XLTime: A Cross-Lingual Knowledge Transfer Framework for Temporal Expression Extraction

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Abstract

Temporal Expression Extraction (TEE) is essential for understanding time in natural language. It has applications in Natural Language Processing (NLP) tasks such as question answering, information retrieval, and causal inference. To date, work in this area has mostly focused on English as there is a scarcity of labeled data for other languages. We propose XLTime, a novel framework for multilingual TEE. XLTime works on top of pre-trained language models and leverages multi-task learning to prompt cross-language knowledge transfer both from English and within the non-English languages. It alleviates problems caused by a shortage of data in the target language. We apply XLTime with different language models and show that it outperforms the previous automatic SOTA methods on French, Spanish, Portuguese, and Basque, by large margins. It also closes the gap considerably on the handcrafted HeidelTime method.

1 Introduction

Temporal Expression Extraction (TEE) refers to the detection of *temporal expressions* (such as dates, durations, etc. as shown in Table 1). It is an important NLP task (UzZaman et al., 2013) and has downstream applications in question answering (Choi et al., 2018), information retrieval (Mitra et al., 2018), and causal inference (Feder et al., 2021). Most TEE methods work on English and are rule-based (Strötgen and Gertz, 2013; Zhong et al., 2017). Deep learning-based methods (Chen et al., 2019; Lange et al., 2020) are less common and report results on par with or inferior to the rule-based SOTAs.

Moreover, methods that work on other languages are rare, because of the scarcity of annotated data. We find that that there is considerable room for improving TEE, especially for low-resource languages (e.g., the previous SOTA performance on the English TE3 dataset (UzZaman et al., 2013) is around 0.90 in F1, while that on the Basque TEE benchmark (Altuna et al., 2016) is merely 0.47). Recent deep learning methods, which have shown gains for many tasks, are underexplored for this important area of NLP.

Table 1: Temporal expressions of different types (See Appendix A for the definitions of the types).

In *the last three months* (Duration), net revenue rose 4.3% to \$525.8 million from \$504.2 million *last year* (Date).
The official news agency, which gives the *daily* (Set) tally of inspections, updated on *Friday evening* (Time).

Developing an approach that can learn using the existing limited amount of training data is crucial for this field because of the effort required to develop high-quality rules for each language. Thus we propose a cross-lingual knowledge transfer framework for multilingual TEE, namely, XLTime. We base our framework on pre-trained multilingual models (Devlin et al., 2019; Conneau et al., 2020). We then use Multi-Task Learning (MTL) (Liu et al., 2019a) to prompt knowledge transfer both from English and within the low-resource languages. We design primary and secondary tasks. The former leverages the existing data of the other languages. It transfers *explicit knowledge* that explicitly tells the forms of the temporal expressions in a *source language*. The latter constructs its training data in a self-supervised (Liu et al., 2021) manner. It transfers *implicit knowledge* by teaching the model to tell if a sentence in the *target language* contains temporal expressions.

Contributions. **1)** We propose XLTime, which prompts cross-lingual knowledge transfer using MTL to address multilingual TEE. **2)** We show that XLTime outperforms the previous automatic SOTA methods by large margins on four languages, i.e., French, Spanish, Portuguese, and Basque, which are "low-resource" for the TEE task. **3)** We show that XLTime also approaches the performance of the heavily handcrafted HeidelTime (Strötgen and

Gertz, 2013), and even outperforms it on two languages (Portuguese and Basque). We make our code and data publicly available.[1]

2 Related Work

While TEE is an important problem in NLP, there is relatively little work in the area, and most of this work focuses on English. Prior art can be divided into two classes: rule/pattern-based and deep learning approaches. In the first class, HeidelTime (Strötgen and Gertz, 2013) is the most commonly used tool and is the top approach to date, and covers over a dozen languages. It is driven by a collect a collection of finely-tuned rules. The approach was later extended to more languages with HeidelTime-auto (Strötgen and Gertz, 2015), which leverages language-independent processing and rules. Other approaches include SynTime (Zhong et al., 2017), which is based on heuristic rules, and SUTIME (Chang and Manning, 2012) and PTime (Ding et al., 2019), which leverages pattern learning.

For the second class, Laparra et al. (2018) proposes a model based on RNNs. Chen et al. (2019) uses BERT with a linear classifier. Lange et al. (2020) inputs mBERT embeddings to a BiLSTM with a CRF layer and outperforms HeidelTime-auto on four languages. However, the reported performances of the deep learning-based methods are inferior to the rule-based ones, which is, in part, due to the complexity of the problem and training data paucity. In our work, we propose a new model which outperforms prior deep learning methods but also closes the gap considerably on HeidelTime.

3 Proposed Method

We formalize TEE as a sequence labeling task, similar to named entity recognition (NER) (Lample et al., 2016). The architecture is shown in Figure 1.

3.1 Pre-trained Multilingual Backbone

We adopt SOTA multilingual models (Devlin et al., 2019; Conneau et al., 2020) as the backbone of XLTime, denoted as: $T(E(X))$. X is the input sequence. E and T are the lexicon and Transformer encoder layers as shown in Figure 1(b). The backbone allows XLTime to acquire semantic and syntactic knowledge of various languages. It is shared by the MTL tasks introduced in Section 3.2.

[1] Github to be added.

3.2 MTL-based Cross-Lingual Knowledge Transfer

XLTime transfers knowledge from multiple *source languages* to the low-resource *target language*. The source languages include English and others for which TEE training data is available. We design *primary* and *secondary* tasks on top of the backbone to prompt *explicit* and *implicit* knowledge transfer. The primary task transfers knowledge that explicitly encodes the forms of the temporal expressions in a source language. It is formalized as sequence labeling and directly leverages the training data of the source language to train the backbone along with the primary task classifier, shown in Figure 1 (b). The primary task minimizes $\mathcal{L}_{sl}$:

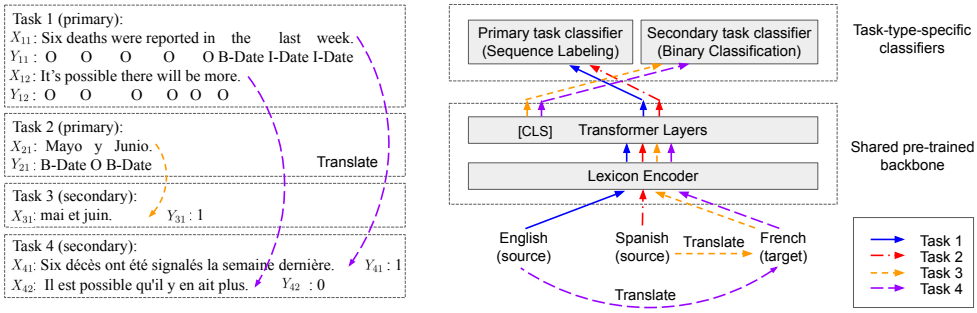
$$\mathcal{L}_{sl} = -\sum_{i=1}^{b}\sum_{j=1}^{m_i} \mathbb{1}(y_{ij}, c) log(softmax(\mathbf{W} \cdot \mathbf{x})), \quad (1)$$

where $\mathbf{x} \in \mathbb{R}^d$ is the embedding of a token output by the backbone. $\mathbf{W} \in \mathbb{R}^{|c| \times d}$ is the primary task classifier. c and y_{ij} are the predicted and ground-truth labels of the token. $\mathbb{1}(,)$ equals to 1 if its two operators are the same and 0 otherwise. b is the total number of input sequences and m_i is the length of the ith sequence.

The secondary task implicitly reveals how the temporal expressions would be expressed in the target language. We translate the sequences in the source language training data into the target language using Google Translate (we observe similar results with AWS Translate). The secondary task is formalized as binary classification, where the input samples are the translated sequences and the labels are indicators of whether or not the sequences contain temporal expressions (can be easily inferred from the original labels). This task tunes the model to learn the characteristics of temporal expressions in the target language in an implicit manner. It is self-supervised and requires no token-level labeling. It trains the backbone and the secondary task classifier by minimizing $\mathcal{L}_{bc}$:

$$\mathcal{L}_{bc} = -\sum_{i=1}^{b} \mathbb{1}(y'_i, c') log(softmax(\mathbf{W}' \cdot \mathbf{x}')), \quad (2)$$

where $\mathbf{x}' \in \mathbb{R}^d$ is the sequence embedding output by the [CLS] of the backbone. $\mathbf{W}' \in \mathbb{R}^{2 \times d}$ is the secondary task classifier. c' and y'_i are the predicted and true sequence labels. We train XLTime concurrently on the primary and secondary tasks (further details found in Appendix B.



(a) Sample Input and label

(b) Architecture of the XLTime Framework

Figure 1: The architecture and sample training input of the proposed XLTime framework (*best viewed in color*).

Table 2: Dataset statistics (more details in Appendix C).

Lang	Dataset	# Exprs
FR	Bittar et al. (2011)	425
ES	UzZaman et al. (2013)	1,094
PT	Costa and Branco (2012)	1,227
EU	Altuna et al. (2016)	847
EN	TE3 (UzZaman et al., 2013)	1,830
	Wikiwars (Mazur and Dale, 2010)	2,634
	Tweets (Zhong et al., 2017)	1,128

Table 3: Results for Multilingual TEE (F1).

Model	FR	ES	PT	EU
Automatic Baseline Models				
HeidelTime-auto	0.55	0.42	0.50	0.17
BiLSTM+CRF	0.64	0.62	0.64	0.47
mBERT	0.63	0.62	0.66	0.65
XLMR-base	0.69	0.54	0.63	0.46
XLMR-large	0.75	0.72	0.75	0.70
Projection Method				
TMP-mBERT	0.56	0.23	0.66	/
TMP-XLMRbase	0.55	0.23	0.64	/
TMP-XLMRlarge	0.56	0.24	0.65	/
Transfer from EN (Ours)				
XLTime-mBERT	0.73	0.71	0.67	0.76
XLTime-XLMRbase	0.78	0.66	0.68	0.71
XLTime-XLMRlarge	0.76	0.72	0.77	*0.78*
Transfer from EN and others (Ours)				
XLTime-mBERT	0.80	**0.77**	*0.80*	0.77
XLTime-XLMRbase	*0.82*	0.72	0.73	**0.79**
XLTime-XLMRlarge	**0.84**	*0.75*	**0.84**	**0.79**
Handcrafted Method				
HeidelTime	0.86	0.86	0.60	/

An Illustrative Example. In Figure 1, Tasks 1 and 4 transfer knowledge from *English* to *French*. Task 1 (primary) reveals the exact forms of English temporal expressions using token-level labels (Y_{11} and Y_{12}). Task 4 (secondary) takes the French translations (X_{41} and X_{42}) of X_{11} and X_{12} as input. Y_{41} and Y_{42} indicate whether the sequences contain temporal expressions or not (can be inferred from Y_{11} and Y_{12}). Task 4 provides indirect knowledge about French temporal expressions. Similarly, Tasks 2 and 3 transfer from *Spanish* to *French*.

4 Experiments

4.1 Experimental Setup

Datasets. We use the English (EN), French (FR), Spanish (ES), Portuguese (PT), and Basque (EU) TEE benchmark datasets. Table 2 shows dataset statistics (see Appendix C for a more detailed description). For each target language, we split its dataset with 10% for validation and 90% for test. For each source language (applicable to XLTime), we use the whole dataset for training.

Baselines. We evaluate against rule-based, deep learning-based, and entity projection-based methods. We compare to the handcrafted HeidelTime (Strötgen and Gertz, 2013) and its automatically extended version, HeidelTime-auto (Strötgen and Gertz, 2015). We also compare to deep learning methods: BiLSTM+CRF (Lange et al., 2020), mBERT, base and large versions of XLMR (trained on English TEE datasets and evaluated on low-resource languages). In addition, we compare to TMP (Jain et al., 2019), a cross-lingual label projection approach which relies on machine translation as well as orthographic and phonetic similarity packages (unavailable for EU). We use TMP to project the English dataset to the target languages, use the projected data to train the language models, then evaluate on the target languages.

Our Approaches. We test out several variants of our proposed model, which can be broken into two classes: 1) Cross-lingual transfer from EN. We apply XLTime on mBERT, base and large versions of XLMR and use EN as the only source language. 2) Cross-lingual transfer from EN and others. We transfer from other languages in addition to EN. Experimental settings are found in Appendix D.

Evaluation Metrics. We report F1in *strict match*

Table 4: Low-resource language TEE with additional source languages (F1 scores). The blue cells are expected to, while the underlined cells actually outperform (by $\geq 4\%$) using EN as the only source language.

Target Language	FR				ES			
Source Language(s)	EN	EN, EU	EN, PT	EN, ES	EN	EN, EU	EN, PT	EN, FR
XLTime-mBERT	0.73	0.76	0.72	0.80	0.71	0.72	0.72	0.77
XLTime-XLMRbase	0.78	0.76	0.78	0.82	0.66	0.68	0.71	0.72
XLTime-XLMRlarge	0.76	0.81	0.80	0.84	0.72	0.72	0.75	0.73
Target Language	**PT**				**EU**			
Source Language(s)	**EN**	**EN, FR**	**EN, ES**	**EN, EU**	**EN**	**EN, PT**	**EN, ES**	**EN, FR**
XLTime-mBERT	0.67	0.80	0.70	0.80	0.76	0.73	0.75	0.77
XLTime-XLMRbase	0.68	0.73	0.63	0.56	0.71	0.74	0.75	0.79
XLTime-XLMRlarge	0.77	0.82	0.84	0.74	0.78	0.79	0.79	0.77

(UzZaman et al., 2013), i.e., all its tokens must be correctly recognized for an expression to be counted as correctly extracted.

We follow the setting in prior work of evaluating "without type" and report the results without considering the types of the temporal expressions (e.g., for 'see you tomorrow', a prediction such as 'O O B-Duration' would be counted as correct, though the proper labeling would be 'O O B-Date').[2]

4.2 Evaluation Results

We evaluate XLTime on multilingual TEE (see Table 3 and Appendix F). We observe: **1)** XLTime-XLMRlarge outperforms the strongest automatic baseline by up to 9% in F1 on all languages. It even outperforms the handcrafted HeidelTime method by a large margin (24% in F1) in PT. **2)** Applying XLTime improves upon the vanilla language models, even when transferring knowledge only from EN. E.g., XLTime-XLMRbase outperforms XLMR-base by 13%, 22%, 8%, and 54% in F1 on FR, ES, PT, and EU. **3)** Introducing additional source languages to XLTime further improves the performance: the F1 improves by up to 19%, 11%, and 11% for XLTime-mBERT, XLTime-XLMRbase, and XLTime-XLMRlarge. **4)** HeidelTime is a very hard baseline to beat given the time and care that went into developing language-specific rules. However, XLTime approaches its performance for FR and ES, outperforms it for PT, and makes predictions for EU (where HeidelTime has no rules). **5)** XLTime-XLMRlarge improves upon XLMR-large by a large margin (11% in F1) in EU. For FR, ES, and PT, the improvements are smaller. This may because XLMR-large, compared to mBERT and XLMR-base, is already very knowledgeable (especially in FR, ES, and PT, which are more common than EU). Therefore, applying XLTime may not provide an improvement (in contrast, applying XLTime on mBERT and XLMR-base dramatically boosts F1 by 8-54%). **6)** TMP performs poorly probably because the falsely projected entities can mislead the language models.

We also study the effect of transferring additional knowledge from low-resource languages, see Table 4 and Appendix F. Our assumption is that similar languages (FR, ES, and PT) would help each other (one exception is PT, as the published dataset is EN text translated to PT and we, therefore, don't expect machine translation to provide additional knowledge). We observe: **1)** In most cases, transferring additional knowledge from similar languages (blue cells) does dramatically improve performance (underlined cells), with F1 increased by up to 13%. **2)** In some rare cases, negative transfer (Wu et al., 2020) occurs as adding source languages hurts performance (e.g., EN, ES $\rightarrow$ PT scores lower than EN $\rightarrow$ PT for XLTime-XLMRbase). We hypothesize this is related to the quality of the datasets and plan to address this in the future (Appendix H).

5 Conclusion

We propose XLTime for multilingual language TEE in low-resource scenarios. It is based on language models and leverages MTL to prompt cross-language knowledge transfer. It greatly alleviates the problems caused by the shortage in training data and shows results superior to the previous automatic SOTA methods on four languages. It also approaches the performance of a highly engineered rule-based system.

[2]We do note that the temporal expression field should ultimately evaluate on the more complex task of identifying temporal expressions as well as their types. This is in the spirit of the annotations and is in line with other sequence labeling tasks, such as NER. Therefore, we also experiment with the "with type" setting and show results in Appendix E. In both settings, the observations made in Section 4.2 hold and XLTime outperforms the previous SOTAs by large margins.

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Algorithm 1: Training XLTime

```
//Initialize model.
Load the parameters of E and T from a
  pre-trained multilingual model.
Initialize W and W' randomly.
// Prepare task data.
for t in {primary, secondary} do
    Split the data of task t into
      mini-batches B_t
B = B_primary ∪ B_secondary
for e in 1, ..., epoch do
    Randomly shuffle B
    //b_t is a mini-batch of task t
    for b_t in B do
        if t is a primary task then
            L_sl = Equation 1
        else
            L_bc = Equation 2
        Compute gradient and update
          model parameters
```

A Types of the Temporal Expressions

According to ISO-TimeML (Pustejovsky et al., 2010), the TEE dataset annotation guideline, there are four types of temporal expressions, i.e., *Date*, *Time*, *Duration*, and *Set*. *Date* refers to a calendar date, generally of a day or a larger temporal unit; *Time* refers to a time of the day and the granularity of which is smaller than a day; *Duration* refers to the expressions that explicitly describe some period of time; *Set* refers to a set of regularly recurring times (Pustejovsky et al., 2010).

B The Training Procedure

We adopt mini-batch-based stochastic gradient descent (SGD) to train XLTime, as shown in Algorithm 1. To concurrently train on the primary and secondary tasks, we split the training data of both tasks into mini-batches and randomly take one at each step. We then calculate loss using that mini-batch and update the parameters of the shared backbone (including E and T) as well as the task-type-specific classifier. The classifier of the other task type is unaffected.

C Detailed Statistics of the Datasets

Table 5 shows the detailed statistics of the datasets used in this study.

Table 5: The statistics of the datasets.

Lang	Dataset	Domain	#Docs	#Exprs	#Dates	#Times	#Durations	#Sets
FR	Bittar et al. (2011)	News	108	425	227	130	52	16
ES	UzZaman et al. (2013)	News	175	1,094	749	57	251	37
PT	Costa and Branco (2012)	News	182	1,227	998	41	176	12
EU	Altuna et al. (2016)	News	91	847	662	22	151	12
EN	TE3 (UzZaman et al., 2013)	News	276	1,830	1,471	34	291	34
	Wikiwars (Mazur and Dale, 2010)	Narrative	22	2,634	2,634	0	0	0
	Tweets (Zhong et al., 2017)	Utterance	942	1,128	717	173	200	38

D Experimental Setting

We set d, the embedding dimension, to be 768 when applying on the base version language models and 1024 on large versions. We use AdamW (Loshchilov and Hutter, 2019) with a learning rate of $7e^{-6}$ and warm-up proportion of 0.1. We train the models for 50 epochs and use the best model as indicated by the validation set for prediction. All datasets are transformed into IOB2 format to fit the sequence labeling setting. For BiLSTM+CRF, we use the hyperparameters as suggested in the original paper. For TMP, we tune δ, the similarity score threshold. We repeat all experiments for 5 times and report the mean result. All experiments are conducted on a 64 core Intel Xeon CPU E5-2680 v4@2.40GHz with 512GB RAM and 1×NVIDIA Tesla P100-PICE GPU.

E Full Results for Low-resource Language TEE

Table 6 shows the full results for low-resource language TEE with/without considering the types of the temporal expressions. Note that the superiority of our proposed XLTime over the previous automatic SOTA still holds.

F Full Results for Low-resource Language TEE with Additional Source Languages

Tables 8 and 9 show the full results for low-resource language TEE with additional source languages.

G Language Models on English TEE

In our early experiments, we reexamine the language models on English TEE. This section presents the results.

G.1 Experimental Setup

We study BERT (Devlin et al., 2019) and XLMR (Conneau et al., 2020) variants, RoBERTa (Liu et al., 2019b) and T5 Encoder (Raffel et al., 2019). We compare them to rule-based methods including HeidelTime (Strötgen and Gertz, 2013), SynTime (Zhong et al., 2017), and PTime (Ding et al., 2019), which report SOTA performances on Wikiwars, TE3, and Tweets, respectively. We experiment on both settings, i.e., "with type" and "without type", and report F1, precision, and recall in strict match (UzZaman et al., 2013). We use the data splits following Ding et al. (2019) and the experimental settings introduced in Appendix D.

G.2 Evaluation Results

Table 7 shows the results. We observe: **1)** When ignoring the types, the language models are inferior to SynTime on TE3, on par with or better than the rule-based methods on Wikiwars and Tweets. **2)** When considering the types, the language models outperform the previous SOTAs by 11-22%, 18-21%, and 30-41% in F1 on TE3, Wikiwars, and Tweets datasets.

H Future Work

We observe negative transfer in some rare cases when transferring from multiple source languages (Tables 4 and 9). As suggested by Wu et al. (2020), the extent of negative transfer is affected by *task covariance*, which measures the similarities between the embedded task samples. We plan to verify this on XLTime by calculating and comparing the task covariances of the positively transferred cases to that of the negatively transferred cases.

One approach to reduce task covariance is to transform task sample embeddings by inserting an alignment layer between the lexicon encoder and the first Transformer layer. Wu et al. (2020) proposes an alignment layer design, i.e., one linear matrix for each of the tasks. However, as the training data for low-resource TEE is sparse, the parameters introduced by these matrices might cause the model to overfit. We plan to design a new alignment layer that is more suitable for XLTime. The new design aims to reduce task covariance while prompting parameter sharing and reducing overfitting.

Table 6: Multilingual TEE results (w/ type | w/o type).

w/ type	FR			ES			PT			EU		
	F1	Pr.	Re.	F1	Pr.	Re.	F1	Pr.	Re.	F1	Pr.	Re.
Automatic Baseline Models												
HeidelTime-auto	0.53	0.63	0.46	0.41	0.56	0.32	0.49	0.66	0.39	0.15	0.60	0.09
BiLSTM+CRF	0.58	0.64	0.51	0.56	0.61	0.51	0.58	0.59	0.58	0.44	0.54	0.37
mBERT	0.56	0.61	0.51	0.56	0.62	0.51	0.60	0.56	0.64	0.59	0.64	0.55
XLMR-base	0.64	0.69	0.59	0.51	0.58	0.46	0.59	0.59	0.59	0.43	0.60	0.34
XLMR-large	0.69	0.70	0.68	*0.68*	*0.71*	**0.66**	0.71	0.69	0.73	0.66	0.70	0.63
Projection Method												
TMP-mBERT	0.50	0.56	0.45	0.23	0.59	0.14	0.60	0.57	0.64	/	/	/
TMP-XLMRbase	0.50	0.60	0.43	0.23	0.57	0.14	0.61	0.58	0.64	/	/	/
TMP-XLMRlarge	0.52	0.61	0.46	0.24	0.59	0.15	0.61	0.58	0.63	/	/	/
Transfer from EN (Ours)												
XLTime-mBERT	0.62	0.62	0.62	0.65	0.70	0.61	0.61	0.58	0.66	0.68	0.72	0.65
XLTime-XLMRbase	0.67	0.67	0.68	0.60	0.63	0.58	0.64	0.62	0.66	0.64	0.68	0.60
XLTime-XLMRlarge	*0.71*	**0.74**	0.68	**0.70**	**0.76**	*0.65*	*0.74*	*0.71*	*0.78*	*0.72*	**0.79**	*0.66*
Transfer from EN and others (Ours)												
XLTime-mBERT	*0.71*	0.69	0.73	*0.68*	0.69	**0.66**	0.73	0.70	0.76	0.68	0.72	0.65
XLTime-XLMRbase	0.70	0.67	*0.74*	0.65	0.69	0.62	0.66	0.64	0.68	0.70	*0.76*	0.65
XLTime-XLMRlarge	**0.75**	*0.72*	**0.78**	**0.70**	**0.76**	*0.65*	**0.81**	**0.79**	**0.84**	**0.74**	**0.79**	**0.69**
Handcrafted Method												
HeidelTime	0.80	0.81	0.79	0.85	0.90	0.80	0.57	0.60	0.53	/	/	/

w/o type	FR			ES			PT			EU		
	F1	Pr.	Re.	F1	Pr.	Re.	F1	Pr.	Re.	F1	Pr.	Re.
Automatic Baseline Models												
HeidelTime-auto	0.55	0.65	0.47	0.42	0.58	0.33	0.50	0.67	0.39	0.17	0.66	0.10
BiLSTM+CRF	0.64	0.73	0.57	0.62	0.68	0.56	0.64	0.66	0.63	0.47	0.58	0.40
mBERT	0.63	0.70	0.58	0.62	0.69	0.56	0.66	0.63	0.69	0.65	0.71	0.60
XLMR-base	0.69	0.75	0.64	0.54	0.61	0.48	0.63	0.64	0.62	0.46	0.64	0.36
XLMR-large	0.75	0.78	0.73	0.72	0.75	0.69	0.75	0.74	0.76	0.70	0.74	0.67
Projection Method												
TMP-mBERT	0.56	0.63	0.50	0.23	0.59	0.14	0.66	0.64	0.69	/	/	/
TMP-XLMRbase	0.55	0.67	0.47	0.23	0.57	0.14	0.64	0.61	0.67	/	/	/
TMP-XLMRlarge	0.56	0.66	0.50	0.24	0.59	0.15	0.65	0.61	0.68	/	/	/
Transfer from EN (Ours)												
XLTime-mBERT	0.73	0.73	0.72	0.71	0.77	0.66	0.67	0.64	0.71	0.76	0.81	0.71
XLTime-XLMRbase	0.78	*0.79*	0.78	0.66	0.70	0.63	0.68	0.67	0.70	0.71	0.76	0.66
XLTime-XLMRlarge	0.76	*0.79*	0.73	0.72	**0.79**	0.67	0.77	0.74	0.81	*0.78*	*0.85*	0.71
Transfer from EN and others (Ours)												
XLTime-mBERT	0.80	0.77	*0.82*	**0.77**	**0.79**	**0.74**	*0.80*	*0.77*	*0.83*	0.77	0.82	0.72
XLTime-XLMRbase	*0.82*	*0.79*	**0.86**	0.72	*0.78*	0.68	0.73	0.72	0.75	**0.79**	**0.86**	*0.73*
XLTime-XLMRlarge	**0.84**	**0.82**	**0.86**	*0.75*	**0.79**	*0.71*	**0.84**	**0.82**	**0.87**	**0.79**	0.84	**0.74**
Handcrafted Method												
HeidelTime	0.86	0.87	0.85	0.86	0.91	0.81	0.60	0.64	0.57	/	/	/

Table 7: Supervised English TEE results (w/ type | w/o type).

Model	Datasets								
	TE3			Wikiwars			Tweets		
	F1	Pr.	Re.	F1	Pr.	Re.	F1	Pr.	Re.
Rule-based Models									
HeidelTime	0.77| 0.81	*0.80*| 0.84	0.75| 0.79	0.80| 0.85	0.86| 0.92	0.75| 0.80	0.80| 0.80	*0.90*| 0.90	0.72| 0.72
SynTime	0.65| **0.92**	0.65| **0.91**	0.66| **0.93**	0.79| 0.79	0.79| 0.79	0.79| 0.79	0.63| 0.92	0.62| 0.91	0.65| 0.95
PTime	0.67| *0.85*	0.68| *0.88*	0.65| 0.83	0.86| 0.86	0.87| 0.87	0.86| 0.86	0.66| **0.95**	0.65| **0.94**	0.67| *0.96*
Language Models									
BERT-base	0.76| 0.82	0.78| 0.85	0.74| 0.80	0.94| 0.94	*0.95*| *0.95*	0.94| 0.94	*0.92*| *0.94*	*0.90*| *0.93*	0.93| 0.95
BERT-large	**0.79**| 0.83	0.77| 0.82	**0.80**| *0.84*	0.95| 0.95	0.94| 0.94	0.96| 0.96	0.86| 0.92	0.84| 0.92	0.88| 0.92
mBERT	**0.79**| 0.84	*0.80*| 0.86	0.77| 0.82	**0.97**| **0.97**	**0.96**| **0.96**	*0.97*| *0.97*	0.87| 0.91	0.85| 0.88	0.90| 0.94
RoBERTa	*0.78*| 0.84	0.79| 0.86	0.77| 0.82	0.95| 0.95	0.94| 0.94	*0.97*| *0.97*	0.91| **0.95**	0.89| *0.93*	*0.94*| **0.97**
XLMR-base	**0.79**| 0.81	*0.80*| 0.82	0.77| 0.81	**0.97**| **0.97**	*0.95*| *0.95*	**0.98**| **0.98**	0.90| *0.94*	0.87| 0.92	0.93| **0.97**
XLMR-large	*0.78*| 0.81	0.78| 0.82	*0.78*| 0.81	*0.96*| *0.96*	0.94| 0.94	*0.97*| *0.97*	**0.93**| **0.95**	**0.91**| *0.93*	**0.95**| *0.96*
T5Encoder	**0.79**| 0.82	**0.82**| 0.85	*0.78*| 0.80	*0.96*| *0.96*	*0.95*| *0.95*	*0.97*| *0.97*	0.87| 0.93	0.84| 0.91	0.91| 0.95

Table 8: Low-resource language TEE with additional source languages (F1, precision, and recall scores w/ type). The blue cells are expected to, while the underlined cells actually outperform (by $\geq 3\%$) using EN as the only source language.

F1								
Target Language	FR				ES			
Source Language(s)	EN	EN, EU	EN, PT	EN, ES	EN	EN, EU	EN, PT	EN, FR
XLTime-mBERT	0.62	0.61	0.61	0.71	0.65	0.66	0.65	0.68
XLTime-XLMRbase	0.67	0.67	0.66	0.70	0.60	0.61	0.64	0.65
XLTime-XLMRlarge	0.71	0.73	0.73	0.75	0.70	0.68	0.69	0.68
Target Language	PT				EU			
Source Language(s)	EN	EN, FR	EN, ES	EN, EU	EN	EN, PT	EN, ES	EN, FR
XLTime-mBERT	0.61	0.72	0.59	0.73	0.68	0.66	0.66	0.68
XLTime-XLMRbase	0.64	0.66	0.55	0.52	0.64	0.66	0.66	0.70
XLTime-XLMRlarge	0.74	0.79	0.81	0.71	0.72	0.71	0.74	0.72
Precision								
Target Language	FR				ES			
Source Language(s)	EN	EN, EU	EN, PT	EN, ES	EN	EN, EU	EN, PT	EN, FR
XLTime-mBERT	0.62	0.59	0.62	0.69	0.70	0.69	0.71	0.69
XLTime-XLMRbase	0.67	0.66	0.67	0.67	0.63	0.64	0.67	0.69
XLTime-XLMRlarge	0.74	0.72	0.76	0.72	0.76	0.65	0.73	0.68
Target Language	PT				EU			
Source Language(s)	EN	EN, FR	EN, ES	EN, EU	EN	EN, PT	EN, ES	EN, FR
XLTime-mBERT	0.58	0.68	0.56	0.70	0.72	0.70	0.69	0.72
XLTime-XLMRbase	0.62	0.64	0.51	0.49	0.68	0.73	0.69	0.76
XLTime-XLMRlarge	0.71	0.75	0.79	0.68	0.79	0.75	0.79	0.79
Recall								
Target Language	FR				ES			
Source Language(s)	EN	EN, EU	EN, PT	EN, ES	EN	EN, EU	EN, PT	EN, FR
XLTime-mBERT	0.62	0.62	0.59	0.73	0.61	0.64	0.60	0.66
XLTime-XLMRbase	0.68	0.67	0.64	0.74	0.58	0.59	0.61	0.62
XLTime-XLMRlarge	0.68	0.73	0.71	0.78	0.65	0.71	0.65	0.67
Target Language	PT				EU			
Source Language(s)	EN	EN, FR	EN, ES	EN, EU	EN	EN, PT	EN, ES	EN, FR
XLTime-mBERT	0.66	0.75	0.62	0.76	0.65	0.63	0.64	0.64
XLTime-XLMRbase	0.66	0.68	0.60	0.55	0.60	0.60	0.63	0.65
XLTime-XLMRlarge	0.78	0.83	0.84	0.74	0.66	0.67	0.69	0.67

Table 9: Low-resource language TEE with additional source languages (precision and recall scores w/o type). The blue cells are expected to, while the underlined cells actually outperform (by $\geq 4\%$) using EN as the only source language.

Precision								
Target Language	FR				ES			
Source Language(s)	EN	EN, EU	EN, PT	EN, ES	EN	EN, EU	EN, PT	EN, FR
XLTime-mBERT	0.73	0.76	0.76	0.77	0.77	0.76	0.79	0.79
XLTime-XLMRbase	0.79	0.77	0.81	0.79	0.70	0.72	0.75	0.78
XLTime-XLMRlarge	0.79	0.81	0.84	0.82	0.79	0.70	0.79	0.74
Target Language	PT				EU			
Source Language(s)	EN	EN, FR	EN, ES	EN, EU	EN	EN, PT	EN, ES	EN, FR
XLTime-mBERT	0.64	0.77	0.67	0.77	0.81	0.78	0.79	0.82
XLTime-XLMRbase	0.67	0.72	0.60	0.54	0.76	0.82	0.79	0.86
XLTime-XLMRlarge	0.74	0.79	0.82	0.72	0.85	0.85	0.84	0.84
Recall								
Target Language	FR				ES			
Source Language(s)	EN	EN, EU	EN, PT	EN, ES	EN	EN, EU	EN, PT	EN, FR
XLTime-mBERT	0.72	0.77	0.69	0.82	0.66	0.69	0.66	0.74
XLTime-XLMRbase	0.78	0.76	0.75	0.86	0.63	0.64	0.68	0.68
XLTime-XLMRlarge	0.73	0.81	0.77	0.86	0.67	0.75	0.71	0.72
Target Language	PT				EU			
Source Language(s)	EN	EN, FR	EN, ES	EN, EU	EN	EN, PT	EN, ES	EN, FR
XLTime-mBERT	0.71	0.83	0.74	0.83	0.71	0.69	0.70	0.72
XLTime-XLMRbase	0.70	0.75	0.66	0.59	0.66	0.67	0.70	0.73
XLTime-XLMRlarge	0.81	0.87	0.87	0.77	0.71	0.74	0.74	0.71