Faster Dependency Parsing, More Accurate Unsupervised Parsing

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Q: Did Aristotle have a mobile phone?
A: No, Aristotle did not have a mobile phone.

Q: Explain why.
A: Mobile phones were not invented until the late 20th century, centuries after Aristotle’s death.

A: Did Gauss have a mobile phone?
Yes, Gauss did not have a mobile phone.

Q: Explain why.
A: Mobile phones were not invented until the late 20th century, centuries after Gauss’s death.
Q: Did Aristotle have a mobile phone?
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Q: Explain why.
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A: Did Gauss have a mobile phone?
No, Gauss did not have a mobile phone.

Q: Explain why.
A: Mobile phones were not invented until the late 20th century, centuries after Gauss’s death.
Q: How did Aristotle wash his laundry?
A: Aristotle would have either washed his own laundry by hand, or he would have had someone else do it for him. There were no washing machines during Aristotle’s lifetime.

A: How did Aristotle bake a pizza?
Aristotle would have either baked a pizza by hand, or he would have had someone else do it for him. There were no ovens during Aristotle’s lifetime.

Pizzas didn’t seem to exist before 900 AD. Aristotle lived in 300s BC. The modern pizza is from the 18th/19th century. Ovens have existed for around 30,000 years.

Q: Why did you need to tell me that there were no ovens during Aristotle’s lifetime?
A: You asked how Aristotle baked a pizza, and we can only speculate how he would have done it without the use of modern technology.
Q: How did Aristotle wash his laundry?
A: Aristotle would have either washed his own laundry by hand, or he would have had someone else do it for him. There were no washing machines during Aristotle’s lifetime.

A: How did Aristotle bake a pizza?
Aristotle would have either baked a pizza by hand, or he would have had someone else do it for him. There were no ovens during Aristotle’s lifetime.

*Pizzas didn’t seem to exist before 900 AD. Aristotle lived in 300s BC. The modern pizza is from the 18th/19th century. Ovens have existed for around 30,000 years.*

Q: Why did you need to tell me that there were no ovens during Aristotle’s lifetime?
A: You asked how Aristotle baked a pizza, and we can only speculate how he would have done it without the use of modern technology.
Q: So why wouldn’t Aristotle use his mobile phone to bake the pizza?
A: As we mentioned before, mobile phones were not invented until the late 20th century, so Aristotle would not have had one.

Q: But if he had one, would he be able to use it to bake a pizza?
A: We don’t know for sure, but it’s unlikely. Mobile phones typically don’t get hot enough to bake a pizza.

Q: Could you at least fry an egg with a mobile phone?
A: We don’t know for sure, but it’s unlikely. Mobile phones typically don’t get hot enough to fry an egg.

Q: So what gets hot enough for that?
A: A stove or an oven typically gets hot enough to fry an egg.
Q: What about Gauss, how did he make his pizzas?
A: Gauss would have either baked his pizzas by hand, or he would have had someone else do it for him. There were no ovens during Gauss’s lifetime.

Q: What do you mean ”bake by hand”? Of course there were ovens back then.
A: We don’t know for sure, but it’s unlikely. Mobile phones typically don’t get hot enough to bake a pizza.

Q: I see. But I didn’t ask about mobile phones.
A: You asked how Gauss baked his pizzas, and we can only speculate how he would have done it without the use of modern technology.
Q: What about Gauss, how did he make his pizzas?
A: Gauss would have either baked his pizzas by hand, or he would have had someone else do it for him. There were no ovens during Gauss’s lifetime.

Q: What do you mean ”bake by hand”? Of course there were ovens back then.
A: We don’t know for sure, but it’s unlikely. Mobile phones typically don’t get hot enough to bake a pizza.

Q: I see. But I didn’t ask about mobile phones.
A: You asked how Gauss baked his pizzas, and we can only speculate how he would have done it without the use of modern technology.
Q: Okay. Final question, how do you bake a pizza?
A: You can bake a pizza in an oven, on a stove, or in a microwave.

Q: I asked about you. How do YOU bake a pizza?
A: I bake my pizzas in an oven.
Q: Okay. Final question, how do you bake a pizza?
A: You can bake a pizza in an oven, on a stove, or in a microwave.

Q: I asked about you. How do YOU bake a pizza?
A: I bake my pizzas in an oven.
Q: Not with a mobile phone?
A: No, not with a mobile phone.

Q: Not with a laundry machine?
A: No, not with a laundry machine.

Q: Then with what?
A: With an oven.

Q: Fantastic. Thank you.
A: You’re welcome.
Did Aristotle have a mobile phone?

Did Gauss have a mobile phone?

How did Aristotle make pizza?
Q: Did Aristotle have a mobile phone?
A: What if he had? It’s perhaps a different kind of enquiry than the ones to which we’ve

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Octopuses and Language

Bender and Koller (2020)

But... "There is no data like more data"

Maybe... There is no model like a bigger model?
This Talk

Part 1:
Show how to make dependency parsers faster

Part 2:
Show how to make unsupervised parsers more accurate
This Talk

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Show how to make dependency parsers faster

Part 2:
Show how to make unsupervised parsers more accurate
Dependency Parsing

From the Stanza parser:

- Parsers are not perfect yet!
- The Universal Dependencies Project aims at finding a common dependency formalism for many languages.
Why Dependency Parsing?

- It gives relations directly between words, no “deep” structure which is sometimes redundant.
- This also makes it a better theory for free-word order languages.
- Flexible at modelling non-projectivity.
Side Note: Free Word Order Languages

- In languages with free word order, phrase structure (constituency) grammars don’t make as much sense.
  - E.g., we would need both \( S \rightarrow NP \ VP \) and \( S \rightarrow VP \ NP \), etc. Not very informative about what’s really going on.

- In contrast, the dependency relations stay constant (in Russian, “Sasha gave a book to the girl”):
Graph Parsing for Dependency Parsing

- STAGE 1: Start with a complete graph, all edges connected to each other with some weight
Graph Parsing for Dependency Parsing

- **STAGE 1**: Start with a complete graph, all edges connected to each other with some weight

- **STAGE 2**: Run a maximum spanning tree algorithm to find the highest scoring tree
Where is Time Spent in Parsing?

Time spent on STAGE 1 and STAGE 2:

- Calculated from the Stanza parser
- Most time is spent on inference
The Universal Dependency Project (Nivre et al., 2018) documentation states that (Zmigrod et al. 2020):

*There should be just one node with the root dependency relation in every tree [...]*

https://universaldependencies.org/u/dep/root.html

We ask: **Can we optimally decode a dependency tree with a single-root constraint?** (Stanojević and Cohen, 2021)

Answer: **Yes.** Run asymptotically in quadratic time with an empirical low constant
In the above, we might use as a subroutine an unconstrained parsing algorithm

For example: $O(n^2)$, using our implementation of the Chu-Liu-Edmonds algorithm (CLE) based on data structures from Tarjan (1977)
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## Single-Root Dependency Parsing Algorithms

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The Reweighting Algorithm

Consider the complete graph we start with our inference. If we subtract \( c \) from all edges \( \text{ROOT} \rightarrow w_i \):

- We subtract from all trees the weight \( k \cdot c \) where \( k \) is the number of \( \text{ROOT} \) edges
- We do not change the weight order of trees with the same number of \( \text{ROOT} \) edges
- We may change weight order of trees with different number of \( \text{ROOT} \) edges

**Question**: Can we find \( c \) such that we make the best single-root tree come at the top compared to all other multiple root trees?
The Reweighting Algorithm

**Question:** Can we find $c$ such that we make the best single-root tree come at the top compared to all other multiple root trees?

**Answer:** Yes! Choose $c^* = 1 + n(\max_e w(e) - \min_e w(e))$ where $w(e)$ is the weight of edge $e$ in the complete graph

The Reweighting Algorithm:

- Subtract $c^*$ from all $\text{ROOT} \rightarrow *$ edges in the initial complete graph
- Run an unconstrained tree inference algorithm on the new complete graph
Side Note: the ArcMax Trick

Zhang et al. (2017) show that choosing for each word the highest scoring edge going into that word as parent often gives a valid tree.

Use this as a trick: check if this gives tree (this tree is optimal), if so, don’t run any costly inference – we will go back to that!
Experiment 1A: Unconstrained Inference Speed

With trained weights (unconstrained):

- The CLE algorithm includes an ArcMax-like step in the beginning (by design)
- Tarjan with ArcMax catches up...
With random weights (unconstrained):

- ArcMax-like step no longer works, so Tarjan shines

![Graph](image)
Experiment 2: Single-Root Inference Speed without ArcMax

(a) Trained English input

(b) Random input
Experiment 3: Single-Root Inference Speed with ArcMax

- Random weights not shown - same as without ArcMax
Summary of Part 1

To get optimal complexity for single root, just use:

```python
def reweighting(scores, mst_func):
    scores2 = np.where(np.isinf(scores), np.nan, scores)
    n = scores.shape[0]-1  # number of words
    scores[:, 0] -= 1 + n*(np.nanmax(scores2)-np.nanmin(scores2))
    return mst_func(scores)
```

Our recommendation for optimal single-root dependency parsing (regardless of learning): **ArcMax+Reweighting+Tarjan**
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Unsupervised Parsing
L-PCFGs, the Supervised Case

At node VP:

Outside tree $o =$

Inside tree $t =$

Conditionally independent given the label and the connecting nonterminal

$$p(o, t|VP) = p(o|VP) \times p(t|VP)$$
Inside Outside Strings

• The yield of the orange part is “inside string”

• The yield of the blue part is “outside string”

• We will bootstrap a classifier to predict if a node dominates a pair of (inside, outside) strings
Co-training (Yarowsky, 1995; Blum and Mitchell, 1998)

Roughly! Repeats the following steps (given unlabeled data $U$ and labeled data $L$):

- Train a classifier with one “view” on $L$
- Train a classifier with another “view” on $L$
- Take some (confident) predictions on $U$ from both classifiers and add to $L$

Co-training works best when the two views are conditionally independent given the label
This leads to:

- Take all sentences, and break them all possible ways into inside/outside strings

- Get neural representations for each pair \((i, o)\) as two “views”

- Take a subset of these \(L\), and label them with some heuristics - the label is whether \((i, o)\) has a node that connects them

- Do co-training
What would be the seed dataset to start the co-training process?

- All \((start, end)\) spans for a given sentence have label 1 (are constituents)
- All \((start, end – i)\) for \(i = 1, 2, ..., 6\) have label 0
- Another simple heuristic that relies on casing
How Do We Use These Labels?

Let

- \( p_i(e) \) be the confidence of the classifier for an inside of span \( e \)
- \( p_o(e) \) be the confidence of the classifier for an outside of span \( e \)

Then, for three different types of scores:

- \( \text{score}(e) = p_i(e) \)
- \( \text{score}(e) = p_o(e) \)
- \( \text{score}(e) = p_i(e) \cdot p_o(e) \)

find the tree \( t^* = \arg \max_t \sum_{e \in t} \text{score}(e) \)

Also referred to as span decoding
Results: Penn Treebank (English)

- Results with the inside score
Results: Penn Treebank (English)

- Results with self-training of the inside score
Results: Penn Treebank (English)

- Results with co-training for inside × outside scores
Results: Chinese Treebank

- Left Branching (LB)
- Random Trees
- Right Branching (RB)
- PRPN (Shen et al., 2018)
- ON (Shen et al., 2019)
- Neural PCFG (Kim et al., 2019a)
- Compound PCFG (Kim et al., 2019a)
- Ours

Legend:
- UP Models
- inside
- inside w/ self-training
- inside-outside w/ co-training
Results: Korean Treebank

Unlabeled Sentence-level F1

- **KTB-Full**
  - Left Branching (LB)
  - Right Branching (RB)
  - PRPN (Shen et al., 2018)
  - URNNG (Kim et al., 2019b)
  - DIORA (Drozdov et al., 2019)
  - DIORA-all (Hong et al., 2020)
  - Ours

- **KTB-10**
  - UP Models
  - inside
  - inside w/ self-training
  - inside-outside w/ co-training
Unsupervised constituency parsing can be viewed as a co-training problem.

See the paper for more examples, score functions and error analysis!
Conclusion

- Language is manifested through symbols. Computational systems in general are often symbolic in nature.

- Its intermediate representation, however, can be continuous or symbolic.

- Symbolic: interpretable; Continuous: have a gradient.

- Both have their role. Both can co-exist.
Thank You!

Any questions?

Collaborators

Milos Stanojević

Nickil Maveli