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Morphology in the Age of Pre-trained Language Models

Ph.D. Thesis Booklet

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Introduction

The field of natural language processing (NLP) has adopted deep learning methods in the past 15 years. Nowadays the state-of-the-art in most NLP tasks is some kind of neural model, often the fine-tuned version of a pre-trained language model. The efficacy of these models is demonstrated on various English benchmarks and increasingly, other monolingual and multimultilingual benchmarks. In this dissertation I explore the application of deep learning models on low level tasks, particularly morphosyntactic¹ tasks in multiple languages.

The first part of this dissertation (Theses 1 and 2) explores the application of deep learning models for classical morphosyntactic tasks such as morphological inflection and generation in dozens of languages with special focus on Hungarian.

The second part of this dissertation (Theses 3 to 5) deals with pre-trained language models, mostly models from the BERT (Devlin et al., 2019) family. I include some experiments on GPT-4o and GPT-4o-mini. These models show excellent performance on various tasks in English and some high density languages. However, their evaluation in medium and low density languages is lacking. I present a methodology for generating morphosyntactic benchmarks in arbitrary languages and I analyze multiple BERT-like models in detail. My main tool for analysis is the probing methodology (Belinkov, 2021).

Thesis 1

Encoder-decoder (a.k.a. sequence-to-sequence or seq2seq) models are well-suited for morphological inflection and generation. This holds for type-level and sentence-level tasks in multiple languages.

Contributions:

- I collected and prepared a silver standard Hungarian dataset for morphological inflection and analysis using a high quality rule-based ana-

¹Morphology is the study of morphemes, the smallest meaningful units of language, while syntax is the study of sentence formation. Morphosyntax refers to the fact that morphemes often have sentence-level functions and the two fields of linguistics are far from independent.

lyzer.

- I implemented two types of sequence-to-sequence or encoder-decoder models with attention: LSTM with soft attention and LSTM with hard attention.
- I trained and evaluated the models on the Hungarian dataset.
- I participated in the CoNLL-SIGMORPHON 2018 Shared Task as an individual team. Task 1 was type-level inflection in over 100 languages, Task 2 was inflection in context (sentence) in 7 languages. I placed 3rd and 2nd in the two tasks respectively with multi-encoder and single-decoder seq2seq neural networks.

These contributions were published in Ács (2018) and they are my sole contribution.

Thesis 2

Differentiable neural pattern matching can extract morphosyntactic patterns in multiple languages when used as an encoder for morphological inflection and analysis.

Contributions:

- I reimplemented the Soft Patterns or SoPa neural model (Schwartz et al., 2018), a restricted and differentiable finite state automaton model originally used for text classification tasks. I added an LSTM decoder and used SoPa as an encoder-decoder model. This model uses pattern matching on the encoder side.
- I applied the model to type-level morphological analysis and inflection in 12 typologically diverse languages.
- I extracted patterns (character sequences) from trained SoPa models and manually examined their linguistic plausibility.

- I introduced a model similarity metric defined for a pair of SoPa models. This metric allows comparing different tasks that use the same input data. The higher the similarity between two tasks, the more likely they are to rely on the same patterns.

These contributions were published in Ács and Kornai (2020). The paper was awarded the best paper award at the Hungarian Computational Linguistics Conference in 2020. The implementation is entirely my contribution.

Thesis 3

Pre-trained language models (PLMs) trained on unannotated text learn morphology. PLMs' representations retain morphosyntactic information across a large set of typologically diverse languages and multiple tasks. This information can be recovered via probing or diagnostic classifiers.

Contributions:

- I introduced the largest multilingual morphosyntactic probing dataset with 247 tasks in 42 families from 10 language families. I define a probing sample as a triplet of a sentence, a particular token called *target token* in the sentence and a morphosyntactic tag corresponding to the target token. I used the Universal Dependencies Treebank (Nivre et al., 2018) to generate probing samples according to this definition.
- I evaluated 6 multilingual PLMs and analyze two, mBERT and XLM-RoBERTa in detail. I compared them to various baselines and show that PLMs indeed learn morphosyntactic information.
- I evaluated GPT-4o and GPT-4o-mini on the test set of the probing dataset via prompting.
- I examined the tokenizer of PLMs and showed that although multilingual models support over 100 languages, the tokenizer works better on languages that use the Latin script, particularly English. (Ács, 2019)

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- Probing as an analysis tool for blackbox models has been criticized for various reasons (Belinkov, 2021). I introduced more than 10 ablation methods and showed that the conclusions drawn from morphosyntactic probing are robust.
 - The token-level usage of PLMs requires a way of handling tokens split into multiple subwords represented by multiple vectors. A pooling function (parametric on non-parametric) may be used to infer a single vectors by token. I showed that the choice of pooling function matters, especially for feature extraction (when the PLM is not fine-tuned). I compared 9 pooling functions in 7 languages and 3 tasks (Ács et al., 2021a).

These contributions were published in (Ács, 2019; Ács et al., 2021a; Ács et al., 2023). The experiment design was done in collaboration with my coauthors and the implementation is my sole contribution.

Thesis 4

Monolingual PLMs are better in their respective languages than multilingual PLMs but the difference is small and often not statistically significant. Moreover both monolingual and multilingual PLMs can be successfully transferred to new languages as long as the new language uses the same writing system.

Contributions:

- I analyzed 5 PLMs with Hungarian support and I found that HuBERT (Nemeskey, 2021), a Hungarian-only model is better at morphological, POS and NER tagging than the multilingual models, especially distilBERT, but the margin is small. (Ács et al., 2021)
- I extended this study to the languages of the Uralic family (Ács et al., 2021b). I drew similar conclusions in Estonian and Finnish, the only Uralic languages with dedicated monolingual PLMs, as in Hungarian.
- I trained POS and NER tagging models in minority Uralic languages by transferring multilingual and monolingual models. The cross-language models are surprisingly successful despite the extremely small training

data available in some languages. The new models appear to be state-of-the-art without any language-specific effort.

These contributions were published in (Ács et al., 2021; Ács et al., 2021b). The experiment design and the result analysis was done in collaboration with my coauthors. The implementation is my contribution.

Thesis 5

The source of morphosyntactic information is often localized in a sentence. Systematic removal of certain information (perturbations) reveals where the information is stored. The role of context in morphosyntax can be quantified via Shapley values and the results often agree with linguistic intuitions.

Contributions:

- I introduced a set of perturbation methods that remove some source of information from a sentence. I retrained the morphosyntactic probes (cf. Thesis 3) on the 247 probing tasks. The results offer insight on where the information is stored in the sentence. We can often find linguistic explanations for them.
- I used the results of perturbations as features for clustering the languages. Such clustering tends to group languages from the same family in the same cluster with some notable exceptions. It also tends to cluster typologically similar but unrelated languages in the same cluster.
- I defined a sentence as a 9-player coalition game where the players are tokens or groups of tokens relative to the target token in the morphosyntactic probe. I applied the Shapley framework on each probing task.
- I analyzed the Shapley values from mBERT, XLM-RoBERTa and an LSTM baseline and found that the inter-model correlation is high which demonstrates that the Shapley values are more descriptive of linguistic structure than of the models. I identified the outlier tasks and I found

that the Shapley values often confirm the linguistic properties of the particular language and task.

These contributions were published in (Ács et al., 2023). The experiment design and the result analysis was done in collaboration with my coauthors. The implementation is my contribution.

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