Deep RNNs Encode Soft Hierarchical Syntax

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Abstract

We present a set of experiments to demonstrate that deep recurrent neural networks (RNNs) learn internal representations that capture soft hierarchical notions of syntax from highly varied supervision. We consider four syntax tasks at different depths of the parse tree; for each word, we predict its part of speech as well as the first (parent), second (grandparent) and third level (great-grandparent) constituent labels that appear above it. These predictions are made from representations produced at different depths in networks that are pre-trained with one of four objectives: dependency parsing, semantic role labeling, machine translation, or language modeling. In every case, we find a correspondence between network depth and syntactic depth, suggesting that a soft syntactic hierarchy emerges. This effect is robust across all conditions, indicating that the models encode significant amounts of syntax even in the absence of an explicit syntactic training supervision.

1 Introduction

Deep recurrent neural networks (RNNs) have effectively replaced explicit syntactic features (e.g. parts of speech, dependencies) in state-of-the-art NLP models (He et al., 2017; Lee et al., 2017; Klein et al., 2017). However, previous work has shown that syntactic information (in the form of either input features or supervision) is useful for a wide variety of NLP tasks (Punyakanok et al., 2005; Chiang et al., 2009), even in the neural setting (Aharoni and Goldberg, 2017; Chen et al., 2017). In this paper, we show that the internal representations of RNNs trained on a variety of NLP tasks encode these syntactic features without explicit supervision.

We consider a set of feature prediction tasks drawn from different depths of syntactic parse trees; given a word-level representation, we attempt to predict the POS tag and the parent, grandparent, and great-grandparent constituent labels of that word. We evaluate how well a simple feedforward classifier can detect these syntax features from the word representations produced by the RNN layers from deep NLP models trained on the tasks of dependency parsing, semantic role labeling, machine translation, and language modeling. We also evaluate whether a similar classifier can predict if a dependency arc exists between two words in a sentence, given their representations.

We find that, across all four types of supervision, the representations learned by these models encode syntax beyond the explicit information they encounter during training; this is seen in both the word-level tasks and the dependency arc prediction task. Furthermore, we also observe that features associated with different levels of syntax tree correlate with word representations produced by RNNs at different depths. Largely speaking, we see that deeper layers in each model capture notions of syntax that are higher-level and more abstract, in the sense that higher-level constituents cover a larger span of the underlying sentence.

These findings suggest that models trained on NLP tasks are able to induce syntax even when direct syntactic supervision is unavailable. Furthermore, the models are able to differentiate this induced syntax into a soft hierarchy across different layers of the model, perhaps shedding some light on why *deep* RNNs are so useful for NLP.

2 Methodology

Given a model that uses multi-layered RNNs, we collect the vector representation $\mathbf{x}_i^l$ of each word i at each hidden layer l. To determine what syntactic information is stored in each word vector, we try to predict a series of constituency-based prop-

Training Signal	Dataset	RNN Layers	Input Dims	Hidden Dims
Dependency Parsing	English Universal Dependencies	4 parallel bidirectional LSTMs	200	400
Semantic Role Labeling	CoNLL-2012	8 alternating-direction LSTMs with highways	100	300
Machine Translation	WMT-2014 English-German	4 parallel bidirectional LSTMs	500	500
Language Modeling	CoNLL-2012	2 sets of 4 unidirectional LSTMs with highways	1000	1000

Table 1: The training data, recurrent architecture, and hyperparameters of each model.
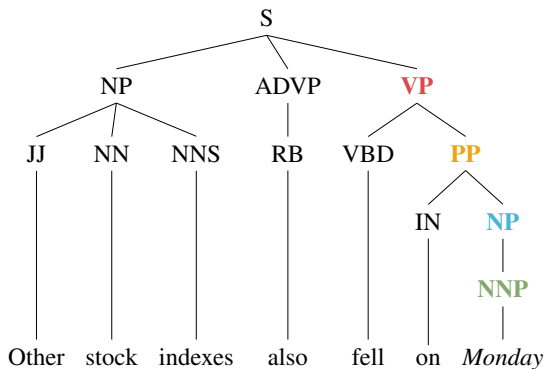

Figure 1: Constituency tree with labels for the word "Monday" for the POS (green), parent constituent (blue), grandparent constituent (orange), and great-grandparent constituent (red) tasks.

erties from the vector alone. Specifically, we predict the word's part of speech (POS), as well as the first (parent), second (grand-parent), and third level (great-grandparent) constituent labels of the given word. Figure 1 shows how these labels correspond to an example constituency tree.

Our methodology follows Shi et al. (2016), who run syntactic feature prediction experiments over a number of different shallow machine translation models, and Belinkov et al. 2017a; 2017b, who use a similar process to study the morphological, part-of-speech, and semantic features learned by deeper machine translation encoders. We extend upon prior work by considering training signals for models other than machine translation, and by applying more stratified word-level syntactic tasks.

2.1 Experiment Setup

We predict each syntactic property with a simple feed-forward network with a single 300-

dimensional hidden layer activated by a ReLU:

$$\mathbf{y}_i^l = \text{SoftMax}(W_2 \text{ReLU}(W_1 \mathbf{x}_i^l)) \quad (1)$$

where i is the word index and l is the layer index within a model. To ensure that the classifiers are not trained on the same data as the RNNs, we train the classifier for each layer l separately using the development set of CoNLL-2012 and evaluate on the test set (Pradhan et al., 2013).

In addition, we compare performance with word-level baselines. We report the per-word majority class baseline; at the POS level, for example, "cat" will be classified as a noun and "walks" as a verb. This baseline outperforms the pre-trained GloVe (Pennington et al., 2014) embeddings on every task. We also consider a contextual baseline, in which we concatenate each word's embedding with the average of its context's embeddings; however, this baseline also performed worse that the reported one.

2.2 Analyzed Models

We consider four different forms of supervision. Table 1 summarizes the differences in data, architecture, and hyperparameters.[1]

Dependency Parsing We train a four-layer version of the Stanford dependency parser (Dozat and Manning, 2017) on the Universal Dependencies English Web Treebank (Silveira et al., 2014). We ran the parser with 4 bidirectional LSTM layers (the default is 3), yielding a UAS of 91.5 and a weighted LAS of 82.18, consistent with the state of the art on CoNLL 2017. Since the parser receives syntactic features as input (POS) and is trained on an explicit syntactic signal, we expect

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[1]While we control for some variables, we mainly rely on existing architectures and hyperparameters that were tuned for the original tasks, limiting the cross-model comparability of absolute performance levels on our syntactic evaluations.
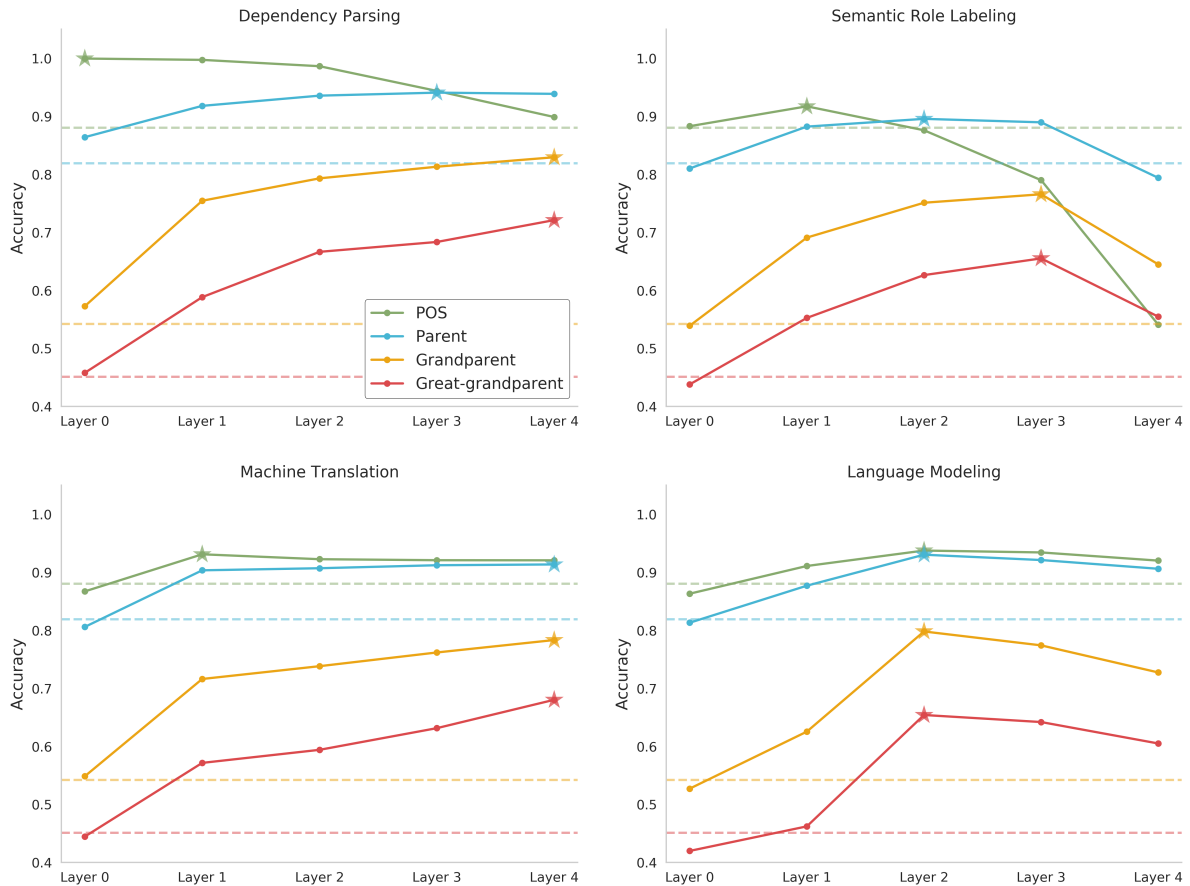
Figure 2: Results of syntax experiments. The best performing layer for each experiment is annotated with a star, and the per-word majority baseline for each task is shown with a dashed line.

its intermediate representations to contain a high amount of syntactic information.

Semantic Role Labeling We use the pre-trained DeepSRL model from (He et al., 2017), which was trained on the training data from the CoNLL-2012 dataset. This model is an alternating bidirectional LSTM, where the model consists of eight total layers that alternate between a forward layer and backward layer. We concatenate the representations from each pair of directional layers in the model for consistency with other models.

Machine Translation We train a machine translation model using OpenNMT (Klein et al., 2017) on the WMT-14 English-German dataset. The encoder (which we examine in our experiments) is a 4-layer bidirectional LSTM; we use the defaults for every other setting. The model achieves a BLEU score of 21.37, which is in the ballpark of other vanilla encoder-decoder attention models on this benchmark (Bahdanau et al., 2015).

Language Modeling We train two separate language models on CoNLL-2012's training set, one going forward and another backward. Each model is a 4-layer LSTM with highway connections, variational dropout, and tied input-output embeddings. After training, we concatenate the forward and backward representations for each layer.[2]

3 Constituency Label Prediction

Figure 2 shows our results (see supplementary material for numerical results). We make several observations:

RNNs can induce syntax. Overall, each model outperforms the baseline and its respective input embeddings on every syntax task, indicating that their internal representations encode some notions

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[2]The model achieved perplexities of 50.56 (forward) and 51.24 (backward) on CoNLL-2012's test set. Since we are not familiar with other perplexity results on this data, we note that retraining the architecture on Penn TreeBank achieved 64.39 perplexity, which is comparable to other high-performing language models.

of syntax. The only exception to this observation is POS prediction with dependency parsing representations; in this case the parser is provided gold POS tags as input, and cannot improve upon them. This result confirms the findings of Shi et al. (2016) and Belinkov et al. (2017b), who demonstrate that neural machine translation encoders learn syntax, and shows that RNNs trained on other NLP tasks also induce syntax.

Deeper layers reflect higher-level syntax. In 11 out of 16 cases, performance improves up to a certain layer and then declines, suggesting that the deeper layers encode less syntactic information that earlier ones in these cases. Strikingly, the higher-level a syntactic task is, the deeper in the network the peak performance occurs; for example, in SRL we see that the parent constituent task peaks one layer after POS, and the grand-parent and great-grandparent tasks peak on the layer after that. One possible explanation is that each layer leverages the shallower syntactic information learned in the previous layer in order to construct a more abstract syntactic representation. In SRL and language modeling, it seems as though the syntactic information is then replaced by task-specific information (semantic roles, word probabilities), perhaps making it redundant.

This observation may also explain a modeling decision in ELMo (Peters et al., 2018), where injecting the contextualized word representations from a pre-trained language model was shown to boost performance on a wide variety of NLP tasks. ELMo represents each word using a task-specific weighted sum of the language model's hidden layers, i.e. rather than use only the top layer, it selects which of the language model's internal layers contain the most relevant information for the task at hand. Our results confirm that, in general, different types of information manifest at different layers, suggesting that post-hoc layer selection can be beneficial.

Language models learn some syntax. We compare the performance of language model representations to those learned with dependency parsing supervision, in order to gauge the amount of syntax induced. While this comparison is not ideal (the models were trained with slightly different architectures and hyperparameters), it does provide evidence that the language model's representations encode some amount of syntax implic-
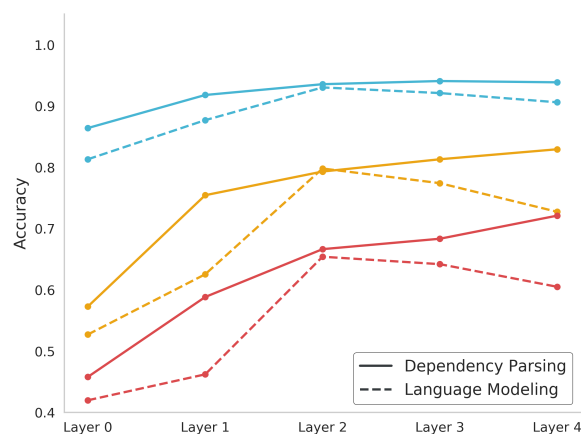

Figure 3: Comparison between the LM and dependency parser on the parent (blue), grandparent (yellow), and great-grandparent (red) constituent prediction tasks.

itly. Specifically, we observe in Figure 3 that the language model and dependency parser perform nearly identically on the three constituent prediction tasks in the second layer of their respective networks. In deeper layers the parser continues to improve, while the language model peaks at layer 2 and drops off afterwards.

These results may be surprising given the findings of Linzen et al. (2016), which found that RNNs trained on language modeling perform below baseline levels on the task of subject-verb agreement. However, the more recent investigation by Gulordava et al. (2018) are in line with our results. They find that language models trained on a number of different languages assign higher probabilities to valid long-distance dependencies than to incorrect ones. Therefore, LMs seem able to induce syntactic information despite being provided with no linguistic annotation.

4   Dependency Arc Prediction

We run an additional experiment that seeks to clarify if the representations learned by deep NLP models capture information about syntactic structure. Using the internal representations from a deep RNN, we train a classifier to predict whether two words share an dependency arc (have a parent-child relationship) in the in the dependency parse tree over a sentence. We find that, similarly to the previous set of tasks, deep RNNs trained on various linguistic signals encode notions of the syntactic relationships between words in a sentence.

Source Model	GloVe	L0	L1	L2	L3	L4
DP	0.50	0.68	0.77	0.81	0.88	**0.95**
SRL	0.50	0.58	0.69	0.76	**0.79**	0.74
MT	0.50	0.61	**0.73**	0.63	0.63	0.63
LM	0.50	0.62	0.74	0.78	**0.80**	0.73

Table 2: Results of the dependency arc prediction task. L0–L4 denote the different layers of the model. DP refers to the RNN trained with dependency parsing supervision.

Setup We use the same pretrained deep RNNs and feed-forward prediction network paradigm. However, we change the input from the previous experiments, as this task is not at the word-level, but rather concerns the relationship between two words; therefore, given a word pair w_c, w_p for which we have a dependency arc label, we input $[w_c; w_p; w_c \circ w_p]$ into the classifier.

We use the Universal Dependencies dataset for this task, such that we train each classifier on the development set of this dataset and evaluate on the test set. We set up the task by generating two pairs of examples for each word in the UD dataset: a positive pair that consists of the word and its parent in the dependency tree, and a negative pair that matches the word with another randomly chosen word from the sentence.

Results The results for this prediction task are given in Table 2. We see the best performance from the dependency parser, finding that the performance for the dependency parser's representations continue to improve in the deepest layers, with a maximum performance of approximately 95% on the last layer. This result is unsurprising, as this closely related to the task on which the model was explicitly trained. In the three other models, we find peaks that occur 12 to 20 accuracy points above the input layer's performance. These results support the findings from the constituency label prediction task and show that these findings hold up across syntactic formalisms.

Similarly to the word-level tasks, we see the best performance from deeper layers in the models, with both SRL and LM performance peaking on the third layer. For the LM, we find that the best performing layer outperforms the initial layer by 18%. This is consistent with our finding in the previous set of experiments, that RNNs encode significant amounts of syntax information even when trained on linguistic tasks without any explicit annotations.

5 Conclusions

In this paper, we run a series of prediction tasks on the internal representations of deep NLP models, and find these RNNs are able to induce syntax without explicit linguistic supervision. We also observe that the representations taken from deeper layers of the RNNs perform better on higher-level syntax tasks than those from shallower layers, suggesting that these recurrent models induce a soft hierarchy over the encoded syntax. These results provide some insight as to why deep RNNs are able to model NLP tasks without annotated linguistic features. Further characterizing the exact aspects of syntax which these models can capture (and perhaps more importantly, those they cannot) is an interesting area for future work.

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A Supplementary Materials for Deep RNNs Encode Soft Hierarchical Syntax

A full list of the accuracy results from the syntax prediction experiments can be found in Table 3.

Source model	Prediction task	MFT	Layer 0	1	2	3	4
DP	POS	0.8801	**0.9990**	0.9964	0.9853	0.9434	0.8962
	Parent	0.8190	0.8681	0.9177	0.9347	**0.9384**	0.9349
	Grandparent	0.5422	0.5721	0.7538	0.7920	0.8094	**0.8253**
	Great-Grandparent	0.4511	0.4648	0.5909	0.6659	0.6826	**0.7183**
SRL	POS	0.8801	0.8732	**0.9063**	0.8691	0.7833	0.5392
	Parent	0.8190	0.7983	0.8727	**0.8892**	0.8835	0.7870
	Grandparent	0.5422	0.5041	0.6812	0.7394	**0.7549**	0.6325
	Great-Grandparent	0.4511	0.4412	0.5415	0.6159	**0.6449**	0.5493
MT	POS	0.8801	0.8618	**0.9274**	0.9198	0.9191	0.9195
	Parent	0.8190	0.8019	0.8975	0.9040	**0.9088**	0.9083
	Grandparent	0.5422	0.5368	0.7072	0.7311	0.7572	**0.7776**
	Great-Grandparent	0.4511	0.4361	0.5631	0.5909	0.6303	**0.6752**
LM	POS	0.8801	0.8608	0.9093	**0.9359**	0.9304	0.9165
	Parent	0.8190	0.8126	0.8724	**0.9232**	0.9137	0.9000
	Grandparent	0.5422	0.5237	0.6251	**0.7862**	0.7606	0.7189
	Great-Grandparent	0.4511	0.4249	0.4702	**0.6423**	0.6302	0.5971

Table 3: Table of accuracy results for the syntax feature prediction experiments with best performing layer in each source model/ prediction task pair in bold. "DP" refers to the dependency parsing model.