level) when sampling from the model. Figure 9 shows a large discrepancy: at low p_{noise} the model underestimates the probability of copying (i.e., too few of the produced samples are *exact copies* of the source), while at high noise levels it overestimates it. Moreover, since our model is smooth, it can assign non-negligible probability mass to partial copies⁷

⁷Partial copies are identified using the IoU at 50% criterion, described in §3.2.

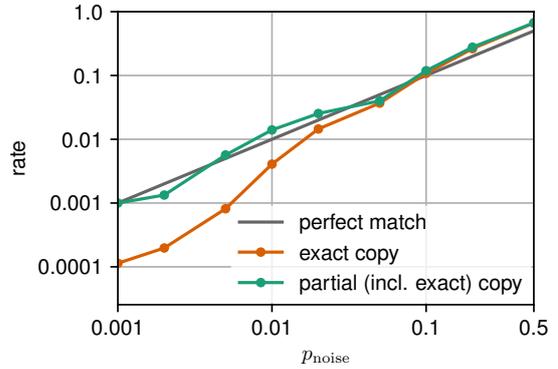


Figure 9: Rate of copy of the source sentence (exact and partial) as a function of the amount of copy noise present in the model’s train data (§5.3). Results on WMT’17 En-De validation set.

which are *not* present in the training data. Indeed, when we consider both partial and exact copies, the model correctly reproduces the amount of copy noise present in the training data. Therefore, although the model appears to under-estimate some hypotheses at low copy rates, it actually **smears probability mass in the hypothesis space**. Overall, this is the first concrete evidence of the model distribution not perfectly fitting the data distribution.

Expected Inter-Sentence BLEU is defined as

$$\mathbb{E}_{x \sim p, x' \sim p} [BLEU(x, x')]$$

which corresponds to the expected BLEU between two translations sampled from a distribution p where x is considered as the hypothesis and x' as the reference. If the model matches the data distribution, then the expected BLEU computed with sentences sampled from the model distribution p_m should match the expected BLEU computed using two independent reference translations (see (§6.3) for further details on data collection).

We find that the expected BLEU is 44.5 and 32.1 for human translations on the WMT’14 En-Fr and WMT’14 En-De datasets, respectively. However, the expected BLEU of the model is only 28.6 and 24.2, respectively. This large discrepancy provides further evidence that **the model spreads too much probability mass across sequences**, compared to what we observe in the actual data distribution.

6.3 Comparing Multiple Model Outputs to Multiple References

Next we assess whether model outputs are similar to those produced by multiple human translators. We collect 10 additional reference translations from 10 distinct humans translators for each of 500 sentences randomly selected from the WMT’14 En-Fr and En-De test sets. Similarly, we collect a large set of translations from the model via beam search ($k = 200$) or sampling. We then compute two versions of *oracle BLEU* at the sentence-level: (i) *oracle reference* reports BLEU for the most likely hypothesis with respect to its best matching reference (according to BLEU); and (ii) *average oracle*

	beam		sampling
	$k = 5$	$k = 200$	$k = 200$
Prob. covered	4.7%	11.1%	6.7%
Sentence BLEU			
single reference	41.4	36.2	38.2
oracle reference	70.2	61.0	64.1
average oracle	65.7	56.4	39.1
- # refs covered	1.9	5.0	7.4
Corpus BLEU (multi-bleu.pl)			
single reference	41.6	33.5	36.9
10 references	81.5	65.8	72.8

Table 2: Sentence and corpus BLEU for beam search hypotheses and 200 samples on a 500 sentence subset of the WMT’14 En-Fr test set. “Single reference” uses the provided reference and the most likely hypothesis, while oracle reference and average oracle are computed with 10 human references.

computes BLEU for every hypothesis with respect to its best matching reference and averages this number over all hypotheses. Oracle reference measures whether one of the human translations is similar to the top model prediction, while average oracle indicates whether most sentences in the set have a good match among the human references. The average oracle will be low if there are hypotheses that are dissimilar from all human references, suggesting a possible mismatch between the model and the data distributions.

Table 2 shows that beam search (besides its degradation due to copy noise) produces not only top scoring hypothesis that are very good (single reference scoring at 41 and oracle reference at 70) but most hypotheses in the beam are close to a reference translation (as the difference between oracle reference and average oracle is only 5 BLEU points). Unfortunately, beam hypotheses lack diversity and they are all close to very few references as indicated by the coverage number, which measures how many *distinct* human references are matched to at least one of the hypotheses. In contrast, hypotheses generated by sampling exhibit opposite behavior: the quality of the top scoring hypothesis is lower, several hypotheses poorly match references (as indicated by the 25 BLEU points gap between oracle reference and average oracle) but coverage is much higher. This finding is again consistent with the previous observation that the **model distribution is too spread in hypothesis space**. We conjecture that the excessive spread may also be partly responsible for the lack of diversity of beam search, as probability mass is spread across similar variants of the same sequence even in the region of high likelihood. This over-smoothing might be due to the function class of NMT; for instance, it is hard for a smooth class of functions to fit a delta distribution (e.g., a source copy), without spreading probability mass also in nearby hypotheses (e.g., partial copies), or to assign exact 0 probability in space, resulting in an overall under-estimation of hypotheses present in the data distribution.

7 Conclusions and Final Remarks

In this study we investigate the effects of uncertainty in NMT model fitting and search. We found that search works remarkably well. While the model is generally well calibrated both at the token and sentence level, it tends to diffuse probability mass too much. We have not investigated the causes of this, although we surmise that it is largely due to the class of smooth functions that NMT models can represent. We instead investigated some of the effects of this mismatch. In particular, excessive probability spread causes poor quality samples from the model. It may also cause the “copy mode” to become more prominent once the probability of genuine hypotheses gets lowered. We show that this latter issue is linked to a form of extrinsic uncertainty which causes deteriorating accuracy with larger beams. Future work will investigate even better tools to analyze distributions and leverage this analysis to design better models.

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Appendices

In this document, we report two additional findings. First, we discuss the experiments that made us realize that larger beam degradation was due to copy noise in the training data. Second, we introduce another necessary condition for the model and the data distribution to match, which is based on the observation that for some source sentences we do have access to hundreds of references, and therefore, we can directly check whether the two distributions match over the set of unique references.

A How We Discovered Copy Noise

In this section we report the initial experiment which led us to the realization that degradation of large beams is due to noise in the training data, as the process may be instructive also for other researchers working in this area.

A nice visualization of samples drawn from the model is via a scatter plot of log-probability VS. BLEU, as shown in Figure 10 for four sentences picked at random from the test set of WMT’14 En-Fr.

First, this plot shows that while high BLEU implies high log-likelihood, the vice versa is not true, as low BLEU scoring samples can have wildly varying log-likelihood values.

Second, the plot makes very apparent that there are some outlier hypotheses that nicely cluster together.

For instance, there are two clusters corresponding to sentence id 2375, marked with (2) and (3) in Figure 10. These clusters have relatively high log-likelihood but very different BLEU score. The source sentence is:

“Should this election be decided two months after we stopped voting?”

The target reference is:

“*Cette élection devrait-elle être décidé deux mois après que le vote est terminé?*”

while a sample from cluster (2) is:

“*Ce choix devrait-il être décidé deux mois après la fin du vote?*”

and a sample from cluster (3) is:

“*Cette élection devrait-elle être décidée deux mois après l’arrêt du scrutin?*”

This example shows that translation (2), which is a valid translation, gets a low BLEU because of a choice of a synonym word with different gender which causes all subsequent words to be inflected differently, yielding overall a very low n-gram overlap with the reference, and hence a low BLEU score. This is an example of the model nicely capturing (intrinsic) uncertainty, but the metric failing at acknowledging that.

Let’s now look at cluster (1) of sentence id 115. This cluster achieves extremely high log-likelihood but also extremely low BLEU score. The source sentence is:

“The first nine episodes of Sheriff [unk]’s Wild West will be available from November 24 on the site [unk] or via

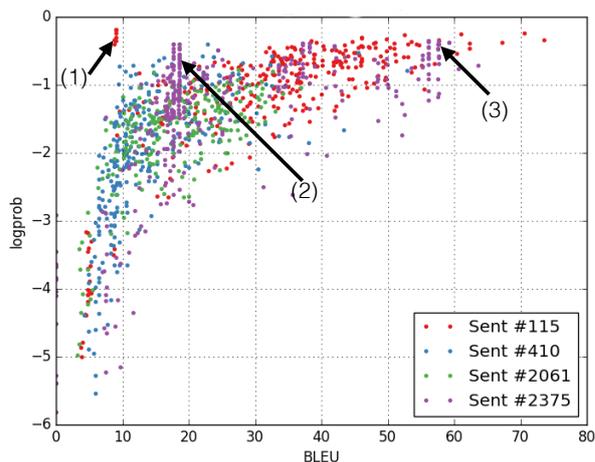


Figure 10: Scatter plot showing log-probability and BLEU of samples drawn from the model for four sentences taken from the test set of WMT’14 En-Fr (each color corresponds to a different test sentence). (1) shows samples where the model copied the source sentence, yielding very large likelihood but low BLEU. (2) and (3) are valid translations of the same source sentence, except that (2) is a cluster of samples using different choice of words.

its application for mobile phones and tablets.”

The target reference is:

“*Les neuf premiers épisodes de [unk] [unk] s Wild West seront disponibles à partir du 24 novembre sur le site [unk] ou via son application pour téléphones et tablettes.*”

while a sample from cluster (1) is:

“*The first nine episodes of Sheriff [unk]’s Wild West will be available from November 24 on the site [unk] or via its application for mobile phones and tablets.*”

In this case, the model copies almost perfectly the source sentence. Examples like these made us discover the “copy issue”, and led us to then link beam search degradation to systematic mistakes in the data collection process.

In conclusion, lots of artifacts and translation issues can be easily spotted by visualizing the data and looking at clusters of outliers.

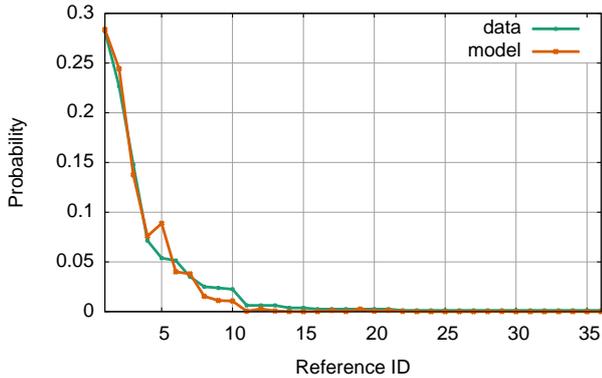


Figure 11: Comparison between the data and the model distributions for the source sentence “(The president cutoff the speaker)”. The data distribution is estimated over 798 references of which 36 are unique. The hypotheses of the data distribution (x-axis) are sorted in descending order of empirical probability mass. The model matches rather well the data distribution.

B Another Necessary Condition: Matching the Full distribution for a Given Source

In §6 we have investigated several necessary conditions for the model distribution to match the data distribution. Those conditions give an aggregate view of the match and they are mostly variants of calibration techniques, whereby the data distribution is approximated via Monte Carlo samples (human translations), since that is all we have access to.

Ideally, we would like to check the two distributions by evaluating their mass at every possible target sequence, but this is clearly intractable and not even possible since we do not have access to the actual data distribution.

However, there are sentences in the training set of WMT’14 En-Fr (EuroParl corpus) that appear several times. For instance, the source sentence “(The President cut off the speaker).” appears almost 800 times in the training set with 36 unique translations. For such cases, we can then have an accurate estimate of the ground truth data distribution (for that given source sentence) and check the match with the model distribution. This is yet another necessary condition: if the model and data distribution match, they also match for a particular source sentence.

Figure 11 shows that for this particular sentence the model output distribution closely matches the data distribution.

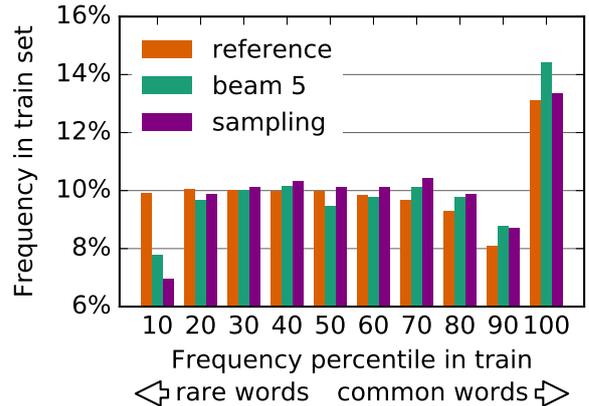
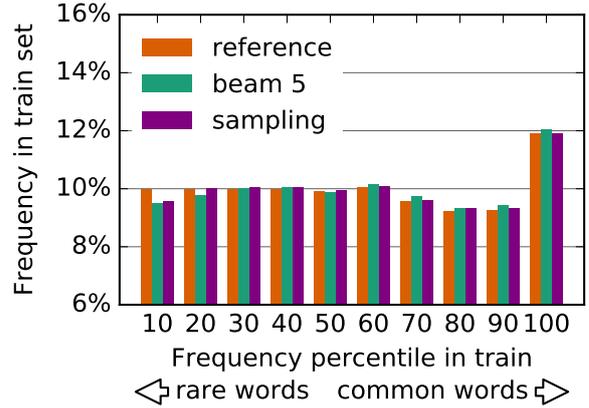


Figure 12: Unigram word frequency over the human references, the output of beam search ($k = 5$) and sampling on the WMT’14 En-Fr (top) and WMT’17 En-De news-commentary portion (bottom) of the training set.

C Does More Data Help?

The findings reported in this paper are quite robust to the choice of architecture as well as dataset. For instance, we compare in Figure 12 the binned unigram word frequencies on the larger WMT’14 En-Fr dataset with the smaller news-commentary portion of the WMT-17 En-De dataset (which was already reported in Figure 6). The En-Fr data is about 100 times bigger than the En-De news-commentary dataset, as described in §4.2 and the En-Fr model performs much better than the En-De, with a BLEU of 41 versus only 21 (see Table 1 and Figure 5). Despite the better quality of the En-Fr model, we observe the same tendency of the model to under-estimate very rare words (compare sampling VS reference in the 10 percentile bin). However, the under-estimation is much less severe in the En-Fr model, only 0.5% as opposed to 3%. Note that the median frequency of words in the 10 percentile bin is 2552 for the En-Fr dataset, but only 12 for the En-De dataset. The NMT model clearly needs more data to better estimate its parameters and fit the data distribution.