Pushing the Limits of Translation Quality Estimation

André F. T. Martins
Unbabel
Instituto de Telecomunicações
Lisbon, Portugal
andre.martins@unbabel.com

Marcin Junczys-Dowmunt
Adam Mickiewicz University in Poznań
Poznań, Poland
junczys@amu.edu.pl

Fabio N. Kepler
Unbabel
L2F/INESC-ID, Lisbon, Portugal
University of Pampa, Alegrete, Brazil
kepler@unbabel.com

Ramón Astudillo
Unbabel
L2F/INESC-ID
Lisbon, Portugal
ramon@unbabel.com

Chris Hokamp
Dublin City University
Dublin, Ireland
chokamp@computing.dcu.ie

Roman Grundkiewicz
Adam Mickiewicz University in Poznań
Poznań, Poland
romang@amu.edu.pl

Abstract
Translation quality estimation is a task of growing importance in NLP, due to its potential to reduce post-editing human effort in disruptive ways. However, this potential is currently limited by the relatively low accuracy of existing systems. In this paper, we achieve remarkable improvements by exploiting synergies between the related tasks of word-level quality estimation and automatic post-editing. First, we stack a new, carefully engineered, neural model into a rich feature-based word-level quality estimation system. Then, we use the output of an automatic post-editing system as an extra feature, obtaining striking results on WMT16: a word-level $F_{\text{MULT}}$ score of 57.47% (an absolute gain of +7.95% over the current state of the art), and a Pearson correlation score of 65.56% for sentence-level HTER prediction (an absolute gain of +13.36%).

1 Introduction
The goal of quality estimation (QE) is to evaluate a translation system’s quality without access to reference translations (Blatz et al., 2004; Specia et al., 2013). This has many potential usages: informing an end user about the reliability of translated content; deciding if a translation is ready for publishing or if it requires human post-editing; highlighting the words that need to be changed. QE systems are particularly appealing for crowd-sourced and professional translation services, due to their potential to dramatically reduce post-editing times and to save labor costs (Specia, 2011). The increasing interest on this problem from an industrial angle comes as no surprise (Turchi et al., 2014; de Souza et al., 2015; Martins et al., 2016; Kozlova et al., 2016).

In this paper, we tackle word-level QE, whose goal is to assign a label of OK or BAD to each word in the translation (Figure 1). Past approaches to this problem include linear classifiers with handcrafted features (Ueffing and Ney, 2007; Bicic, 2013; Shah et al., 2013; Luong et al., 2014), sometimes subject to feature selection (Avramidis, 2012; Beck et al., 2013), recurrent neural networks (de Souza et al., 2014; Kim and Lee, 2016), and systems that combine linear and neural models (Kreutzer et al., 2015; Martins et al., 2016). We start by proposing a “pure” QE system (§3) consisting of a new, carefully engineered neural model (NEURALQE), stacked into a linear feature-rich classifier (LINEARQE). Along the way, we provide a rigorous empirical analysis to better understand the contribution of the several groups of features and to justify the architecture of the neural system.

A second contribution of this paper is bringing in the related task of automatic post-editing (APE; Simard et al. (2007)), which aims to au-
The Sharpen tool sharpens areas in an image.

Der Schärfen-Werkzeug Bereiche in einem Bild schärfer erscheint.

Mit dem Scharfzeichner können Sie einzelne Bereiche in einem Bild scharfzeichnen.

BAD BAD OK OK OK BAD BAD OK || HTER = 66.7%

Figure 1: Example from the WMT16 word-level QE training set. Shown are the English source sentence, the German translation (MT), its manual post-edition (PE), and the conversion to word quality labels made with the TERCOM tool (QE). Words labeled as OK are shown in green, and those labeled as BAD are shown in red. We also show the HTER (fraction of edit operations to produce PE from MT) computed by TERCOM.

Automatically correct the output of machine translation (MT). We show that a variant of the APE system of Junczys-Dowmunt and Grundkiewicz (2016), trained on a large amount of artificial “roundtrip translations,” is extremely effective when adapted to predict word-level quality labels (yielding APEQE, §4). We further show that the pure and the APE-based QE system are highly complementary (§5): a stacked combination of LINEARQE, NEURALQE, and APEQE boosts the scores even further, leading to a new state of the art in the WMT15 and WMT16 datasets: for the latter, we achieve an $F_1$ score of 57.47%, which represents an absolute improvement of +7.95% over the previous best system.

Finally, we provide a simple word-to-sentence conversion to adapt our system to sentence-level QE. This results in a new state of the art for human-targeted translation error rate (HTER) prediction, where we obtain a Pearson’s $r$ correlation score of 65.56% (+13.36% absolute gain), and for sentence ranking, which achieves a Spearman’s $\rho$ correlation score of 65.92% (+17.62%). We complement our findings with error analysis that highlights the synergies between pure and APE-based QE systems.

2 Datasets and System Architecture

Datasets. For developing and evaluating our systems, we use the datasets listed in Table 1. These datasets have been used in the QE and APE tasks in WMT 2015–2016 (Bojar et al., 2015, 2016).

They span two language pairs (English-Spanish and English-German) and two different domains (news translations and information technology). We used the standard train, development and test splits. Each split contains the source and automatically translated sentences (which we use as inputs), the manually post-edited sentences (output for the APE task), and a sequence of OK/BAD quality labels, one per each translated word (output for the word-level QE task); see Figure 1. Besides these datasets, for training the APE system we make use of artificial roundtrip translations; this will be detailed in §4.

Evaluation. For all experiments, we report the official evaluation metrics of each dataset’s year. For WMT15, the official metric for the word-level QE task is the $F_1$ score of the BAD labels ($F_{BAD}^1$). For WMT16, it is the product of the $F_1$ scores for the OK and BAD labels (denoted $F_{MULT}^1$). For sentence-level QE, we report the Pearson’s $r$ correlation for HTER prediction and the Spearman’s $\rho$ correlation score for sentence ranking (Graham, 2015).

From post-edited sentences to quality labels. In the datasets above, the word quality labels are obtained automatically by aligning the translated and the post-edited sentence with the TERCOM software tool (Snover et al., 2006), with the default settings (tokenized, case insensitive, exact matching only, shifts disabled). This tool computes the HTER (the normalized edit distance) between the translated and post-edited sentence. As a by-product, it aligns the words in the two sentences, identifying substitution errors, word deletions (i.e. words omitted by the translation system), and insertions (redundant words in the translation). The substitution errors and the insertions originate the BAD quality labels.

The fact that the quality labels are automatically obtained from the post-edited sentences is not just an artifact of these datasets, but a procedure that is highly convenient for developing QE systems in an industrial setting. Manually annotating word-level quality labels is time-consuming and expensive; on the other hand, post-editing translated sentences is

---

1Publicly available at http://www.statmt.org/wmt15 and http://www.statmt.org/wmt16.

2http://www.cs.umd.edu/~snover/tercom.
Table 1: Datasets used in this work.

| Dataset      | Language pair | # sents | # words |
|--------------|---------------|---------|---------|
| WMT15, Train | En-Es         | 11,271  | 257,548 |
| WMT15, Dev   | En-Es         | 1,000   | 23,207  |
| WMT15, Test  | En-Es         | 1,817   | 40,899  |
| WMT16, Train | En-De         | 12,000  | 210,958 |
| WMT16, Dev   | En-De         | 1,000   | 19,487  |
| WMT16, Test  | En-De         | 2,000   | 34,531  |

commonly part of the workflow of crowd-sourced and professional translation services. Thus, getting quality labels for free from sentences that have already been post-edited is a much more realistic and sustainable process. This observation suggests that we can tackle word-level QE in two ways:

1. **Pure QE**: run the TER alignment tool (i.e. TER-COM) on the post-edited data, and then train a QE system directly on the generated quality labels;

2. **APE-based QE**: train an APE system on the original post-edited data, and at runtime use the TER alignment tool to convert the automatically post-edited sentences to quality labels.

From a machine learning perspective, QE is a sequence labeling problem (i.e., whose output sequence has a fixed length and a small number of labels), while APE is a sequence-to-sequence problem (where the output is of variable length and spans a large vocabulary). Therefore, we can regard APE-based QE as a “projection” of a more complex and fine-grained output (APE) into a simpler output space (QE). APE-based QE systems have the potential for being more powerful since they are trained with this finer-grained information (provided there is enough training data to make them generalize well). We report results in §4 confirming this hypothesis.

Our system architecture, described in full detail in the following sections, consists of state-of-the-art pure QE and APE-based QE systems, which are then combined to yield a new, more powerful, QE system.

### 3 Pure Quality Estimation

The best performing system in the WMT16 word-level QE task was developed by the Unbabel team (Martins et al., 2016). It is a pure but rather complex QE system, ensembling a linear feature-based classifier with three different neural networks with different configurations. In this section, we provide a simpler version of their system, by replacing the three ensembled neural components by a single one, which we engineer in a principled way. We evaluate the resulting system on additional data (WMT15 in addition to WMT16), covering a new language pair and a new content type. Overall, we obtain a slightly higher accuracy with a much simpler system.

In this section, we describe the linear (§3.1) and neural (§3.2) components of our system, as well as their combination (§3.3).

#### 3.1 Linear Sequential Model

We start with the linear component of our model, a discriminative feature-based sequential model (called LINEARQE), based on Martins et al. (2016). The system receives as input a tuple \((s, t, A)\), where \(s = s_1 \ldots s_M\) is the source sentence, \(t = t_1 \ldots t_N\) is the translated sentence, and \(A \subseteq \{(m, n) \mid 1 \leq m \leq M, 1 \leq n \leq N\}\) is a set of word alignments. It predicts as output a sequence \(\hat{y} = y_1 \ldots y_N\), with each \(y_i \in \{\text{BAD}, \text{OK}\}\). This is done as follows:

\[
\hat{y} = \arg \max_y \sum_{i=1}^{N} w^\top \phi_u(s, t, A, y_i) + \sum_{i=1}^{N+1} w^\top \phi_b(s, t, A, y_i, y_{i-1}).
\]

Above, \(w\) is a vector of weights, \(\phi_u(s, t, A, y_i)\) are unigram features (depending only on a single output label), \(\phi_b(s, t, A, y_i, y_{i-1})\) are bigram features (depending on consecutive output labels), and \(y_0\) and \(y_{N+1}\) are special start/stop symbols.

**Features.** Table 2 shows the unigram and bigram features used in the LINEARQE system. Like the baseline systems provided in WMT15/16, we include features that depend on the target word and its aligned source word, as well as the context surrounding them.\(^3\) A distinctive aspect of our system is the inclusion of syntactic features, which

---

\(^3\)Features involving the aligned source word are replaced by NIL if the target word is unaligned. If there are multiple aligned source words, they are concatenated into a single feature.
were found useful to detect grammatically incorrect constructions, as we shall see.\footnote{While syntactic features have been used previously in sentence-level QE (Rubino et al., 2012), they have never been applied to the finer-grained word-level variant tackled here.} We use features that involve the dependency relation, the head word, and second-order sibling and grandparent structures. Features involving part-of-speech (POS) tags and syntactic information are obtained with TurboTagger and TurboParser (Martins et al., 2013).\footnote{http://www.cs.cmu.edu/~ark/TurboParser.}

**Training.** The feature weights are learned by running 50 epochs of the max-loss MIRA algorithm (Crammer et al., 2006), with regularization constant $C \in \{10^{-k}\}_{k=1}^{4}$ and a Hamming cost function placing a higher penalty on false positives than on false negatives ($c_{FP} \in \{0.5, 0.55, \ldots, 0.95\}, c_{FN} = 1 - c_{FP}$), to account for the existence of fewer BAD labels than OK labels in the data. These values are tuned on the development set.

**Results and feature contribution.** Table 3 shows the results. To help understand the contribution of each group of features, we evaluated different variants of the LINEARQE system on the development sets of WMT15/16. As expected, the use of bigrams improves the simple unigram model, and the syntactic features help even further. The impact of these features is more prominent in WMT16: the rich bigram features lead to scores about 3 points above a sequential model with a single indicator bigram feature, and the syntactic features contribute another 2.5 points. The net improvement exceeds 6 points over the unigram model.

### Table 2: Features used in the LINEARQE system (see Martins et al., 2016 for a detailed description). Features marked with * are included in the WMT16 baseline system. Those marked with † were proposed by Kreutzer et al. (2015).

| Features | Label | Input (referenced by the $i$th target word) |
|----------|-------|--------------------------------------------|
| unigram  | $y_i \land \ldots$ | *BIAS WORD, LEFTWORD, RIGHTWORD  
*SOURCEWORD, SOURCELEFTWORD, SOURCERIGHTWORD  
*LARGESTNGRAMLEFT/RIGHT, SOURCERIGHTNGRAMLEFT/RIGHT  
*POSTAG, SOURCEPOSTAG  
†WORD+LEFTWORD, WORD+RIGHTWORD  
†WORD+SOURCEWORD, POSTAG+SOURCEPOSTAG |
| simple bigram | $y_i \land y_{i-1} \land \ldots$ | *BIAS |
| rich bigrams | $y_i \land y_{i-1} \land \ldots$, all above  
$y_{i+1} \land y_i \land \ldots$ | WORD+SOURCEWORD, POSTAG+SOURCEPOSTAG |
| syntactic | $y_i \land \ldots$ | DEPREL, WORD+DEPREL  
HEADWORD/POSTAG+WORD/POSTAG  
LEFTSIBWORD/POSTAG+WORD/POSTAG  
RIGHSIBWORD/POSTAG+WORD/POSTAG  
GRANDWORD/POSTAG+HEADWORD/POSTAG+WORD/POSTAG |

| Features | WMT15 ($F_{1}^{BAD}$) | WMT16 ($F_{1}^{MULT}$) |
|----------|-----------------------|-----------------------|
| unigrams only | 41.77 | 40.05 |
| +simple bigram | 42.20 | 40.63 |
| +rich bigrams | 42.80 | 43.65 |
| +syntactic (full) | 43.68 | 46.11 |

Table 3: Performance on the WMT15 (En-ES) and WMT16 (En-De) development sets of several configurations of LINEARQE. We report the official metric for these shared tasks, $F_{1}^{BAD}$ for WMT15 and $F_{1}^{MULT}$ for WMT16.

3.2 Neural System

Next, we describe the neural component of our pure QE system, which we call NEURALQE. In WMT15 and WMT16, the neural QUETCH system (Kreutzer et al., 2015) and its ensemble with other neural models (Martins et al., 2016) were components of the winning systems. However, none of these neural models managed to outperform a linear model when considered in isolation—for example, QUETCH ob-
tained a $F_1^{BAD}$ of 35.27% in the WMT15 test set, far below the 40.84% score of the linear system built by the same team. By contrast, our carefully engineered NEURALQE model attains a performance superior to that of the linear system, as we shall see.

**Architecture.** The architecture of NEURALQE is depicted in Figure 2. We used Keras (Chollet, 2015) to implement our model. The system receives as input the source and target sentences $s$ and $t$, their word-level alignments $A$, and their corresponding POS tags obtained from TurboTagger. The input layer follows a similar architecture as QUETCH, with the addition of POS features. A vector representing each target word is obtained by concatenating the embedding of that word with those of the aligned word in the source.\(^6\) The immediate left and right contexts for source and target words are also concatenated. We use the pre-trained 64-dimensional Polyglot word embeddings (Al-Rfou et al., 2013) for English, German, and Spanish, and refine them during training. In addition to this, POS tags for each source and target word are also embedded and concatenated. POS embeddings have size 50 and are initialized as described by Glorot and Bengio (2010). A dropout probability of 0.5 is applied to the resulting vector representations.

The following layers are then applied in sequence:

1. Two feed-forward layers of size 400 with rectified linear units (ReLU; Nair and Hinton (2010));
2. A layer with bidirectional gated recurrent units (BiGRU, Cho et al. (2014)) of size 200, where forward and backward vectors are concatenated, trained with layer normalization (Ba et al., 2016);
3. Two feed-forward ReLU layers of size 200;
4. A BiGRU layer of size 100 with identical configuration to the previous BiGRU;
5. Two more feed-forward ReLU layers of sizes 100 and 50, respectively.

As the output layer, a softmax transformation over the OK/BAD labels is applied. The choice for this architecture was dictated by experiments on the WMT16 development data, as we explain next.

**Training.** We train the model with the RMSProp algorithm (Tieleman and Hinton, 2012) by minimizing the cross-entropy with a linear penalty for BAD word predictions, as in Kreutzer et al. (2015). We set the BAD weight factor to 3.0. All hyperparameters are adjusted based on the development set. Target sentences are bucketed by length and then processed in batches (without any padding or truncation).

**Results and architectural choices.** The final results are shown in Table 4. Overall, the final NEURALQE model achieves an $F_1^{MULT}$ score of 46.80% on the WMT16 development set, compared with the 46.11% obtained with the LINEARQE system (cf. Table 3). This contrasts with previous neural systems, such as QUETCH (Kreutzer et al., 2015) and any of the three neural systems developed by Martins et al. (2016), which could not outperform a rich feature linear classifier.

To justify the most relevant choices regarding the architecture of NEURALQE, we also evaluated several variations of it on the WMT16 development set. The use of recurrent layers yields the largest contribution to the performance of NEURALQE, as the scores drop sharply (by more than 4 points) if they are replaced by feed-forward layers (which would correspond to a mere deeper QUETCH model). The first BiGRU is particularly effective, as scores drop more than 2 points if it is removed. The use of layer normalization on the recurrent layers also contributes positively (+1.20) to the final score. As expected, the use of POS tags adds another large improvement: everything staying the same, the model

---

\(^6\)For the cases in which there are multiple source words aligned to the same target word, the embeddings are averaged.
without POS tags as input performs almost 2.5 points worse. Finally, varying the size of the hidden layers and the depth of the network hurts the final model’s performance, albeit more slightly.

### 3.3 Stacking Neural and Linear Models

We now stack the NEURALQE system (§3.2) into the LINEARQE system (§3.1) as an ensemble strategy; we call the resulting system STACKEDQE.

Stacking architectures (Wolpert, 1992; Breiman, 1996) have proved effective in structured NLP problems (Cohen and de Carvalho, 2005; Martins et al., 2008). The underlying idea is to combine two systems by letting the prediction of the first system be used as an input feature for the second system. During training, it is necessary to jackknife the first system’s predictions to avoid overfitting the training set. This is done by splitting the training set in $K$ folds (we set $K = 10$) and training $K$ different instances of the first system, where each instance is trained on $K - 1$ folds and makes predictions for the left-out fold. The concatenation of all the predictions yields an unbiased training set for the second classifier.

**Neural intra-ensembles.** We also evaluate the performance of intra-ensembled neural systems. We train independent instances of NEURALQE with different random initializations and different data shuffles, following the approach of Jean et al. (2015) in neural MT. In Tables 5–6, we report the performance on the WMT15 and WMT16 datasets of systems ensembling 5 and 15 of these instances, called respectively NEURALQE-5 and NEURALQE-15. The instances are ensembled by taking the averaged probability of each word being BAD. We see consistent benefits (both for WMT15 and WMT16) in ensembling 5 neural systems and (somewhat surprisingly) some degradation with ensembles of 15.

**Stacking architecture.** The individual instances of the neural systems are incorporated in the stacking architecture as different features, yielding STACKEDQE. In total, we have 15 predictions (probability values given by each NEURALQE system) for every word in the training, development and test datasets. These predictions are plugged as additional features in the LINEARQE model. As unigram features, we used one real-valued feature for every model prediction at each position, conjoined with the label. As bigram features, we used two real-valued features for every model prediction at the two positions, conjoined with the label pair.

### Table 5: Performance of the pure QE systems on the WMT15 datasets.

The best performing system in the WMT15 competition was by Esplà-Gomis et al. (2015), followed by Kreutzer et al. (2015)’s QUETCH+, which is also an ensemble of a linear and a neural system.

| Model         | $F_{1}^{MULT}$ dev | $F_{1}^{MULT}$ test |
|---------------|---------------------|---------------------|
| Best system in WMT15 | 43.1                | 43.12               |
| QUETCH+ (2nd best) | –                   | 43.05               |
| LINEARQE      | 46.11               | 46.16               |
| NEURALQE      | 46.80               | 47.29               |
| NEURALQE-5    | 47.30               | 48.50               |
| NEURALQE-15   | 46.77               | 47.98               |
| STACKEDQE     | 49.16               | 50.27               |

### Table 6: Performance of the pure QE systems on the WMT16 datasets.

The best performing system in the WMT16 competition was by Martins et al. (2016), followed by a linear system developed by the same team (Unbabel-Linear).

| Model         | $F_{1}^{MULT}$ dev | $F_{1}^{MULT}$ test |
|---------------|---------------------|---------------------|
| Best system in WMT16 | 49.25               | 49.52               |
| Unbabel-Linear (2nd best) | 45.94               | 46.29               |
| LINEARQE      | 46.11               | 46.16               |
| NEURALQE      | 46.80               | 47.29               |
| NEURALQE-5    | 47.30               | 48.50               |
| NEURALQE-15   | 46.77               | 47.98               |
| STACKEDQE     | 49.16               | 50.27               |

---

**Table 4:** Effect of architectural changes in NEURALQE on the WMT16 development set.

| Architectural Change | $F_{1}^{MULT}$ |
|----------------------|---------------|
| No POS tags          | 44.41 (-2.39) |
| Replace BiGRU by FF  | 42.36 (-4.44) |
| Only the first BiGRU | 45.76 (-1.04) |
| Only the second BiGRU| 44.37 (-2.43) |
| Remove FF between BiGRUs | 46.35 (-0.45) |
| Narrower layers      | 45.09 (-1.71) |
| Broader layers       | 45.02 (-1.78) |
| One more layer at the end | 46.31 (-0.49) |
| No layer normalization | 45.60 (-1.20) |
The results obtained with this stacked architecture on the WMT15 and WMT16 datasets are shown respectively in Tables 5 and 6. In WMT15, it is unclear if stacking helps over the best intra-ensembled neural system, with a slight improvement in the development set, but a degradation in the test set. In WMT16, however, stacking is clearly beneficial, with a boost of about 2 points over the best intra-ensembled neural system and 3–4 points above the linear system, both in the development and test partitions. For the remainder of this paper, we will take STACKEDQE as our pure QE system.

4 APE-Based Quality Estimation

Now that we have described a pure QE system, we move on to an APE-based QE system (APEQE).

Our starting point is the system submitted by the Adam Mickiewicz University (AMU) team to the APE task of WMT16 (Junczys-Dowmunt and Grundkiewicz, 2016). They explored the application of neural translation models to the APE problem and achieved good results by treating different models as components in a log-linear model, allowing for multiple inputs (the source \(s\) and the translated sentence \(t\)) that were decoded to the same target language (post-edited translation \(p\)). Two systems were considered, one using \(s\) as the input (\(s \rightarrow p\)) and another using \(t\) as the input (\(t \rightarrow p\)). A simple string-matching penalty integrated within the log-linear model was used to control for higher faithfulness with regard to the raw MT output. The penalty fires if the APE system proposes a word in its output that has not been seen in \(t\).

To overcome the problem of too little training data, Junczys-Dowmunt and Grundkiewicz (2016) generated large amounts of artificial data via round-trip translations: a large corpus of monolingual sentences is first gathered for the target language in the domain of interest (each sentence is regarded as an artificial post-edited sentence \(p\)); then an MT system is run to translate these sentences to the source language (which are regarded as the source sentences \(s\)), and another MT system in the reverse direction translates the latter back to the target language (playing the role of the translations \(t\)). The artificial data is filtered to match the HTER statistics of the training and development data for the shared task.\(^7\) Their submission improved over the uncorrected baseline on the unseen WMT16 test set by -3.2% TER and +5.5% BLEU and outperformed any other system submitted to the shared-task by a large margin.

4.1 Training the APE System

We reproduce the experiments from Junczys-Dowmunt and Grundkiewicz (2016) using Nematus (Sennrich et al., 2016) for training and AmuNMT (Junczys-Dowmunt et al., 2016) for decoding.

As stated in §3.3, jackknifing is required to avoid overfitting during the training procedure of the stacked classifiers (§5), therefore we start by preparing four jackknifed models. We perform the following steps:

- We divide the original WMT16 training set into four equally sized parts, maintaining correspondences between different languages. Four new training sets are created by leaving out one part and concatenating the remaining three parts.
- For each of the four new training sets, we train one APE model on a concatenation of a smaller set of artificial data (denoted as “round-trip.n1” in Junczys-Dowmunt and Grundkiewicz (2016), consisting of 531,839 sentence triples) and a 20-fold oversampled new training set. Each of these newly created four APE models has not seen a different part of the quartered original training data.
- To avoid overfitting, we use scaling dropout\(^8\) over GRU steps and input embeddings, with dropout probabilities 0.2, and over source and target words with probabilities 0.1 (Sennrich et al., 2016).
- We use Adam (Kingma and Ba, 2014) instead of Adadelta (Zeiler, 2012).
- We train both models (\(s \rightarrow p\) and \(t \rightarrow p\)) until convergence up to 20 epochs, saving model checkpoints every 10,000 mini-batches.

\(^7\)The artificial filtered data has been made available by the authors at https://github.com/emjotde/amunmt/wiki/AmuNMT-for-Automatic-Post-Editing.

\(^8\)Currently available in the MRT branch of Nematus at https://github.com/rsennrich/nematus
The last four model checkpoints of each training run are averaged element-wise (Junczys-Dowmunt et al., 2016) resulting in new single models with generally improved performance.

To verify the quality of the APE system, we ensemble the 8 resulting models (4 times $s \rightarrow p$ and 4 times $t \rightarrow p$) and add the APE penalty described in Junczys-Dowmunt and Grundkiewicz (2016). This large ensemble across folds is only used during test time. For creating the jackknifed training data, only the models from the corresponding fold are used. Since we combine models of different types, we tune weights on the development set with MERT\(^9\) (Och, 2003) towards TER, yielding the model denoted as “APE TER-tuned”. Results are listed in Table 7 for the APE shared task (WMT 16). For the purely $s \rightarrow p$ and $t \rightarrow p$ ensembles, models are weighted equally. We achieve slightly better results in terms of TER, the main task metric, than the original system using less data.

For completeness, we also apply this procedure to WMT15 data, generating a similar resource of 500K artificial English-Spanish-Spanish post-editing triplets via roundtrip translation.\(^{10}\) The training, jackknifing and ensembling methods are the same as for the WMT16 setting. For the WMT15 APE shared task, results are less persuasive than for WMT16: none of the shared task participants was able to beat the uncorrected baseline and our system fails at this as well. However, we produced the second strongest system for case-sensitive TER (Table 7, WMT15) and the strongest for case-insensitive TER (22.49 vs. 22.54).

### 4.2 Adaptation to QE and Task-Specific Tuning

As described in §2, APE outputs can be turned into word quality labels using TER-based word alignments. Somewhat surprisingly, among the APE systems introduced above, we observe in Table 9 that the $s \rightarrow p$ APE system is the so-far strongest stand-alone QE system for the WMT16 task in this work. This system is essentially a retrained neural MT component without any additional features.\(^{11}\) The $t \rightarrow p$ system and the TER-tuned APE ensemble are much weaker in terms of $F_{1}^{\text{MULT}}$. This is less surprising in the case of the full ensemble, as it has been tuned towards TER for the APE task specifically. However, we can obtain even better APE-based QE systems for both shared task settings by tuning the full APE ensembles towards $F_{1}^{\text{MULT}}$, the official WMT16 QE metric, and towards $F_{1}^{\text{BAD}}$ for WMT15.\(^{12}\) With this approach, we produce our new best stand-alone QE-systems for both shared tasks, which we denote as APEQE.

---

\(^9\)We found MERT to work better when tuning towards TER than kb-MIRA which has been used in the original paper.

\(^{10}\)Our artificially created data might suffer from a higher mismatch between training and development data. While we were able to match the TER statistics of the dev set, BLEU scores are several points lower. The artificial WMT16 data we created in Junczys-Dowmunt and Grundkiewicz (2016) matches both, TER and BLEU scores, of the respective development set.

\(^{11}\)Note that this system resembles other QE approaches which use pseudo-reference features (Albrecht and Hwa, 2008; Soricut and Narsale, 2012; Shah et al., 2013), since the $s \rightarrow p$ is essentially an “alternative” MT system.

\(^{12}\)Using again MERT and executing 7 iterations on the official development set with an n-best list size of 12.
5 Full Stacked System

Finally, we consider a larger stacked system where we stack both NEURALQE and APEQE into LINEARQE. This will mix pure QE with APE-based QE systems; we call the result FULLSTACKEDQE. The procedure is analogous to that described in §3.3, with one extra binary feature for the APE-based word quality label predictions. For training, we used jackknifing as described in §3.3.

5.1 Word-Level QE

The performance of the FULLSTACKEDQE system on the WMT15 and WMT16 datasets are shown in Tables 10–11. We compare with the other systems introduced in this paper, and with the best participating systems at WMT15–16 (Esplà-Gomis et al., 2015; Martins et al., 2016).

We can see that the APE-based and the pure QE systems are complementary: the full combination of the linear, neural, and APE-based systems improves the scores with respect to the best individual system (APEQE) by about 1 point in WMT15 and 2 points in WMT16. Overall, we obtain for WMT16 an $F^\text{MULT}_1$ score of 57.47%, a new state of the art and an absolute gain of +7.95% over Martins et al. (2016). This is a remarkable improvement that can pave the way for a wider adoption of word-level QE systems in industrial settings. For WMT15, we also obtain a new state of the art, with a less impressive gain of +3.96% over the best previous system. In §6 we analyze the errors made by the pure and the APE-based QE systems to better understand how they complement each other.

5.2 Sentence-Level QE

Encouraged by the strong results obtained with the FULLSTACKEDQE system in word-level QE, we investigate how we can adapt this system for HTER prediction at sentence level. Prior work (de Souza et al., 2014) incorporated word-level quality predictions as features in a sentence-level QE system, training a feature-based linear classifier. Here, we show that a very simple conversion, which requires no training or tuning, is enough to obtain a substantial improvement over the state of the art.

For the APE system, it is easy to obtain a prediction for HTER: we can simply measure the HTER between the translated sentence $t$ and the predicted corrected sentence $\hat{p}$. For a pure QE system, we apply the following word-to-sentence conversion technique: (i) run a QE system to obtain a sequence of OK and BAD word quality labels; (ii) use the fraction of BAD labels as an estimate for HTER. Note that this procedure, while not requiring any training, is far from perfect: words that are not in the translated sentence but exist in the reference post-edited sentence do not originate BAD labels, and therefore will not contribute to the HTER estimate. Yet, as we will see, this procedure applied to the STACKEDQE system (i.e. without the APEQE component) is already sufficient to obtain state of the art results. Finally, to combine the APE and pure QE systems toward sentence-level QE, we simply take the average of the two HTER predictions above.

Table 12 shows the results obtained with our pure QE system (STACKEDQE), with our APE-based system (APEQE), and with the combination of the two (FULLSTACKEDQE). As baselines, we
Table 12: Performance of our sentence-level QE systems on the WMT15 and WMT16 datasets, as measured by the WMT16 official evaluation script. The baselines are the best WMT15–16 systems in the HTER prediction track (Bicici et al., 2015; Kozlova et al., 2016) and in the sentence ranking track (Langlois, 2015; Kim and Lee, 2016).

|                  | Pearson dev | Pearson test | Spearman dev | Spearman test |
|------------------|-------------|--------------|--------------|--------------|
| **WMT15**        |             |              |              |              |
| Best system in WMT15 (ranking) | –           | 39.41        | –            | 36.49        |
| Best system in WMT15 (HTER)     | –           | 38.46        | –            | 36.81        |
| STACKEDQE        | 32.29       | 36.96        | 33.22        | 34.44        |
| APEQE            | 29.33       | 40.39        | 30.80        | 38.74        |
| FULLSTACKEDQE    | **36.07**   | **44.99**    | **36.68**    | **42.30**    |
| **WMT16**        |             |              |              |              |
| Best system in WMT16 (ranking) | –           | 52.5         | –            | –            |
| Best system in WMT16 (HTER)     | –           | 46.0         | –            | 48.3         |
| STACKEDQE        | 55.30       | 54.93        | 56.46        | 55.34        |
| APEQE            | 59.04       | 61.27        | 61.06        | 62.48        |
| FULLSTACKEDQE    | **64.04**   | **65.56**    | **65.52**    | **65.92**    |

report the performance of the two best systems in the sentence-level QE tasks at WMT15 and WMT16 (Bicici et al., 2015; Langlois, 2015; Kozlova et al., 2016; Kim and Lee, 2016).

The results are striking: for WMT16, even our weakest system (STACKEDQE) with the simple conversion procedure above is already sufficient to obtain state of the art results, outperforming Kozlova et al. (2016) and Kim and Lee (2016) by a considerable margin. The APEQE system gives a very large boost over these scores, which are further increased by the combined FULLSTACKEDQE system. Overall, we obtain absolute gains of +13.36% in Pearson’s $r$ correlation score for HTER prediction, and +17.62% in Spearman’s $\rho$ correlation for sentence ranking, a considerable advance over the previous state of the art. For WMT15, we also obtain a new state of the art, with less sharp (but still significant) improvements: +5.08% in Pearson’s $r$ correlation score, and +5.81% in Spearman’s $\rho$ correlation.

6 Error Analysis

Performance over sentence length. To better understand the differences in performance between the pure QE system (STACKEDQE) and the APE-based system (APEQE), we analyze how the two systems, as well as their combination (FULLSTACKEDQE), perform as a function of the sentence length.

Figure 3 shows the averaged number of BAD predictions made by the three systems for different sentences lengths, in the WMT16 development set. For comparison, we show also the true average number of BAD words in the gold standard. We observe that, for short sentences (less than 5 words), the pure QE system tends to be too optimistic (i.e., it under-predicts BAD words) and the APE-based system too pessimistic (overpredicting them). In the range 5-10 words, the pure QE system matches the proportion of BAD words more accurately than the APE-based system. For medium/long sentences, we observe the opposite behavior (this is particularly clear in the 20-25 word range), with the APE-based system being generally better. On the other hand, the combination of the two systems (FULLSTACKEDQE) manages to find a good balance between these two biases, being much closer to the true proportion of BAD labels for both shorter and longer sentences than any of the individual systems. This shows that the two systems complement each other well in the combination.

Illustrative examples. Table 13 shows concrete examples of quality predictions on the WMT16 development data. In the top example, we can see that the APE system correctly replaced Angleichungsfarbe by Mischfarbe, but is under-corrective in other parts; the APEQE system therefore misses several BAD words, but manages to get the correct label (OK) for den. By contrast, the pure QE system erroneously flags this word as incorrect, but it makes the right decision on Farbton and zu erstellen, being more accurate than APEQE. The combination of the two systems (pure QE and APEQE) leads to the correct sequential prediction. In the bottom ex-
Combines the hue value of the blend color with the luminance and saturation of the base color to create the result color.

MT Kombiniert den Farbton Wert der Angleichungsfarbe mit der Luminanz und Sättigung der Grundfarbe zu erstellen.

PE (Reference) Kombiniert den Farbtonwert der Mischfarbe mit der Luminanz und Sättigung der Grundfarbe.

APE Kombiniert den Farbton der Mischfarbe mit der Luminanz und die Sättigung der Grundfarbe, um die Ergebnisfarbe zu erstellen.

STACKEDQE Kombiniert den Farbton Wert der Angleichungsfarbe mit der Luminanz und Sättigung der Grundfarbe zu erstellen.

APEQE Kombiniert den Farbton Wert der Angleichungsfarbe mit der Luminanz und Sättigung der Grundfarbe zu erstellen.

FULLSTACKEDQE Kombiniert den Farbton Wert der Angleichungsfarbe mit der Luminanz und Sättigung der Grundfarbe zu erstellen.

The Video Preview plug-in supports RGB, grayscale, and indexed images.

MT Mit dem Zusatzmodul Videovorschau unterstützt RGB-, Graustufen- und indizierte Bilder.

PE (Reference) Das Zusatzmodul Videovorschau unterstützt RGB-, Graustufen- und indizierte Bilder.

APE Das Dialogfeld Videovorschau unterstützt RGB-, Graustufen- und indizierte Bilder.

STACKEDQE Mit dem Zusatzmodul Videovorschau unterstützt RGB-, Graustufen- und indizierte Bilder.

APEQE Mit dem Zusatzmodul Videovorschau unterstützt RGB-, Graustufen- und indizierte Bilder.

FULLSTACKEDQE Mit dem Zusatzmodul Videovorschau unterstützt RGB-, Graustufen- und indizierte Bilder.

Table 13: Examples on WMT16 validation data. Shown are the source and translated sentences, the gold post-edited sentences, the output of the APE system, and the QE predictions of our pure QE and APE-based QE systems as well as their combination. Words predicted as OK are shown in green, those predicted as BAD are shown in red, and differences between the translated and the post-edited sentences are shown in blue. For both examples, the full stacked system predicts all quality labels correctly.

Figure 3: Averaged number of words predicted as BAD by the different systems in the WMT16 gold dev set, for different bins of the sentence length.

Example, the pure QE system assigns the correct label to Zusatzmodul, while the APE system mistranslates this word to Dialogfeld, leading to a wrong prediction by the APEQE system. On the other hand, pure QE misclassifies unterstützt RGB- as BAD words, while the APEQE gets them right. Overall, the APEQE is more accurate in this example. Again, these decisions complement each other well, as can be seen by the combined QE system which outputs the correct word labels for the entire sentence.

7 Conclusions

We have presented new state-of-the-art systems for word-level and sentence-level QE that are considerably more accurate than previously existing systems on the WMT15 and WMT16 datasets.

First, we proposed a new pure QE system which stacks a linear and a neural system, and is simpler and slightly more accurate than the currently best word-level system. Then, by relating the tasks of APE and word-level QE, we derived a new APE-based QE system, which leverages additional artificial roundtrip translation data, achieving a larger improvement. Finally, we combined the two systems via a full stacking architecture, boosting the scores even further. Error analysis shows that the pure and APE-based systems are highly complementary. The full system was extended to sentence-level QE by virtue of a simple word-to-sentence conversion, requiring no further training or tuning.
Acknowledgments

We thank the reviewers for their insightful comments. This work was partially supported by the the EXPERT project (EU Marie Curie ITN No. 317471), and by Fundação para a Ciência e Tecnologia (FCT), through contracts UID/EEA/50008/2013 and UID/CEC/50021/2013, the LearnBig project (PTDC/EEI-SII/7092/2014), the GoLocal project (grant CMUPERI/TIC/0046/2014), and the Amazon Academic Research Awards program.

References

Rami Al-Rfou, Bryan Perozzi, and Steven Skiena. 2013. Polyglot: Distributed word representations for multilingual nlp. arXiv preprint arXiv:1307.1662.

Joshua Albrecht and Rebecca Hwa. 2008. The role of pseudo references in MT evaluation. In Proceedings of the Third Workshop on Statistical Machine Translation, pages 187–190.

Eleftherios Avramidis. 2012. Quality estimation for machine translation output using linguistic analysis and decoding features. In Proceedings of the Seventh Workshop on Statistical Machine Translation, pages 84–90.

Jimmy Lei Ba, Jamie Ryan Kiros, and Geoffrey E Hinton. 2016. Layer normalization. arXiv preprint arXiv:1607.06450.

Daniel Beck, Kashif Shah, Trevor Cohn, and Lucia Specia. 2013. SHEF-Lite: When less is more for translation quality estimation. In Proceedings of the Eighth Workshop on Statistical Machine Translation, pages 335–340.

Ergun Biçici, Qun Liu, and Andy Way. 2015. Referential translation machines for predicting translation quality and related statistics. In Proceedings of the Tenth Workshop on Statistical Machine Translation, pages 304–308.

Ergun Biçici. 2013. Referential translation machines for quality estimation. In Proceedings of the Eighth Workshop on Statistical Machine Translation, pages 343–351.

John Blatz, Erin Fitzgerald, George Foster, Simona Gandrabur, Cyril Goutte, Alex Kulesza, Alberto Sanchis, and Nicola Ueffing. 2004. Confidence estimation for machine translation. In Proc. of the International Conference on Computational Linguistics, page 315.

Ondřej Bojar, Rajan Chatterjee, Christian Federmann, Barry Haddow, Chris Hokamp, Matthias Huck, Varvara Logacheva, Philipp Koehn, Christof Monz, Matteo Negri, Pavel Pecina, Matt Post, Carolina Scarton, Lucia Specia, and Marco Turchi. 2015. Findings of the 2015 Workshop on Statistical Machine Translation. In Tenth Workshop on Statistical Machine Translation.

Ondřej Bojar, Rajan Chatterjee, Christian Federmann, Yvette Graham, Barry Haddow, Matthias Huck, Antonio Jimeno Yepes, Philipp Koehn, Varvara Logacheva, Christof Monz, Matteo Negri, Aurelie Neveol, Mariana Neves, Martin Popel, Matt Post, Raphael Rubino, Carolina Scarton, Lucia Specia, Marco Turchi, Karin Verspoor, and Marcos Zampieri. 2016. Findings of the 2016 conference on machine translation. In Proceedings of the First Conference on Machine Translation, pages 131–198.

Leo Breiman. 1996. Stacked regressions. Machine Learning, 24:49.

Kyunghyun Cho, Bart Van Merriënboer, Caglar Gulcehre, Dzmitry Bahdanau, Fethi Bougares, Holger Schwenk, and Yoshua Bengio. 2014. Learning Phrase Representations Using RNN Encoder-Decoder for Statistical Machine Translation. In Proc. of Empirical Methods in Natural Language Processing.

François Chollet. 2015. Keras. https://github.com/fchollet/keras.

William W. Cohen and Vitor R. de Carvalho. 2005. Stacked sequential learning. In Proc. of International Joint Conference on Artificial Intelligence.

Koby Crammer, Ofer Dekel, Joseph Keshet, Shai Shalev-Shwartz, and Yoram Singer. 2006. Online Passive-Aggressive Algorithms. Journal of Machine Learning Research, 7:551–585.

José G. C. de Souza, Jesús González-Rubio, Christian Buck, Marco Turchi, and Matteo Negri. 2014. FBK-UPV-UEdin participation in the WMT14 Quality Estimation shared-task. In Proceedings of the Ninth Workshop on Statistical Machine Translation, pages 322–328.

José G. C. de Souza, Marcello Federico, and Hasen Sawaf. 2015. MT Quality Estimation for E-Commerce Data. In Proc. of MT Summit XV, vol. 2: MT Users’ Track, pages 20–29.

Miquel Esplà-Gomis, Felipe Sánchez-Martínez, and Mikel Forcada. 2015. UAlacant word-level machine translation quality estimation system at WMT 2015. In Proceedings of the Tenth Workshop on Statistical Machine Translation, pages 309–315, September.

Xavier Glorot and Yoshua Bengio. 2010. Understanding the difficulty of training deep feedforward neural networks. In International Conference on Artificial Intelligence and Statistics, pages 249–256.

Yvette Graham. 2015. Improving evaluation of machine translation quality estimation. In Proc. of the Annual Meeting of the Association for Computational Linguistics, pages 1804–1813.
Nicola Ueffing and Hermann Ney. 2007. Word-level confidence estimation for machine translation. *Computational Linguistics*, 33(1):9–40.

D. Wolpert. 1992. Stacked generalization. *Neural Networks*, 5(2):241–260.

Matthew D. Zeiler. 2012. Adadelta: An adaptive learning rate method. *arXiv preprint arXiv:1212.5701*. 