

Joint Universal Syntactic and Semantic Parsing

Elias Stengel-Eskin
Johns Hopkins University

Kenton Murray
Johns Hopkins University

Sheng Zhang
Microsoft Research

Aaron Steven White
University of Rochester

Benjamin Van Durme
Johns Hopkins University

Abstract

While numerous attempts have been made to jointly parse syntax and semantics, high performance in one domain typically comes at the price of performance in the other. This trade-off contradicts the large body of research focusing on the rich interactions at the syntax-semantics interface. We explore multiple model architectures which allow us to exploit the rich syntactic and semantic annotations contained in the Universal Decompositional Semantics (UDS) dataset, jointly parsing Universal Dependencies and UDS to obtain state-of-the-art results in both formalisms. We analyze the behaviour of a joint model of syntax and semantics, finding patterns supported by linguistic theory at the syntax-semantics interface. We then investigate to what degree joint modeling generalizes to a multilingual setting, where we find similar trends across 8 languages.

1 Introduction

Given their natural expression in terms of hierarchical structures and their well-studied interactions, syntax and semantics have long been treated as parsing tasks, both independently and jointly. One would expect joint models to outperform separate or pipelined ones; however, many previous attempts have yielded mixed results, finding that while one level can be used as an additional signal to benefit the other (Swayamdipta et al., 2017, 2018; Johansson and Nugues, 2008), obtaining high performance in both syntax and semantics simultaneously is difficult (Krishnamurthy and Mitchell, 2014; Hajič et al., 2009).

A variety of tree- and graph-based representations have been devised for representing syntactic structure (e.g. varieties of constituency and dependency parse trees) as well as semantic structure, e.g. Abstract Meaning Representation (AMR; Banarescu et al., 2013), Universal Conceptual

Cognitive Annotation (UCCA; Abend and Rappoport, 2013), and Semantic Dependency Parsing formalisms (SDP; Oepen et al., 2014a,b, 2016). These semantic representations have varying degrees of abstraction from the input and syntax, ranging from being directly tied to the input tokens (e.g. SDP formalisms) to being heavily abstracted away from it (e.g. AMR, UCCA). Universal Decompositional Semantics (UDS; White et al., 2020) falls between these extremes, with a semantic graph that is closely tied to the syntax while not being constrained to match the input tokens. Crucially, UDS graphs not only represent the predicate-argument relationships in the input, but also host scalar-valued crowdsourced annotations encoding a variety of semantic inferences, described in §3. These provide another level for linguistic analysis and make UDS unique among meaning representations. Furthermore, as UDS graphs build on Universal Dependency (UD) parses, UDS is naturally positioned to take full advantage of the extensive and linguistically diverse set of UD annotations.

We extend the transductive sequence-to-graph UDS parser proposed by Stengel-Eskin et al. (2020) to simultaneously perform Universal Dependencies (UD) and UDS parsing, finding that joint modeling offers concomitant benefits to both tasks. In particular, after exploring several multitask learning objectives and model architectures for integrating syntactic and semantic information, we obtain our best overall results with an encoder-decoder semantic parsing model, where the encoder is shared with a biaffine syntactic parser (Dozat and Manning, 2017). Because the UDS dataset is annotated on an existing UD corpus, our experiments isolate the effect of adding a semantic signal without the confound of additional data: all our monolingual systems are trained on the same set of sentences.

In contrast to previous work on joint syntax-semantics parsing, we are able to achieve high performance in both domains with a single, unified

model; this is particularly salient to UDS parsing, as the UD parse is a central part of a *complete* UDS analysis. Our best joint model’s UDS performance beats the previous best by a large margin, while also yielding SOTA scores on a semantically valid subset of English Web Treebank (EWT). We introduce a model optimized for UD, which can obtain competitive UDS performance while matching the current SOTA UD parser on the whole of EWT.¹

We analyze these objectives and architectures with LSTM encoders and decoders as well as novel Transformer-based sequence-to-graph architectures, which outperform the LSTM variants. While previous work suggests that contextualized encoders largely obviate the need for an explicit syntactic signal in semantic tasks (Swayamdipta et al., 2019; Glavaš and Vulić, 2020), we find that syntactic (and semantic) annotations provide consistent performance gains even when such encoders are used. This suggests that the UD and UDS signals are complementary to the signal encoded by a pretrained encoder, and so we tune the encoder at various depths, further improving performance.

Building on this result, we leverage the shared multilingual representation space of XLM-R (Conneau et al., 2020) to examine UD parsing in 8 languages across 5 families and varying typological settings, where we demonstrate a cross-lingual benefit of UDS parsing on UD parsing.

2 Background and Related Work

In both language production and comprehension, syntax and semantics play complementary roles. Their close relationship has also been noted in language acquisition research, with the “semantic bootstrapping” hypothesis proposing that infants use semantic role information as an inductive bias for acquiring syntax (Pinker, 1979, 1984),² while Landau and Gleitman (1985); Gleitman (1990) and Naigles (1990) present evidence that infants use syntactic information when acquiring novel word meanings. Their connection was codified in Montague (1970)’s seminal work formalizing the link between syntactic structures and formal semantics. Broadly, their interactions can be split into “bottom-up” constraints on the semantics of an utterance from its syntax, and “top-down” constraints on the syntax, based on the semantics. Despite their close

empirical and theoretical ties, work on predicting syntax and semantic structures jointly has often struggled to attain high performance in one domain without compromising on performance in the other.

CCG-based parsing Following in the Montogian tradition, several computational formalisms and models have focused on the syntax-semantics interface, including the Head-Driven Phrase Structure Grammar (Pollard and Sag, 1994) and Combinatory Categorical Grammar (CCG) (Steedman, 2000). In particular, CCG syntactic types can be paired with functional semantic types (e.g. λ calculus strings) to compositionally construct logical forms. Krishnamurthy and Mitchell (2014) model this process with a linear model over both syntactic derivations and logical forms, trained with a discriminative objective that combines direct syntactic supervision with distant supervision from the logical form, finding that while joint modeling is feasible, it slightly lowers the syntactic performance. By way of contrast, Lewis et al. (2015) find that a joint CCG and Semantic Role Labelling (SRL) dependency parser outperforms a pipeline baseline. The semantic signal can also be used to induce syntax without using syntactic supervision.

AMR parsing CCG approaches have also been applied to semantics-only AMR parsing (Artzi et al., 2015; Misra and Artzi, 2016; Beschke, 2019). Jointly modeling AMR and syntax, Zhou et al. (2020) induce a soft syntactic structure with a latent variable model, obtaining slight improvements over semantics-only models in low-resource settings.

SRL parsing SRL dependency parsing—the task of labeling an utterance’s predicates and their respective arguments in a possibly non-projective directed acyclic graph (DAG)—is more akin to the UDS parsing task than CCG parsing and has an equally robust foundation of empirical results, having been the focus of several CoNLL shared tasks—most relevantly the 2008 and 2009 shared tasks, which were on joint syntactic and SRL dependency parsing (Surdeanu et al., 2008; Hajič et al., 2009). The upshot of these tasks was that a joint syntactic and semantic analysis could provide benefits over a separated system (Johansson and Nugues, 2008) but that in a multilingual setting, SRL-only systems slightly outperformed joint systems on average (Hajič et al., 2009). While the systems presented in these challenges used hand-crafted features, Swayamdipta et al. (2016) replicated many of their results in a neural setting. For SRL tagging,

¹Models/code: github.com/esteng/miso_uds

²Abend et al. (2017) presents an implementation of the semantic bootstrapping hypothesis.

Strubell et al. (2018) introduce an end-to-end neural model that also uses UD parsing as a multitask intermediate task, akin to our intermediate model.

Syntactic scaffolds Like our models, work on syntactic scaffolds introduces a multitask learning (Caruana, 1997) framework, where a syntactic auxiliary task is introduced for the benefit of a semantic task; in contrast to the systems presented here, the syntactic task is treated as a purely auxiliary signal, with the model evaluation coming solely from the semantic task. Swayamdipta et al. (2017) first introduce the notion of a syntactic scaffold for frame-semantic parsing, where a lightweight syntactic task (constituent labeling) is used as an auxiliary signal in a multitask learning setup to the benefit of the semantic task. Swayamdipta et al. (2018) introduce a similar syntactic scaffolding objective for three semantic tasks. However, Swayamdipta et al. (2019) find that the benefits of shallow syntactic objectives are largely eclipsed by the implicit information captured in contextualized encoders.

3 Data

A number of factors make the Universal Decompositional Semantics representation (UDS; White et al., 2020) particularly well-suited to our purposes, especially the existence of parallel manually-annotated syntactic and semantic data. In UDS, a semantic graph is built on top of existing English Web Treebank (EWT; Bies et al., 2012) UD parses, which are mapped to nodes and edges in a semantic DAG via a set of deterministic rules (White et al., 2016; Zhang et al., 2017). This semantic graph, which represents the predicate-argument relationships in the text, is then annotated with crowdsourced scalar-valued attributes falling into the following categories: factuality (how likely a predicate is to have occurred), genericity (how general or specific a predicate/argument is), time (how long an event took), word sense (which word senses apply to a predicate/argument) and semantic proto-roles, which break the traditional SRL ontologies into simpler “proto-agent” properties (e.g. volition, awareness, sentience) and “proto-patient” properties (e.g. change of state, change of location, being used). Note that while the semantic graph structure is tied to the syntax, the attribute values, encoding fine-grained, abstracted semantic inferences, are not. These attributes are unique among graph-based semantic representations. All of these properties are annotated on a scale of -3 to 3 ; for more

details on the dataset, we refer the reader to White et al. (2020) and Stengel-Eskin et al. (2020), as well as Fig. 1. We train and evaluate on a semantically valid subset of EWT.³ We similarly limit our baselines to these examples for our UD analysis, and release our cleaned UD dataset, for which we report state-of-the-art parsing performance.

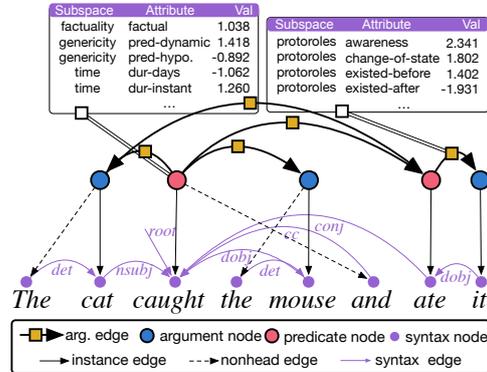


Figure 1: A UDS graph with syntactic and semantic parses, as well as node- and edge-level properties.

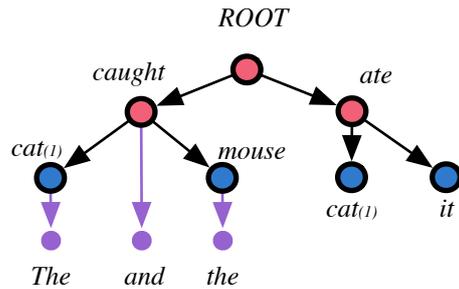


Figure 2: Conversion of Fig. 1 to an arborescence.

Arborescence Following Zhang et al. (2019a) and Stengel-Eskin et al. (2020), we convert the UDS graph into an arborescence, or tree. Re-entrant semantic nodes are copied and co-indexed, so that a DAG can be recovered via a deterministic post-processing step. Each node is assigned a token label, taken from the token corresponding to the syntactic head of the semantic node (instance edges in Fig. 1). All syntactic nodes not assigned as labels to semantic nodes are included as nodes dominated by their corresponding semantic node (pink edges in Fig. 2).⁴ An example conversion of the UDS graph in Fig. 1 can be found in Fig. 2. In the “semantics only” setting, only the semantic nodes are included in the graph. A pre-order traversal

³This excludes roughly 20% of the EWT data; excluded sentences include forms of address (e.g. “Dear Nina, ”), URLs, and discourse markers (e.g. “(Applause .)”) which lack predicate-argument structures.

⁴“and” is assigned to “caught” based on it being the head of the *cc* relation in the UD parse

sal linearizes the arborescence into a sequence of nodes, indices, edge heads and labels, and the corresponding node and edge attributes.

4 Models

We build on the transductive parsing model presented by Stengel-Eskin et al. (2020), which itself builds on the broad-coverage semantic parsing model of Zhang et al. (2019b) and relies heavily on AllenNLP (Gardner et al., 2018). The transductive parsing paradigm recasts graph-based parsing as a sequence-to-graph problem, using an attentional sequence-to-sequence model to transduce the input sentence into a set of nodes while incrementally predicting edge and edge labels for those nodes. The UDS semantic parser consists of 7 modules:

The encoder module embeds the input features (type-level GloVe and contextualized word embeddings, POS tags, charCNN features) into a latent space, producing one vector per input token. BERT representations are pooled over subword units.⁵

The decoder embedding module embeds the categorical information of the previous timestep (e.g. the token identity and index, the head token identity and index, the edge type) into a real space.

The target node module builds node representations from the decoder embedding module’s output.

The target label module extends the Pointer-Generator network (See et al., 2017), which supports both generating new token labels from a vocabulary and copying tokens from the input, with a “target-copy” operation, additionally allowing the model to predict a token label by copying a previously predicted node, conditioned on a target node. This three-operation approach (i.e. generate, source-copy, target-copy) enables the parser to seamlessly handle lexicalized and non-lexicalized formalisms, while also natively supporting re-entrancy through the target-copy operation.

The relation module is a graph-based dependency parser based on the parser presented by Dozat and Manning (2017) which uses separate head and dependency MLPs followed by a biaffine transformation to predict the dependency scores and labels between each node in a fully connected graph. For semantic parsing, we follow a greedy decoding strategy since the linearization of the arborescence implicitly enforces a well-formed output; this allows for single-step online decoding.

⁵This input is augmented with a sinusoidal position embedding for the Transformer models.

The node attribute module uses the node representations to predict whether each attribute applies to each node, and what its value should be. Deciding whether the attribute applies and the prediction of its value are performed by separate MLPs.

The edge attribute module is similar to the node attribute module, but passes a bilinear transformation of two node representations to the MLPs, which predict edge-level properties and masks.

In this work, we make several modifications to this model. Firstly, we replace the encoder and target node modules with Transformer-based architectures (Vaswani et al., 2017). Next, we introduce a second biaffine parser on top of the output of the encoder module, which is tasked with performing dependency parsing on the UD data. During training, we use greedy decoding, while at test time the Chu-Liu-Edmonds Maximum Spanning Tree algorithm (Chu, 1965; Edmonds, 1967) is used.

More specifically, the encoded input representations s_t in Stengel-Eskin et al. (2020) were obtained from a stacked bidirectional LSTM. While the input to this module remains the same in our Transformer-based implementation, the representation s_t is now given by the final layer of a multi-head multi-layer Transformer model. Crucially, following Nguyen and Salazar (2019) we replace the layer normalization layer with a ScaleNorm layer and place it *before* the feed-forward network. The syntactic biaffine parser uses the encoder representations s to predict a head and head label for each token. This task is different from the semantic parsing task as the graph is lexicalized (i.e. there is a bijection between input tokens and graph nodes).

Similarly, the node representations z_i are computed by a Transformer decoder with both self-attention (as in the encoder) and source-side attention. The first layer of node representations for the decoder is given by learned continuous embeddings of the head token and current token representation, their respective indices, and the relationship between them. During training, the gold nodes and heads are used (i.e. teacher forcing), and the attention is computed with an autoregressive mask, so that each token is only able to attend to tokens in its left context. We take $z_i = \text{ScaleNorm}(x_i^L)$, x_i^L being the output of the final layer in a stack of L Transformer layers. We also follow Nguyen and Salazar in scaling the attention head weight initialization by a factor of k .

5 Experiment 1: Joint English Parsing

To determine the effect of jointly parsing the syntax and semantics, we consider a number of baselines and experimental settings. First, we contrast our re-implementation of [Stengel-Eskin et al. \(2020\)](#)’s LSTM-based model with their results. We then report the results of our Transformer-based model, described in §4. After establishing these baselines, we consider different methods of incorporating the syntactic signal into the model:

Concat-before (CB): Here, we linearize the syntactic UD parse, which is a tree, via a pre-order traversal, yielding a sequence of nodes, edge heads, and edge labels, which we prepend to the corresponding sequences obtained by linearizing the semantic parse, separated by a special separation token. At inference time, we use this token to split the output into syntactic and semantic parses.

Concat-after (CA): This setting is identical to the concat-before setting, except that the syntactic graph is appended at the end of the semantic sequence. These two settings incorporate some syntactic signal into the semantic parse, but do not exploit UD parsing’s lexicalization assumption; thus we expect them to yield subpar UD results.

Encoder-side (EN): We do make use of this assumption here, adding a biaffine parser to the encoder states $\mathbf{s}_{1:T}$. We introduce an additional syntactic parsing objective, which allows us to take advantage of the strong lexicalized bias. However, the syntactic signal only enters the model implicitly via backprop, i.e. during the forward pass, the model has no access to syntactic information.

Intermediate (IN): We incorporate the syntactic information by re-encoding the predicted syntactic parse and passing it to the decoder. Due to the close syntactic correspondence of the UDS semantic graph, we would expect that allowing the decoder to access the predicted dependency parse would benefit both the semantic parse as well as the syntactic parse. We enable this by concatenating edge information to $\mathbf{s}_{1:T}$ and linearly projecting it. Specifically, given edge head scores $\mathbf{E} \in \mathbb{R}^{T \times T}$, where each row i is a distribution over possible heads for token i , the output of the parser’s head MLP $\mathbf{H} \in \mathbb{R}^{T \times d_h}$, and the output of the parser’s edge type MLP $\mathbf{T} \in \mathbb{R}^{T \times d_t}$, we compute the new encoder representations \mathbf{s}' as:

$$\mathbf{H}' = \mathbf{H}^T \mathbf{E}, \quad \mathbf{T}' = \mathbf{T}^T \mathbf{E}$$
$$\mathbf{s}'_i = [\mathbf{s}_i; \mathbf{H}'_i; \mathbf{T}'_i]^T \mathbf{W}^I, \quad \mathbf{W}^I \in \mathbb{R}^{(d_s + d_h + d_t) \times d_s}$$

Transformer Hyperparameters Unlike the LSTM-based model, which is fairly robust to hyperparameter changes, the Transformer-based architecture was found to be sensitive to such changes. We use a random search strategy ([Bergstra and Bengio, 2012](#)) with 40 replicants, tuning the number of layers $l \in [6, 8, 12]$, the initialization scaling factor $k \in [4, 32, 128, 512]$, the number of heads $H \in [4, 8]$, the dropout factor $d \in [0.20, 0.33]$, and the number of warmup steps for the optimizer $w \in [1000, 4000, 8000]$. This was performed with the base model, with the best hyperparameters used in all other models.

5.1 Evaluation Metrics

UAS/LAS: Unlabeled Attachment Score (UAS) computes the fraction of tokens with correctly assigned heads in a dependency parse. Labeled Attachment Score (LAS) computes the fraction with correct heads and arc labels. Both are standard metrics for UD parsing.

Pearson’s ρ : For UDS attributes, we compute the Pearson correlation between the predicted attributes at each node and the gold annotations in the UDS corpus. This is obtained under an “oracle” setting, where the gold graph structure is provided.

Attribute F1: Following the original description of semantic proto-roles as binary attributes ([Dowty, 1991](#)), we also measure whether the direction of the attributes matches that of the gold annotations, e.g. whether a predicate is likely factual (*factuality-factual* $> \theta$) or not (*factuality-factual* $< \theta$).⁶ We tune θ per attribute type on validation data. It is abbreviated as F1 (attr), and along with ρ , measures performance on the attribute prediction task.

S-score: Following the Smatch metric ([Cai and Knight, 2013](#)), which uses a hill-climbing approach to find an approximate graph matching between a reference and predicted graph, S-score ([Zhang et al., 2017](#)) provides precision, recall, and F1 score for nodes, edges, and attributes. Note that while S-score enables us to match scalar attributes jointly with nodes and edges, for the sake of clarity we have chosen to bifurcate the evaluations: S-score for nodes and edges only (functionally equivalent to Smatch), and ρ and F1 (attr) for attributes. We use two variants of S-score: one evaluates against full UDS arborescences with linearized syntactic subtrees included as children of semantic heads (abbreviated as F1 (syn)), while the semantics-only set-

⁶Like ρ , we use an oracle decode of the structure here.

ting evaluates only on semantics nodes (F1 (sem)). This metric measures performance on the semantic graph structure prediction task.

6 Experiment 1: Results and Analysis

The Transformer outperforms the LSTM on UDS parsing. We first observe that, with modifications and tuning, the Transformer architecture strictly outperforms the LSTM despite the relatively low number of training examples (12.5K). Fig. 3, which corresponds to Table 1 rows 2 and 3, shows that the Transformer outperforms the LSTM on the S-score metric (with syntactic nodes included, following Stengel-Eskin et al. (2020)) as well as attribute F1 and Pearson’s ρ . Note that in this figure, as well as the others in this section, the vertical axis is scaled to highlight relevant contrasts.

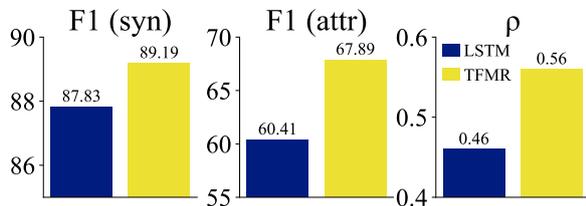


Figure 3: Contrasting LSTM and TFMR performance on graph structure with syntax nodes as well as Pearson’s ρ and binarized attribute F1.

Joint Transformer model slightly outperforms syntax-only model on syntactic parsing.

Fig. 4, corresponding to rows 4-6 and 11 in Table 1, shows that an LSTM encoder with a biaffine parser and no semantic decoder (LSTM + BI) outperforms both baselines (Chen and Manning, 2014; Dozat and Manning, 2017, C+M and D+M, respectively). Note that this model has no semantic signal, and is trained only on UD parsing. In the LSTM case, the addition of the UDS semantic signal via the encoder-side model described in §5 slightly lowers performance. However, this is not the case for the Transformer; the syntax-only Transformer (TFMR + BI) model outperforms the LSTM model, and is slightly outperformed by the joint syntax-semantics Transformer model.

Joint training has little impact on attribute metrics for non-baseline models. Fig. 5 shows Pearson’s ρ and binarized attribute F1 (with θ tuned on the development set); this corresponds to the 2nd two rows and final 10 rows of Table 1.

We see that both for the LSTM and the Transformer, the encoder-side model has about the same performance for ρ and attribute F1 as the UDS-only model, and the Transformer variants consistently

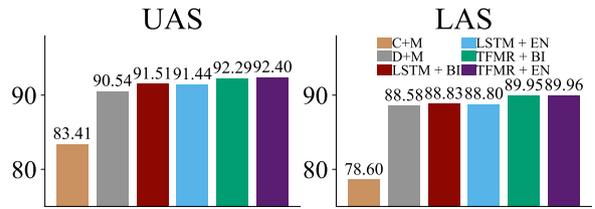


Figure 4: LSTM and TFMR performance on English EWT UD parsing, contrasted with Chen and Manning (2014) and Dozat and Manning (2017) baselines. Models with semantic information (+EN) outperform their syntax-only baselines (+BI)

out-perform their LSTM counterparts. In contrast, the addition of syntactic information through concatenation (concat-before, concat-after) seems to diminish the performance on these metrics. For the LSTM, the intermediate model has lower performance than the encoder-side variant, while for the Transformer it is almost identical.

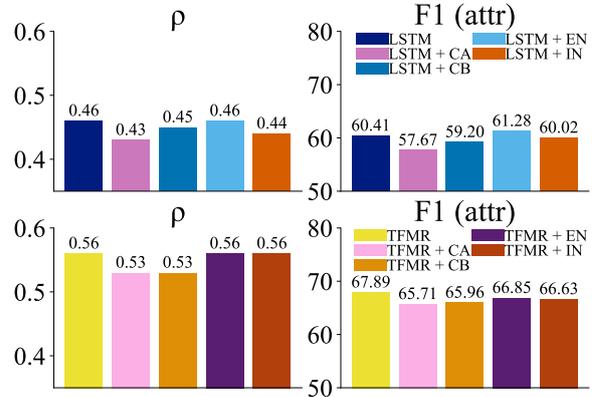


Figure 5: LSTM and TFMR attribute ρ and binarized F1 score.

Joint parsing slightly improves semantic structural performance.

Fig. 6 shows the structural F1 computed by S score, where we observe that the LSTM’s performance, which is lower than the Transformer’s in the baseline setting, benefits most from the concatenation settings, while suffering under the encoder and intermediate settings.

By way of contrast, the Transformer, whose baseline performance is higher, benefits most from the encoder-side biaffine parsing setting, which also boasts the best UD performance (cf. Fig. 4).

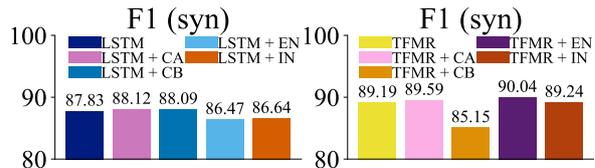


Figure 6: LSTM and TFMR S-score F1 (with syntax nodes included).

While the concat-after setting offers S score improvements for both encoder/decoder types, the

Model	P (syn)	R (syn)	F1 (syn)	P (sem)	R (sem)	F1 (sem)	Attr. ρ	Attr. F1	UAS	LAS
SE 2020	84.97	78.52	81.62	91.28	87.23	89.21	0.34	50.66	—	—
LSTM	89.90	85.85	87.83	89.24	87.47	88.34	0.46	60.41	—	—
TFMR	90.04	87.98	89.19	92.26	91.09	91.67	0.56	67.89	—	—
C+M	84.83	75.22	79.74	84.72	88.51	86.57	—	—	83.41	78.60
D+M	—	—	—	—	—	—	—	—	90.54	88.58
LSTM + BI	—	—	—	—	—	—	—	—	91.51	88.83
LSTM + CB	88.16	88.01	88.09	92.26	90.67	91.46	0.45	59.20	54.44	52.75
LSTM + CA	88.58	87.67	88.12	92.36	91.30	91.83	0.43	57.67	50.89	49.33
LSTM + EN	87.44	86.47	86.47	92.52	90.90	91.70	0.46	61.28	91.44	88.80
LSTM + IN	86.80	86.49	86.64	91.50	90.35	90.92	0.44	60.02	91.00	88.31
TFMR + BI	—	—	—	—	—	—	—	—	92.29	89.95
TFMR + CB	92.87	78.62	85.15	93.66	85.42	89.35	0.53	65.96	58.05	56.75
TFMR + CA	91.31	87.94	89.59	93.15	91.94	92.54	0.53	65.71	51.13	50.07
TFMR + EN	91.09	89.01	90.04	93.76	91.50	92.61	0.56	66.85	92.40	89.96
TFMR + IN	91.50	87.09	89.24	93.26	91.25	92.24	0.56	66.63	92.16	89.52

Table 1: Syntactic and semantic metrics across all models. Note that binarized semantic attribute F1 and ρ are computed w.r.t. to the models trained with linearized syntactic yields, while the (sem) S-score metrics are reported on models trained on semantics nodes alone (on the decoder side).

syntactic performance in this setting is very poor (< 60 UAS). The Transformer encoder-side multitask model is able to improve structural performance for the encoder-side while *simultaneously* boosting UAS and LAS (see Fig. 4).

These results demonstrate that explicitly incorporating a syntactic signal into a transductive semantic parsing model can be done without damaging semantic performance, both for UDS attributes and structure. Perhaps more surprisingly, the semantic signal coming from the UDS attributes and structure improves the syntactic performance of the model when the syntactic model is able to take advantage of the lexicalized nature of UD. Note that due to the parallel nature of the UD and UDS data, we can conclude that the improvements here result from the additional structural signal, and not merely from the addition of more sentences. We see that for the concatenation settings, while the semantic structural performance may increase, the syntactic parsing results are dismal. This is true whether we concatenate the syntactic graph before or after the semantic one. This may be explained by the fact that, by using a transductive model for a lexicalized parsing task like UDS, we are complicating what the model needs to learn. Rather than simply labelling existing nodes, the model must reproduce these nodes via source-side copying.

While *prima facie*, we would expect the intermediate model to outperform the multitask encoder-side model, as its decoder has explicit access to the syntactic parse, we see that this is not the case; it shows lower structural and attribute performance. This represents a direction for future work.

The Role of the Encoder The results in Fig. 5 show that the Transformer-based model has a heavy advantage over the LSTM-based model in terms of attribute prediction. This might be due to an improved ability by the Transformer encoder to incorporate signals from across the input, since the self-attention mechanism has equal access to all positions, while the BiLSTM has only sequential access which may become corrupted or washed out over longer distances. Given the highly contextual nature of UDS inferences, we would expect a model which better captures context to have a distinct advantage, as the crucial tokens for correctly inferring an attribute value may be found in a distant part of the input sentence: for example, if we wish to infer the factuality of “*left*” in the sentence “Bill eventually confessed to the officers that, contrary to his previous statements, Joan had *left* the party early,” most of the signal would come from the token “confessed,” producing a high score. The construction of UDS and its attributes’ scalar nature allow us to test this hypothesis by examining the Pearson correlation between predicted and true attributes at different positions in the input.⁷ In order to compare the correlations across sentences, we group the predicted and reference attributes into 10 percentile ranges, based on the ratio of the node position and the sentence length, i.e. what percentage into the sentence the node occurs. We then average all Pearson ρ values across all attribute types in each bin, obtaining average ρ values by sentence completion percentile. With this data, we

⁷We use the syntactic head nodes of each semantic node to propagate positional information to the semantic nodes.

can compare two models on a very fine-grained level, asking questions such as, “how much better does the Transformer model do than the BiLSTM on nodes that are between 0% and 10% into the sentence.” Fig. 7 shows such comparisons between a unidirectional left-to-right LSTM encoder and the bidirectional LSTM, and between the bidirectional LSTM and the Transformer. While the unidirectional LSTM actually outperforms the BiLSTM in the central percentiles, it struggles near the edges. This could be explained on the left edge by a lack of right context, and on the right edge by difficulties with long-range dependencies. Furthermore, the Transformer outperforms the BiLSTM at all positional percentiles, but particularly in the central regions, suggesting that, while the BiLSTM is able to incorporate contextual information well at the edges of a sentence, the information is diluted in the central region, while the Transformer’s self-attention mechanism is equally able to draw from arbitrary positions at all timesteps.

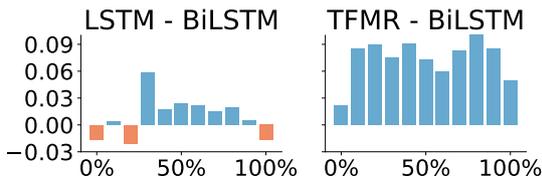


Figure 7: Δ in mean ρ for each sentence position between (left) LSTM and BiLSTM and between (right) TFMR and BiLSTM. The TFMR’s gains in ρ come mainly from the middle percentiles.

7 Experiment 2: Tuning BERT

The results in Fig. 4 and Fig. 6 not only demonstrate that the addition of one structural modality (i.e. syntax, semantics) can benefit the other, but also suggest that these signals are complementary to the signal already given by the input features, which include contextualized features obtained from BERT. This stands in contrast to previous results by Swayamdipta et al. (2019) that the benefits to be gained from multitask learning with shallow syntactic objectives are largely eclipsed by contextualized encoders. However, we note that our models require full UD parses in the multitask settings rather than a light scaffolding.

If indeed the combination of UDS and UD signals provides information not yet encoded in BERT, then fine-tuning BERT with these signals should yield additional benefits. Following observations that syntax and semantics are encoded to varying degrees at different depths in contextualized

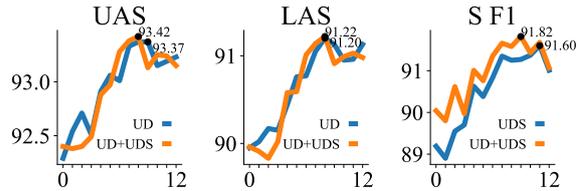


Figure 8: Test metrics when freezing/tuning different levels of BERT. X-axis represents number of layers tuned (from the top layer). Tuning the encoder provides significant benefits over a frozen encoder (0 layers tuned) but the optimal number of tuned layers is not the full 12 layers.

encoders (Hewitt and Liang, 2019; Tenney et al., 2019; Jawahar et al., 2019) with syntactic information typically lower in the network, we explore the trade-off between freezing and tuning various layers of the BERT encoder. Specifically, we tune the top n layers, starting from a completely frozen encoder and moving to tuning all 12 layers.⁸

Intuitively, one might expect to see a monotonic increase as the number of tuned layers increases, as each additional unfrozen layer provides the model with more capacity. However, the results presented in Fig. 8 show a more nuanced trend: while the performance across syntactic and semantic metrics increases up to a point, they begin to decrease again when additional layers are unfrozen. This may be due to data sparsity; given the relatively small size of the UDS corpus, the addition of too many parameters may encourage overfitting, resulting in decreased test performance. Note that the encoder-side model all three panels of Fig. 8 is the same model, i.e. the best UAS, LAS, and S score performance is obtained by the same model, and that the performance of the joint model at any given tuning depth typically falls above that of the baseline.

In contrast to the findings of Glavaš and Vulić (2020), who conclude that the benefits of UD pre-training for semantic language understanding tasks are limited when using contextualized encoders, our results in §6 show a small but consistent positive effect of syntactic information on semantic parsing, as well as improved syntactic performance from a semantic signal. Furthermore, our results here show that the UD signal can actually be used to fine-tune a contextualized encoder, which benefits not only the UD parsing performance but also the UDS performance. In fact, after training and evaluating their model (which, to our knowledge, has the highest performance to date on EWT) on

⁸As the BERT encoder is pre-trained, a separate static learn rate of $1e - 5$ was used to optimize the BERT parameters.

our cleaned subset of EWT, we find that our best performing UAS/LAS values, 93.42 and 91.22, outperform their values of 92.83 and 90.11. These values also slightly outperform the syntax-only version of the same model, with the same amount of tuning. The tuned encoder-side model also provides the best semantic performance, with a max score of 91.82, compared to 90.04 in the TFMR + EN setting (cf. Table 1).

Prepositional Phrase Attachment Ambiguity
Looking at the results in Figs. 4 and 6, which are mirrored in the tuned results visualized in Fig. 8, a natural question to ask is where the syntactic performance gains are coming from in the encoder-side model. One hypothesis, in line with literature on semantic bootstrapping, is that the semantic signal helps the model to discriminate between ambiguous parses. Consider, for example, the sentence “I shot an elephant in my pyjamas.” Syntactically, there are two valid heads for the prepositional phrase (PP) “in my pyjamas”, but the semantics of the phrase indicates to us that it is less likely to be attached to “elephant”. Perhaps adding an explicit semantic signal, like that of UDS, would improve a syntactic parser’s ability to disambiguate sentences like this. In order to test this hypothesis, we use a dataset introduced by Gardner et al. (2020), consisting of 300 sentences with UD annotations. 150 sentences were chosen from a combination of English UD treebanks with potential PP attachment ambiguities, 75 with PP with nominal heads, and 75 with verbal heads. Minimal semantic changes were then made to the sentence to switch the head (i.e. nominal heads were switched to verbal heads). For example, the sentence, “They demanded talks *with local US commanders*” becomes: “They demanded talks *with great urgency*” (noun to verb).

A model’s performance on this dataset is measured not only by its raw performance on the unaltered sentences, but, crucially, by its performance on the altered ones. As the altered sentences are constructed to be different from those seen in the training set, we expect there to be a drop in performance if the model has learned simple heuristics (e.g. always attach to a noun) rather than robust rules based on semantic understanding. An ideal model would have high performance and no drop. Fig. 9 compares the tuned syntax-only UD baseline (right column) and the tuned UDS parser with encoder-side parsing (left column) on this task, both for noun-to-verb and verb-to-noun alterations. In all cases, we see a significant drop in performance on the

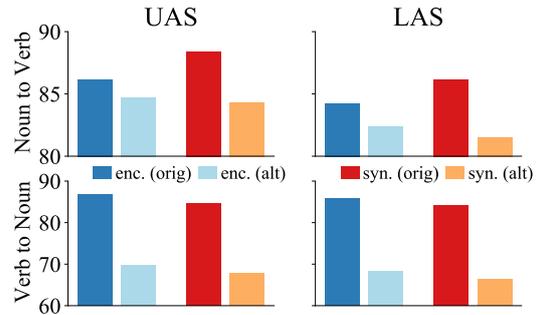


Figure 9: Encoder-side and syntax-only performance on sentences with PP attachment ambiguities. A joint syntax-semantics model is slightly more robust to manual adjustment of the prepositional head than a syntax-only model.

altered examples. In the noun-to-verb case, we see that, while the syntax-only baseline’s initial performance is higher, it experiences a larger drop in performance than the encoder-side model, with its performance on the altered dataset being lower on UAS and LAS. In the verb-to-noun case, while both models undergo roughly the same major performance loss in the altered context, the initial performance of the encoder-side model is higher.

These results, taken together, suggest that the addition of the UDS signal may provide a small benefit when disambiguating PP attachment ambiguities. However, such ambiguities are fairly rare in UD corpora, and are thus unlikely to explain the whole difference between the models. To this end, we examine the difference in UAS performance between systems on the 10 most frequent relation types in Fig. 10. When comparing a joint UD-UDS parser, we see that small gains are realized for the most frequent relations, but some relations suffer minor losses as well. In contrast, when comparing the tuned and untuned systems, nearly all the most frequent relations see fairly large improvements.

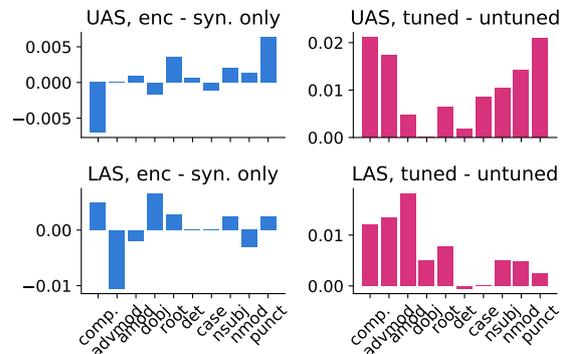


Figure 10: Δ between (left) a joint UDS-UD model and a UD only model and (right) a joint UDS-UD model with an encoder tuned through layer 4 vs. one with a frozen encoder.

UDS attributes and UD relations The close link between UD parses and the UDS annotations in the dataset allows us not only to train multitask models for joint syntactic and semantic parsing, but also to inspect the interactions between syntactic relations and semantic attributes more closely. Each cell in Fig. 12 shows the Pearson ρ between true and predicted attributes for a variety of UDS annotations conditioned on UD dependency relations. The node attributes (annotated on semantic nodes in the UDS graph) are paired with the UD relation of the corresponding syntactic head node. Predictions are obtained from the best tuned model with encoder-side UD parsing (TFMR + EN), under an oracle decode of the graph structure.

We see variation across a given attribute and dependency relation. For example, factuality annotations display a high ρ value for `root` and `conj` annotations, but a lower correlation for `xcomp`. These correlations are visualized in Fig. 11, where we plot the true vs. predicted value, with the line defined by ρ overlaid. The close correspondence between UD and UDS lets us observe this type of discrepancy, which echoes findings by White et al. (2018), who used factuality prediction to probe neural models’ ability to make inferences based on lexical and syntactic factuality triggers. Furthermore, it is in holding with semantic theories, as the `xcomp` relation is used for open clausal complements, i.e. non-finite embedded clauses, with an overt control subject in the main clause (e.g. object or subject control). In English, `xcomp` relations correspond to infinitival embedded clauses, e.g. “I remembered *to turn off the stove*.” As pointed out by White (2020), factuality inferences are particularly hard in these contexts, as they are not only sensitive to the lexical category of the embedding predicate (i.e. “remembered” vs. “forgot”) but also its polarity (i.e. “remembered” vs. “didn’t remember”). This separates them from finite clausal complements, where a matrix negation still results in the same factuality inference; e.g. in both “I remembered *that I turned off the stove*” and “I didn’t remember *that I turned off the stove*” we infer that the stove was turned off. Furthermore, `xcomp` relations are present in object and subject control cases, which may be difficult even for human speakers to acquire (Chomsky, 1969; Cromer, 1970).

Beyond comparing our model predictions to theoretical predictions at the syntax-semantics interface, we can also use this analysis to examine the

data on which the model was trained. For instance, homing in on the `genericity-arg-kind` annotations (reflecting the level to which an argument refers to a *kind* of thing) for direct objects `dobj`, we see that for some examples, while the model prediction differs from the annotation, it is not wrong per se. One example is, “Take a *look* at this spreadsheet” where “look” is annotated as high for `kind` (1.41), but predicted as low (-1.09). In another example, “...I could not find one *place* in Tampa Bay that sells...”, the argument “place” has a high predicted `kind` value (0.72) but is annotated otherwise (-0.87). In both these cases, one could argue that the model’s prediction is not entirely incorrect.

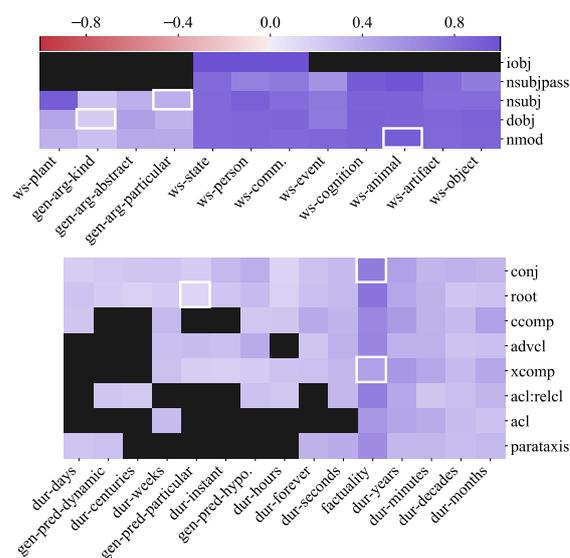


Figure 12: ρ on argument (top) and predicate (bottom) UDS properties (subset) at relevant UD relations. Black cells indicate no significant correlation. Outlined boxes plotted in detail in Fig. 11.

8 Experiment 3: Multilingual Parsing

The results in §6 that English UD parsing and UDS parsing are mutually beneficial naturally give rise to a follow-up question: does this relationship extend to a multilingual setting. As in the monolingual case, we explore both the impact of UD parsing on UDS, and vice versa. UD is by design highly multilingual, spanning scores of languages from a diverse typological range, often with multiple treebanks per language. This has led to interest in evaluating the performance of UD parsing models not just on English, but across a range of languages and language families; both the 2017 and 2018 CoNLL shared tasks focused on multilingual UD parsing (Zeman et al., 2017, 2018). The introduction of multilingual contextualized encoders, such as mBERT (Devlin et al., 2019; Devlin, 2018) and

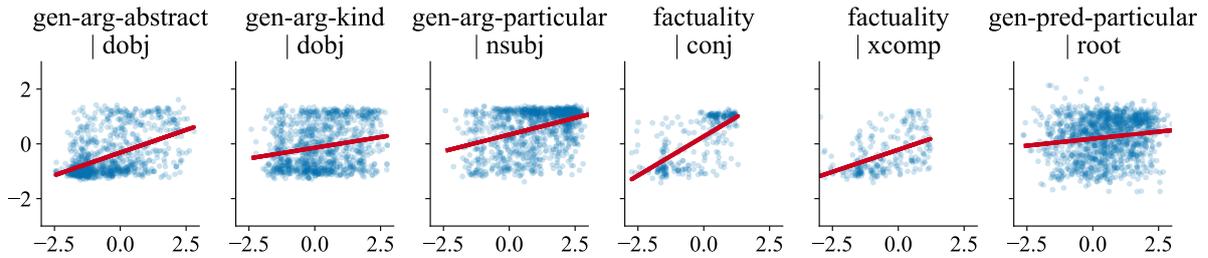


Figure 11: True and predicted values for UDS attributes at UD relation types, outlined in Fig. 12

XLM-R (Conneau et al., 2020) has enabled models to perform UD parsing in multiple languages simultaneously by using features obtained by a single multilingual encoder (Schuster et al., 2019; Konratyuk and Straka, 2019).

By initializing weights for one task (syntactic or semantic) with weights learned on the other, and leveraging the shared input representation space of XLM-R, we examine bottom-up effects of representations learned with a syntactic objective on semantic parsing performance, and top-down effects the semantic objective on syntactic performance. Note that unlike in §6, we do not have parallel data in these settings, leading to the use of pre-training rather than simultaneous multitask learning. Note also that we are examining the relationship between *English* semantic parsing and multilingual, *non-English* syntactic parsing. We do not make use of pre-trained type-level word embeddings in these experiments, leading us to expect slightly lower absolute performance on the UDS parsing task as compared to Table 1. Based on the syntactic results in §6, we explore only the Transformer models in our multilingual experiments. We tune the XLM-R encoder through layer 5, based on our observations on the development set in §6.⁹

Languages 8 languages in 5 families from the 2018 CoNLL Shared Task (Zeman et al., 2018) were chosen, across both higher and lower resource settings. Table 2 gives further details and highlights the range of resource settings examined.¹⁰

Bottom-up Effects Examining bottom-up effects of syntax on semantics, we pre-train a multilingual UD model on all 8 languages simultaneously, using alternating batches from each language and capping each epoch at 20,000 examples. We then initialize the encoder and biaffine parser in UDS parser with the weights learned on UD

Code	Language	Family	#Train	#Test
AF	Afrikaans	Germanic	2630	850
DE	German	Germanic	13814	977
FI	Finnish	Uralic	27198	4422
FR	French	Romance	17836	1598
GL	Galician	Romance	2272	861
HU	Hungarian	Uralic	910	449
HY	Armenian	Armenian	1975	278
KK	Kazakh	Turkic	28	1047

Table 2: Language data and # train/test sentences

parsing and continue training on joint UDS and EWT UD parsing, as in Experiment 1. In Table 3 we see that syntactic parsing performance on English EWT UD parsing improves with pretraining for the intermediate model, but decreases for the encoder-side model. A similar trend holds for the S-score, where the intermediate model improves with pre-training while the encoder-side model’s performance suffers. However, for attribute F1 and ρ , the encoder-side model with pre-training outperforms the encoder-side model without, while the opposite is true of the intermediate model, whose performance decreases with pretraining. Unlike in §6, the intermediate model outperforms the encoder-side model here, obtaining the highest overall UD parsing score of any model looked at thus far.

The UAS/LAS of the pre-trained intermediate model is the strongest even when compared against the best monolingual models in Table 1. In fact, when trained and evaluated on the entirety of the EWT UD corpus, the XLM-R-based intermediate model with pre-training obtains the same exact UAS/LAS performance the best XLM-R model reported by Glavaš and Vulić (2020): 93.1 UAS, 90.5 LAS. Since our model is additionally capable of performing UDS parsing at a level competitive with the best system presented in Table 1, we encourage others to make use of it in the future.

The trends here suggest that a multilingual syntactic signal, when incorporated well into a UDS model, can provide benefit to the syntactic performance without necessarily reducing the semantic

⁹We also re-tuned the Transformer hyperparameters, as the input space changed from BERT and GloVe to XLM-R.

¹⁰Note that despite its relatively large test set size, the Kazakh train set is very small ($n = 31$). Of these sentences, 3 were used for validation, leaving 28 train sentences.

Model	P	R	F1	Attr. ρ	Attr. F1	UAS	LAS
TFMR	90.80	89.08	89.93	0.51	63.62	—	—
TFMR + EN	91.72	89.17	90.42	0.48	60.12	93.44	91.21
TFMR + IN	90.51	87.68	89.07	0.46	59.47	93.47	91.20
TFMR + PRE + EN	91.24	88.97	90.09	0.50	63.23	93.35	91.21
TFMR + PRE + IN	90.65	88.45	89.54	0.46	58.86	93.62	91.37

Table 3: Full UDS and English UD results for XLM-R models with and without pre-training.

performance. Note that unlike in §6, the syntactic data used to pretrain the syntactic encoder and biaffine parser is neither parallel to the UDS dataset, nor is it in English. Thus, that the syntactic data can act as a signal for semantic parsing, albeit with small effects, is surprising.

Top-down Effects In the top-down direction (semantics to syntax) we train the encoder-side and intermediate variants of the joint UDS and syntactic parsing model and subsequently load the weights from their encoders and biaffine parsers into separate UD models for all 8 languages. These are compared against a baseline model with weights initialized from a English UD parsing model. Thus any improvement obtained by the encoder and intermediate models comes strictly from the semantic signal, since the syntactic signal is shared with the baseline model. Table 4 shows the LAS and UAS performance of these models, with arrows indicating the direction of change from the baseline model. We see that almost all of the languages see benefits from the addition of semantic signal in at least one model variant, with the exception of Finnish, which performs worse across all variants and metrics when the semantic signal is included. For Galician, Hungarian, and Armenian, we see a sizeable improvement between the models. With the exception of Kazakh, whose train set is miniscule, these are among the lowest-resource languages considered. While, given the typical pipeline view of syntax as a substrate for semantics, we might expect the bottom-up results to be stronger than top-down results, here we find that the syntactic benefits of pretraining on a semantic task are more consistent and stronger than in the other direction.

Discussion On the whole, the multilingual top-down and bottom-up effects seem to mimic the monolingual results, albeit with smaller relative improvements. In §6, we saw a mutually beneficial relationship between UD and UDS parsing in a number of settings; here, we see that in several cases, this pattern generalizes to a case where we pretrain on data that is not only in a different domain than the evaluation (i.e. syntax vs. semantics) but also in a different language. These effects hint

Lang.	Base	Encoder	Intermediate
AF	86.10 / 89.06	86.40 \uparrow / 89.28 \uparrow	85.27 \downarrow / 88.39 \downarrow
DE	84.30 / 88.45	84.23 \downarrow / 88.49 \uparrow	83.49 \downarrow / 87.85 \downarrow
FI	80.94 / 85.83	80.53 \downarrow / 85.52 \downarrow	80.50 \downarrow / 85.44 \downarrow
FR	86.66 / 90.02	86.82 \uparrow / 90.07 \uparrow	86.71 \uparrow / 89.94 \downarrow
GL	78.60 / 82.46	79.58 \uparrow / 83.08 \uparrow	79.77 \uparrow / 83.19 \uparrow
HU	82.90 / 87.76	83.67 \uparrow / 88.33 \uparrow	82.01 \downarrow / 86.75 \downarrow
HY	77.97 / 83.72	79.31 \uparrow / 85.08 \uparrow	76.48 \downarrow / 82.79 \downarrow
KK	51.05 / 67.09	51.25 \uparrow / 65.49 \downarrow	48.85 \downarrow / 63.08 \downarrow
AVG	78.56 / 84.30	78.97 \uparrow / 84.42 \uparrow	77.88 \downarrow / 83.43 \downarrow

Table 4: LAS/UAS for models with weights transferred from EWT UD parsing compared with those from encoder-side and intermediate UDS models.

at useful commonalities not only between syntactic parses across multiple languages, but also between multilingual syntax and the UDS representation.

9 Conclusion

In §5, we introduced a number of multitask architectures for joint syntactic and semantic parsing, which we demonstrated in §6 can perform UD and UDS parsing simultaneously without sacrificing performance, as evaluated across a number of syntactic and semantic metrics. In particular, we observed a top-down benefit to syntactic parsing from the semantic signal as well as a bottom-up benefit to semantic performance from syntactic parsing. We contrasted both LSTM and Transformer-based variants of these architectures, finding the Transformer to be better on all metrics. Finding the syntactic and semantic information present in the data to be complementary to that encoded in a frozen contextualized encoder, we experimented in §7 with tuning the encoder to varying depths, finding that tuning the top-most layers provides the greatest benefit. We analyzed the models resulting from this tuning step on their ability to resolve attachment ambiguities, as well as examining interactions between UDS annotations and UD dependency relations. Furthermore, in §8, we extended our experiments beyond English, using a transfer-learning experimental paradigm to investigate effects between multilingual syntactic parsing in 8 languages and English semantic parsing, where we found similar trends to the English-only setting. Based on these multilingual results, we believe that expanding the UDS data paradigm (i.e. UD-based graph structure, continuous attributes) beyond English and building robust multilingual parsing models is a particularly promising direction for future work. Other directions include improving the robustness of the Transformer model in low-resource settings and improvements to the attribute modules.

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References

- Omri Abend, Tom Kwiatkowski, Nathaniel J Smith, Sharon Goldwater, and Mark Steedman. 2017. Bootstrapping language acquisition. *Cognition*, 164:116–143.
- Omri Abend and Ari Rappoport. 2013. [Universal Conceptual Cognitive Annotation \(UCCA\)](#). In *Proceedings of the 51st Annual Meeting of the Association for Computational Linguistics (Volume 1: Long Papers)*, pages 228–238, Sofia, Bulgaria. Association for Computational Linguistics.
- Yoav Artzi, Kenton Lee, and Luke Zettlemoyer. 2015. [Broad-coverage CCG semantic parsing with AMR](#). In *Proceedings of the 2015 Conference on Empirical Methods in Natural Language Processing*, pages 1699–1710, Lisbon, Portugal. Association for Computational Linguistics.
- Laura Banarescu, Claire Bonial, Shu Cai, Madalina Georgescu, Kira Griffitt, Ulf Hermjakob, Kevin Knight, Philipp Koehn, Martha Palmer, and Nathan Schneider. 2013. [Abstract Meaning Representation for sembanking](#). In *Proceedings of the 7th Linguistic Annotation Workshop and Interoperability with Discourse*, pages 178–186, Sofia, Bulgaria. Association for Computational Linguistics.
- James Bergstra and Yoshua Bengio. 2012. Random search for hyper-parameter optimization. *The Journal of Machine Learning Research*, 13(1):281–305.
- Sebastian Beschke. 2019. [Exploring graph-algebraic CCG combinators for syntactic-semantic AMR parsing](#). In *Proceedings of the International Conference on Recent Advances in Natural Language Processing (RANLP 2019)*, pages 112–121, Varna, Bulgaria. INCOMA Ltd.
- Ann Bies, Justin Mott, Colin Warner, and Seth Kulick. 2012. English Web Treebank. *Linguistic Data Consortium, Philadelphia, PA*.
- Shu Cai and Kevin Knight. 2013. [Smatch: an evaluation metric for semantic feature structures](#). In *Proceedings of the 51st Annual Meeting of the Association for Computational Linguistics (Volume 2: Short Papers)*, pages 748–752, Sofia, Bulgaria. Association for Computational Linguistics.
- Rich Caruana. 1997. Multitask learning. *Machine learning*, 28(1):41–75.
- Danqi Chen and Christopher Manning. 2014. [A fast and accurate dependency parser using neural networks](#). In *Proceedings of the 2014 Conference on Empirical Methods in Natural Language Processing (EMNLP)*, pages 740–750, Doha, Qatar. Association for Computational Linguistics.
- Carol Chomsky. 1969. The acquisition of syntax in children from 5 to 10.
- Yoeng-Jin Chu. 1965. On the shortest arborescence of a directed graph. *Scientia Sinica*, 14:1396–1400.
- Alexis Conneau, Kartikay Khandelwal, Naman Goyal, Vishrav Chaudhary, Guillaume Wenzek, Francisco Guzmán, Edouard Grave, Myle Ott, Luke Zettlemoyer, and Veselin Stoyanov. 2020. [Unsupervised cross-lingual representation learning at scale](#). In *Proceedings of the 58th Annual Meeting of the Association for Computational Linguistics*, pages 8440–8451, Online. Association for Computational Linguistics.
- Richard F Cromer. 1970. ‘Children are nice to understand’: Surface structure clues for the recovery of a deep structure. *British Journal of Psychology*, 61(3):397–408.
- Jacob Devlin. 2018. [Multilingual BERT README document](#).
- Jacob Devlin, Ming-Wei Chang, Kenton Lee, and Kristina Toutanova. 2019. [BERT: Pre-training of deep bidirectional transformers for language](#)

- [understanding](#). In *Proceedings of the 2019 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies, Volume 1 (Long and Short Papers)*, pages 4171–4186, Minneapolis, Minnesota. Association for Computational Linguistics.
- David Dowty. 1991. Thematic proto-roles and argument selection. *Language*, 67(3):547–619.
- Timothy Dozat and Christopher D. Manning. 2017. [Deep biaffine attention for neural dependency parsing](#). In *5th International Conference on Learning Representations, ICLR 2017, Toulon, France, April 24-26, 2017, Conference Track Proceedings*. OpenReview.net.
- Jack Edmonds. 1967. Optimum branchings. *Journal of Research of the national Bureau of Standards B*, 71(4):233–240.
- Matt Gardner, Yoav Artzi, Victoria Basmov, Jonathan Berant, Ben Bogin, Sihao Chen, Pradeep Dasigi, Dheeru Dua, Yanai Elazar, Ananth Gottumukkala, Nitish Gupta, Hannaneh Hajishirzi, Gabriel Ilharco, Daniel Khoshnabi, Kevin Lin, Jiangming Liu, Nelson F. Liu, Phoebe Mulcaire, Qiang Ning, Sameer Singh, Noah A. Smith, Sanjay Subramanian, Reut Tsarfaty, Eric Wallace, Ally Zhang, and Ben Zhou. 2020. [Evaluating models’ local decision boundaries via contrast sets](#). In *Findings of the Association for Computational Linguistics: EMNLP 2020*, pages 1307–1323, Online. Association for Computational Linguistics.
- Matt Gardner, Joel Grus, Mark Neumann, Oyvind Tafjord, Pradeep Dasigi, Nelson F. Liu, Matthew Peters, Michael Schmitz, and Luke Zettlemoyer. 2018. [AllenNLP: A deep semantic natural language processing platform](#). In *Proceedings of Workshop for NLP Open Source Software (NLP-OSS)*, pages 1–6, Melbourne, Australia. Association for Computational Linguistics.
- Goran Glavaš and Ivan Vulić. 2020. Is supervised syntactic parsing beneficial for language understanding? an empirical investigation. *arXiv preprint arXiv:2008.06788*.
- Lila Gleitman. 1990. The structural sources of verb meanings. *Language acquisition*, 1(1):3–55.
- Jan Hajič, Massimiliano Ciaramita, Richard Johansson, Daisuke Kawahara, Maria Antònia Martí, Lluís Màrquez, Adam Meyers, Joakim Nivre, Sebastian Padó, Jan Štěpánek, Pavel Straňák, Mihai Surdeanu, Nianwen Xue, and Yi Zhang. 2009. [The CoNLL-2009 shared task: Syntactic and semantic dependencies in multiple languages](#). In *Proceedings of the Thirteenth Conference on Computational Natural Language Learning (CoNLL 2009): Shared Task*, pages 1–18, Boulder, Colorado. Association for Computational Linguistics.
- John Hewitt and Percy Liang. 2019. [Designing and interpreting probes with control tasks](#). In *Proceedings of the 2019 Conference on Empirical Methods in Natural Language Processing and the 9th International Joint Conference on Natural Language Processing (EMNLP-IJCNLP)*, pages 2733–2743, Hong Kong, China. Association for Computational Linguistics.
- Ganesh Jawahar, Benoît Sagot, and Djamel Seddah. 2019. [What does BERT learn about the structure of language?](#) In *Proceedings of the 57th Annual Meeting of the Association for Computational Linguistics*, pages 3651–3657, Florence, Italy. Association for Computational Linguistics.
- Richard Johansson and Pierre Nugues. 2008. [Dependency-based syntactic–semantic analysis with PropBank and NomBank](#). In *CoNLL 2008: Proceedings of the Twelfth Conference on Computational Natural Language Learning*, pages 183–187, Manchester, England. Coling 2008 Organizing Committee.
- Dan Kondratyuk and Milan Straka. 2019. [75 languages, 1 model: Parsing Universal Dependencies universally](#). In *Proceedings of the 2019 Conference on Empirical Methods in Natural Language Processing and the 9th International Joint Conference on Natural Language Processing (EMNLP-IJCNLP)*, pages 2779–2795, Hong Kong, China. Association for Computational Linguistics.
- Jayant Krishnamurthy and Tom M. Mitchell. 2014. [Joint syntactic and semantic parsing with Combinatory Categorical Grammar](#). In *Proceedings of the 52nd Annual Meeting of the Association for Computational Linguistics (Volume 1: Long Papers)*, pages 1188–1198, Baltimore, Maryland. Association for Computational Linguistics.

- Barbara Landau and Lila R. Gleitman. 1985. *Language and Experience: Evidence from the Blind Child*. Number 8 in Cognitive Science Series. Harvard University Press, Cambridge, MA.
- Mike Lewis, Luheng He, and Luke Zettlemoyer. 2015. [Joint A* CCG parsing and semantic role labelling](#). In *Proceedings of the 2015 Conference on Empirical Methods in Natural Language Processing*, pages 1444–1454, Lisbon, Portugal. Association for Computational Linguistics.
- Dipendra Kumar Misra and Yoav Artzi. 2016. [Neural shift-reduce CCG semantic parsing](#). In *Proceedings of the 2016 Conference on Empirical Methods in Natural Language Processing*, pages 1775–1786, Austin, Texas. Association for Computational Linguistics.
- Richard Montague. 1970. Universal grammar. *Theoria*, 36(3):373–398.
- Letitia Naigles. 1990. Children use syntax to learn verb meanings. *Journal of child language*, 17(2):357–374.
- Toan Q Nguyen and Julian Salazar. 2019. Transformers without tears: Improving the normalization of self-attention. *arXiv preprint arXiv:1910.05895*.
- Stephan Oepen, Marco Kuhlmann, Yusuke Miyao, Daniel Zeman, Silvie Cinková, Dan Flickinger, Jan Hajič, Angelina Ivanova, and Zdeňka Urešová. 2016. [Towards comparability of linguistic graph Banks for semantic parsing](#). In *Proceedings of the Tenth International Conference on Language Resources and Evaluation (LREC’16)*, pages 3991–3995, Portorož, Slovenia. European Language Resources Association (ELRA).
- Stephan Oepen, Marco Kuhlmann, Yusuke Miyao, Daniel Zeman, Dan Flickinger, Jan Hajič, Angelina Ivanova, and Yi Zhang. 2014a. [SemEval 2014 task 8: Broad-coverage semantic dependency parsing](#). In *Proceedings of the 8th International Workshop on Semantic Evaluation (SemEval 2014)*, pages 63–72, Dublin, Ireland. Association for Computational Linguistics.
- Stephan Oepen, Marco Kuhlmann, Yusuke Miyao, Daniel Zeman, Dan Flickinger, Jan Hajič, Angelina Ivanova, and Yi Zhang. 2014b. [SemEval 2014 task 8: Broad-coverage semantic dependency parsing](#). In *Proceedings of the 8th International Workshop on Semantic Evaluation (SemEval 2014)*, pages 63–72, Dublin, Ireland. Association for Computational Linguistics.
- S Pinker. 1984. 1984: Language learnability and language development. Cambridge, MA: Harvard University Press.
- Steven Pinker. 1979. [Formal models of language learning](#). *Cognition*, 7(3):217 – 283.
- Carl Pollard and Ivan A Sag. 1994. *Head-driven phrase structure grammar*. University of Chicago Press.
- Tal Schuster, Ori Ram, Regina Barzilay, and Amir Globerson. 2019. [Cross-lingual alignment of contextual word embeddings, with applications to zero-shot dependency parsing](#). In *Proceedings of the 2019 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies, Volume 1 (Long and Short Papers)*, pages 1599–1613, Minneapolis, Minnesota. Association for Computational Linguistics.
- Abigail See, Peter J. Liu, and Christopher D. Manning. 2017. [Get to the point: Summarization with pointer-generator networks](#). In *Proceedings of the 55th Annual Meeting of the Association for Computational Linguistics (Volume 1: Long Papers)*, pages 1073–1083, Vancouver, Canada. Association for Computational Linguistics.
- Mark Steedman. 2000. *The syntactic process*, volume 24. MIT press Cambridge, MA.
- Elias Stengel-Eskin, Aaron Steven White, Sheng Zhang, and Benjamin Van Durme. 2020. [Universal compositional semantic parsing](#). In *Proceedings of the 58th Annual Meeting of the Association for Computational Linguistics*, pages 8427–8439, Online. Association for Computational Linguistics.
- Emma Strubell, Patrick Verga, Daniel Andor, David Weiss, and Andrew McCallum. 2018. [Linguistically-informed self-attention for semantic role labeling](#). In *Proceedings of the 2018 Conference on Empirical Methods in Natural Language Processing*, pages 5027–5038, Brussels, Belgium. Association for Computational Linguistics.

- Mihai Surdeanu, Richard Johansson, Adam Meyers, Lluís Màrquez, and Joakim Nivre. 2008. [The CoNLL 2008 shared task on joint parsing of syntactic and semantic dependencies](#). In *CoNLL 2008: Proceedings of the Twelfth Conference on Computational Natural Language Learning*, pages 159–177, Manchester, England. Coling 2008 Organizing Committee.
- Swabha Swayamdipta, Miguel Ballesteros, Chris Dyer, and Noah A. Smith. 2016. [Greedy, joint syntactic-semantic parsing with stack LSTMs](#). In *Proceedings of The 20th SIGNLL Conference on Computational Natural Language Learning*, pages 187–197, Berlin, Germany. Association for Computational Linguistics.
- Swabha Swayamdipta, Matthew Peters, Brendan Roof, Chris Dyer, and Noah A Smith. 2019. Shallow syntax in deep water. *arXiv preprint arXiv:1908.11047*.
- Swabha Swayamdipta, Sam Thomson, Chris Dyer, and Noah A Smith. 2017. Frame-semantic parsing with softmax-margin segmental rnns and a syntactic scaffold. *arXiv preprint arXiv:1706.09528*.
- Swabha Swayamdipta, Sam Thomson, Kenton Lee, Luke Zettlemoyer, Chris Dyer, and Noah A. Smith. 2018. [Syntactic scaffolds for semantic structures](#). In *Proceedings of the 2018 Conference on Empirical Methods in Natural Language Processing*, pages 3772–3782, Brussels, Belgium. Association for Computational Linguistics.
- Ian Tenney, Dipanjan Das, and Ellie Pavlick. 2019. [BERT rediscovers the classical NLP pipeline](#). In *Proceedings of the 57th Annual Meeting of the Association for Computational Linguistics*, pages 4593–4601, Florence, Italy. Association for Computational Linguistics.
- Ashish Vaswani, Noam Shazeer, Niki Parmar, Jakob Uszkoreit, Llion Jones, Aidan N Gomez, Łukasz Kaiser, and Illia Polosukhin. 2017. Attention is all you need. In *Advances in neural information processing systems*, pages 5998–6008.
- Aaron Steven White. 2020. Lexically triggered veridicality inferences. *Handbook of Pragmatics: 22nd Annual Installment*, 22:115.
- Aaron Steven White, Drew Reisinger, Keisuke Sakaguchi, Tim Vieira, Sheng Zhang, Rachel Rudinger, Kyle Rawlins, and Benjamin Van Durme. 2016. [Universal decompositional semantics on Universal Dependencies](#). In *Proceedings of the 2016 Conference on Empirical Methods in Natural Language Processing*, pages 1713–1723, Austin, Texas. Association for Computational Linguistics.
- Aaron Steven White, Rachel Rudinger, Kyle Rawlins, and Benjamin Van Durme. 2018. [Lexicosyntactic inference in neural models](#). In *Proceedings of the 2018 Conference on Empirical Methods in Natural Language Processing*, pages 4717–4724, Brussels, Belgium. Association for Computational Linguistics.
- Aaron Steven White, Elias Stengel-Eskin, Siddharth Vashishtha, Venkata Subrahmanyam Govindarajan, Dee Ann Reisinger, Tim Vieira, Keisuke Sakaguchi, Sheng Zhang, Francis Ferraro, Rachel Rudinger, Kyle Rawlins, and Benjamin Van Durme. 2020. [The universal decompositional semantics dataset and decomp toolkit](#). In *Proceedings of the 12th Language Resources and Evaluation Conference*, pages 5698–5707, Marseille, France. European Language Resources Association.
- Daniel Zeman, Jan Hajič, Martin Popel, Martin Potthast, Milan Straka, Filip Ginter, Joakim Nivre, and Slav Petrov. 2018. [CoNLL 2018 shared task: Multilingual parsing from raw text to Universal Dependencies](#). In *Proceedings of the CoNLL 2018 Shared Task: Multilingual Parsing from Raw Text to Universal Dependencies*, pages 1–21, Brussels, Belgium. Association for Computational Linguistics.
- Daniel Zeman, Martin Popel, Milan Straka, Jan Hajič, Joakim Nivre, Filip Ginter, Juhani Luotolahti, Sampo Pyysalo, Slav Petrov, Martin Potthast, Francis Tyers, Elena Badmaeva, Memduh Gokirmak, Anna Nedoluzhko, Silvie Cinková, Jan Hajič jr., Jaroslava Hlaváčová, Václava Kettnerová, Zdeňka Uřešová, Jenna Kanerva, Stina Ojala, Anna Missilä, Christopher D. Manning, Sebastian Schuster, Siva Reddy, Dima Taji, Nizar Habash, Herman Leung, Marie-Catherine de Marneffe, Manuela Sanguinetti, Maria Simi, Hiroshi Kanayama, Valeria de Paiva, Kira Droganova, Héctor Martínez Alonso, Çağrı

Çöltekin, Umut Sulubacak, Hans Uszkoreit, Vivien Macketanz, Aljoscha Burchardt, Kim Harris, Katrin Marheinecke, Georg Rehm, Tolga Kayadelen, Mohammed Attia, Ali Elkahky, Zhuoran Yu, Emily Pitler, Saran Lertpradit, Michael Mandl, Jesse Kirchner, Hector Fernandez Alcalde, Jana Strnadová, Esha Banerjee, Ruli Manurung, Antonio Stella, Atsuko Shimada, Sookyoung Kwak, Gustavo Mendonça, Tatiana Lando, Rattima Nitisaroj, and Josie Li. 2017. [CoNLL 2017 shared task: Multilingual parsing from raw text to Universal Dependencies](#). In *Proceedings of the CoNLL 2017 Shared Task: Multilingual Parsing from Raw Text to Universal Dependencies*, pages 1–19, Vancouver, Canada. Association for Computational Linguistics.

Sheng Zhang, Xutai Ma, Kevin Duh, and Benjamin Van Durme. 2019a. [AMR parsing as sequence-to-graph transduction](#). In *Proceedings of the 57th Annual Meeting of the Association for Computational Linguistics*, pages 80–94, Florence, Italy. Association for Computational Linguistics.

Sheng Zhang, Xutai Ma, Kevin Duh, and Benjamin Van Durme. 2019b. [Broad-coverage semantic parsing as transduction](#). In *Proceedings of the 2019 Conference on Empirical Methods in Natural Language Processing and the 9th International Joint Conference on Natural Language Processing (EMNLP-IJCNLP)*, pages 3786–3798, Hong Kong, China. Association for Computational Linguistics.

Sheng Zhang, Rachel Rudinger, and Benjamin Van Durme. 2017. [An evaluation of PredPatt and open IE via stage 1 semantic role labeling](#). In *IWCS 2017 — 12th International Conference on Computational Semantics — Short papers*.

Qiji Zhou, Yue Zhang, Donghong Ji, and Hao Tang. 2020. [AMR parsing with latent structural information](#). In *Proceedings of the 58th Annual Meeting of the Association for Computational Linguistics*, pages 4306–4319, Online. Association for Computational Linguistics.