A Dynamic Oracle for Arc-Eager Dependency Parsing

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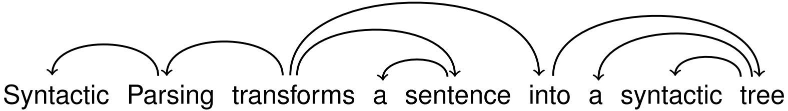
COLING 2012

This talk is about parsing

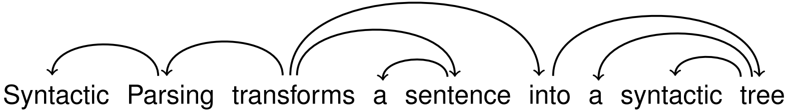
Syntactic Parsing

Syntactic Parsing transforms a sentence into a syntactic tree

Syntactic Parsing



Syntactic Parsing



- A useful signal for various downstream tasks:
  - Entity extraction and resolution
  - Knowledge Acquisition
  - Question Answering (query understanding)
  - Voice-commands
  - Translation

Approaches to parsing

Approaches to parsing

Global Optimization

- **Define** a scoring function over <sentence,tree> pairs.
- **Search** for best-scoring structure.
- Simpler scoring $\Rightarrow$ easier search.

Approaches to parsing

Global Optimization

`argmax over combinatorial space`

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Greedy decoding

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Greedy decoding

- Start with an unparsed sentence.
- Apply **locally-optimal** actions until sentence is parsed.
- **Don’t look back.**

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Greedy decoding

`while (!done) { do best thing }`

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- Apply **locally-optimal** actions until sentence is parsed.
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Approaches to parsing

Global Optimization `argmax over combinatorial space`

- Accurate (best we have).
- Well studied.
- Well understood.
- Strong theoretical foundations.

Greedy decoding `while (!done) { do best thing }`

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Greedy decoding

`while (!done) { do best thing }`

- Use whatever features you want.
- Surprisingly accurate.
- Can be extremely fast.

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Greedy decoding `while (!done) { do best thing }`

- Use whatever features you want.
- Surprisingly accurate.
- Can be extremely fast.
- Still less accurate than search-based.
- Very little theoretical work.
- Not well understood.

Main question motivating this work

What's the best we can do with the greedy approach?

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Practical:

Better fast parsers!

- Provide accurate results.
- ...without paying for more machines.

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Practical:

Better fast parsers!

- Provide accurate results.
- ...without paying for more machines.

Academic:

Incremental processing!

- Human processing probably more similar to greedy than to search.
- Cool learning problem.
- If we understand greedy better, we may do better on search-based.

The old world
(up until mid-2012)

Intro to Transition-based Dependency Parsing

An abstract machine composed of a **stack** and a **buffer**.

Machine is initialized with the words of a sentence.

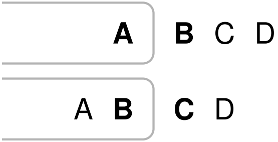
A set of actions process the words by moving them from buffer to stack, removing them from the stack, or adding links between them.

A specific set of actions define a transition system.

The Arc-Eager Transition System

- **SHIFT** move first word from buffer to stack.

  (pre: Buffer not empty.)



The Arc-Eager Transition System

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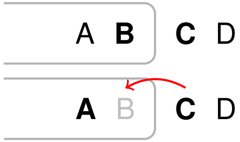
  (pre: Stack not empty. Top of stack does not have a parent.)



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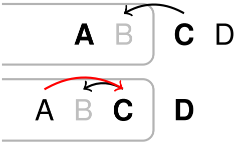

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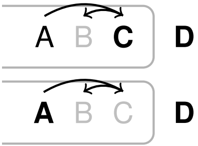
- **RIGHTARC**$_{label}$ make top of stack head of first in buffer, move first in buffer to stack.
  (pre: Buffer not empty.)
- **REDUCE** pop the stack
  (pre: Stack not empty. Top of stack has a parent.)



Parsing Example

She ate pizza with pleasure

Parsing Example

She ate pizza with pleasure

Parsing Example

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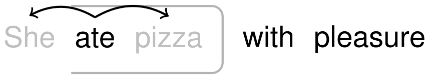

Parsing Example

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Parsing Example

What do we know about the arc-eager transition system?

- Every sequence of actions result in a valid projective structure.
- Every projective tree is derivable by (at least one) sequence of actions.
- **Given a tree, finding a sequence of actions for deriving it. ("static oracle")**

Parsing Algorithm

```
sequence ← oracle(sentence, tree)
configuration ← initialize(sentence)
while not configuration.IsFinal() do
    action ← sequence.next()
    configuration ← configuration.apply(action)
return configuration.tree
```

Parsing Algorithm

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Parsing Algorithm

summarize the configuration
as a feature vector

start with weight vector w
configuration $\leftarrow$ initialize(sentence)
while not configuration.IsFinal() **do**
    action $\leftarrow$ predict(w, ϕ(configuration))
    configuration $\leftarrow$ configuration.apply(action)
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Parsing Algorithm

summarize the configuration
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while not configuration.IsFinal() **do**
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predict the action based on the features

Parsing Algorithm

summarize the configuration
as a feature vector

start with weight vector w
configuration ← initialize(sentence)
while not configuration.IsFinal() **do**
    action ← predict(w, ϕ(configuration))
    configuration ← configuration.apply(action)
return configuration.tree

predict the action based on the features

need to learn the correct weights

Training Algorithm

Learning a parser (online)

$w \leftarrow 0$
for sentence,tree pair in corpus **do**
  sequence $\leftarrow$ oracle(sentence, tree)
  configuration $\leftarrow$ initialize(sentence)
  while not configuration.IsFinal() **do**
    action $\leftarrow$ sequence.next()
    features $\leftarrow \phi$(configuration)
    predicted $\leftarrow$ predict(w, ϕ(configuration))
    if predicted $\neq$ action **then**
      w.update(ϕ(configuration), action, predicted)
    configuration $\leftarrow$ configuration.apply(action)
return w

The new world
(2012 -)

How can we improve the training procedure?

How can we improve the training procedure?

re-examine the process.

Another look at training

Algorithm: Training with a static oracle

$w \leftarrow 0$
for sentence,tree pair in corpus **do**
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  while not conf.IsFinal() **do**
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w ← 0
for sentence,tree pair in corpus do
    sequence ← oracle(sentence, tree)
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    while not conf.IsFinal() do
        action ← sequence.next()
        predicted ← predict(w, φ(conf))
        if predicted ≠ action then
            w.update(φ(conf), action, predicted)
        conf ← conf.apply(action)
return w
```

Another look at training

Algorithm: Training with a static oracle

$w \leftarrow 0$
for sentence,tree pair in corpus **do**
  sequence $\leftarrow$ oracle(sentence, tree)
  conf
  while
    ac
    pr
    if
      d)
    conf $\leftarrow$ conf.apply(action)
return w

Oracle produces a static, **single** sequence of actions to follow.

Often, **many** sequences lead to the gold tree (spurious ambiguity)

Spurious Ambiguity

he wrote her a letter

Spurious Ambiguity

he wrote her a letter

SH

Spurious Ambiguity

he wrote her a letter

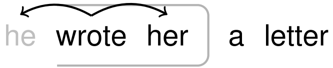
SH LEFT

Spurious Ambiguity

he wrote her a letter

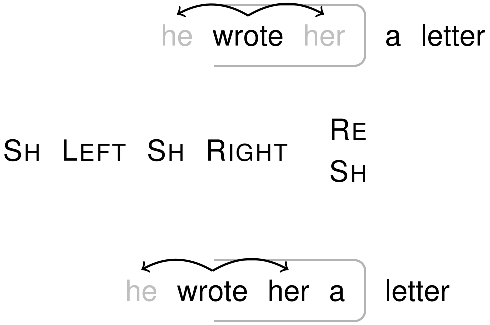
SH LEFT SH

Spurious Ambiguity



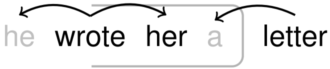
SH LEFT SH RIGHT

Spurious Ambiguity



Spurious Ambiguity

SH LEFT SH RIGHT RE SH
SH LEFT



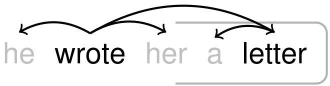
Spurious Ambiguity

Sh Left Sh Right

Re Sh Left

Sh Left Re

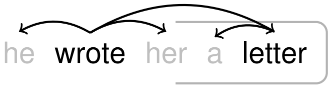
Spurious Ambiguity



SH LEFT SH RIGHT

RE SH LEFT RIGHT

SH LEFT RE RIGHT



Spurious Ambiguity

SH	LEFT	SH	RIGHT		RE	SH	LEFT	RIGHT
					SH	LEFT	RE	RIGHT

Which sequence is better?

Spurious Ambiguity

SH	LEFT	SH	RIGHT

RE	SH	LEFT	RIGHT
SH	LEFT	RE	RIGHT

Which sequence is easier to learn?

Spurious Ambiguity

Currently, oracles always prefer SH in a SH/RE conflict.

This is a reasonable choice:
preferring RE often leads to somewhat worse scores.

But maybe we should let the classifier
choose in a context-dependent way?

Which sequence is easier to learn?

Replacing the static oracle

Algorithm: Training with a dynamic oracle

$w \leftarrow 0$
for sentence,tree pair in corpus **do**
  sequence $\leftarrow$ oracle(sentence, tree)
  conf $\leftarrow$ initialize(sentence)
  while not conf.IsFinal() **do**
    predicted $\leftarrow$ predict(w, ϕ(conf))
    action $\leftarrow$ sequence.next()
    if predicted $\neq$ action **then**
      w.update(ϕ(conf), action, predicted)
    conf $\leftarrow$ conf.apply(action)
return w

Replacing the static oracle

Algorithm: Training with a dynamic oracle

```
w ← 0
for sentence,tree pair in corpus do

    conf ← initialize(sentence)
    while not conf.IsFinal() do
        predicted ← predict(w, φ(conf))
        action ← predicted
        if not is_allowed(predicted, conf, tree) then
            action ← highest scoring allowed action
            w.update(φ(conf), action, predicted)
        conf ← conf.apply(action)
return w
```

Replacing the static oracle

Algorithm: Training with a dynamic oracle

$w \leftarrow 0$
for sentence,tree pair in corpus **do**

> Instead of producing a single sequence upfront, the oracle is dynamically queried at each step.

    while not conf.is_final() **do**
        predicted $\leftarrow$ predict(w, ϕ(conf))
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return w

> Great! but...where do
> we find such an oracle?

The static oracle
is a function from a **tree** to a **sequence** of actions.

What we really want
is a function from a **configuration** to a **set** of actions.

The function should answer
"if we take action A at configuration C, can we still reach the gold tree?"

Reachability

Easy question: Arc Reachability

I am at configuration C. Is there a sequence of actions that will result in the addition of arc (i, j)*?*

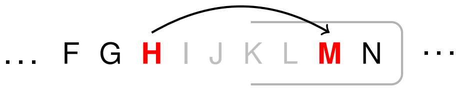
Solution

It is very easy to construct such a sequence or prove that it cannot exist.

Arc Reachability in Arc-eager

Reachability of arc (H,M)

Trivial case: (H,M) was already derived – it’s reachable.



Arc Reachability in Arc-eager

Reachability of arc (H,M)

In order to add (H,M) we need:

- one item on top of stack, and the other first on buffer.
- Modifier should not have a head

. . . F G **H** I J K L **M** N . . .

Arc Reachability in Arc-eager

Reachability of arc (H,M)

If one or more items are reduced, can't add.

... F G H I J K L **M** N ...

Arc Reachability in Arc-eager

Reachability of arc (H,M)

If both items are on stack, can't add.

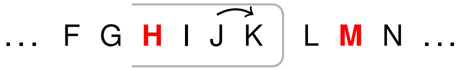
… F G **H** I J K L **M** N …

Arc Reachability in Arc-eager

Reachability of arc (H,M)

One item on the buffer and other on the stack:

1. SHIFT until M if first in buffer.

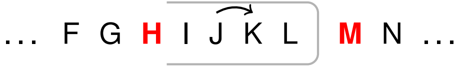


Arc Reachability in Arc-eager

Reachability of arc (H,M)

One item on the buffer and other on the stack:

1. SHIFT until M if first in buffer.
2. LEFT or REDUCE until H on top of stack.



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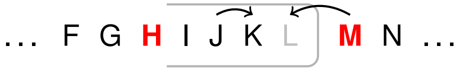

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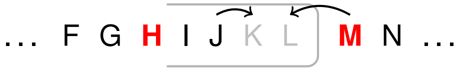

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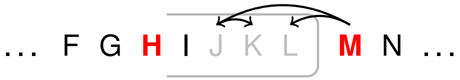

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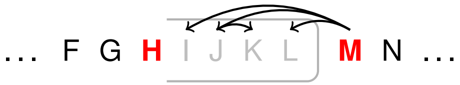
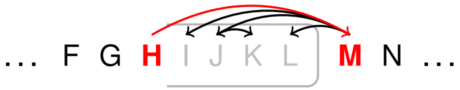


Arc Reachability in Arc-eager

Reachability of arc (H,M)

One item on the buffer and other on the stack:

1. SHIFT until M if first in buffer.
2. LEFT or REDUCE until H on top of stack.
3. Add (H,M).



Arc Reachability in Arc-eager

Reachability of arc (H,M)

Arc Reachability in Arc-eager

Reachability of arc (H,M)

Both items are on the buffer:

1. SHIFT until one of them is on the stack.

… F	G **H** I J K L **M** N …

Arc Reachability in Arc-eager

Reachability of arc (H,M)

Both items are on the buffer:

1. SHIFT until one of them is on the stack.
2. And we already did this case..

… F G **H** I J K L **M** N …

Arc Reachability in Arc-eager

Reachability of arc (H,M)

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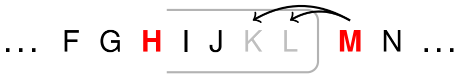

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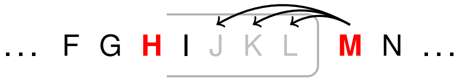

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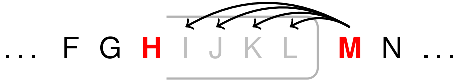

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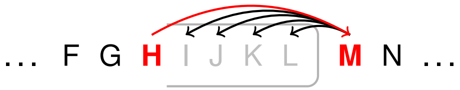

Arc Reachability in Arc-eager

Reachability of arc (H,M)

We can add arc (h,m) iff:

- The arc (h,m) already exist.
- *m* is not assigned a parent.
- either:
  - both *m* and *h* are on buffer,
  - one of them is on stack and other is on buffer.

Reachability

Easy question: Arc Reachability

I am at configuration C. Is there a sequence of actions that will result in the addition of arc (i, j)*?*

Solution

It is very easy to construct such a sequence or prove that it cannot exist.

- For all transitions systems we know of, this can be answered in O(1), perhaps after a O(n) preprocessing.

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- For all transitions systems we know of, this can be answered in O(1), perhaps after a O(n) preprocessing.

The question we care about: Arc Set Reachability

*I am at configuration C. Is there a sequence of actions that will result in the addition of **all** the arcs $(i_1, j_1) \cdots (i_k, j_k)$?*

Reachability

Easy question: Arc Reachability

I am at configuration C. Is there a sequence of actions that will result in the addition of arc (i, j)?

Solution

It is ve… that it canno…

This is easy because we do not care about the other actions in the sequence

- For all transitions systems we know of, this can be a… …ssing.

This is hard because actions can interact with each other

The question we care about: Arc Set Reachability

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A formal property

Definition

A transition system is **arc decomposable** if it satisfies the following property:

If a set of arcs $\mathcal{A}$ are individually reachable from a configuration C, then every subset of them which can be extended to form a projective spanning tree is reachable from configuration C.

The good stuff

Theorem (stated without proof)

The ArcEager *system is arc decomposable.*

The good stuff

Theorem (stated without proof)

The ARCEAGER *system is arc decomposable.*

Corollary

We can work in terms of reachable arcs and reason about reachable structures.

A Dynamic Oracle

If we can reach all the gold arcs individually, we can reach the gold tree.

⇓

Stay in configurations from which all gold arcs are reachable.

A Dynamic Oracle

If we can reach all the gold arcs individually, we can reach the gold tree.

↓

Stay in configurations from which all gold arcs are reachable.

$$allowed\_actions(conf, \mathcal{G}) =$$

$$\{action \mid reachable\_arcs(conf.apply(action)) \supseteq \mathcal{G}\}$$

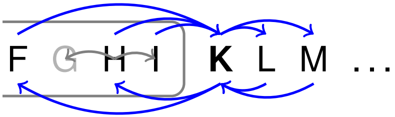
Can calculate which arcs are lost by each action

Example: SHIFT

K is moved from buffer to stack.

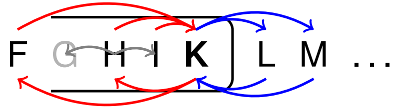
Before SHIFT

K on buffer:
- can be modifier of all visible items - can be head of all head-less visible items



After SHIFT

K on stack:
- cannot head stack items
- cannot modify stack items



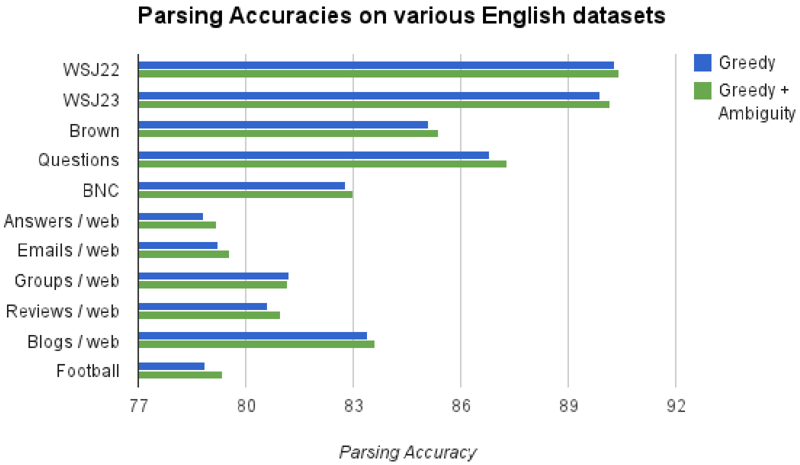
Replacing the static oracle

Algorithm: Training with a dynamic oracle

```
w ← 0
for sentence,tree pair in corpus do

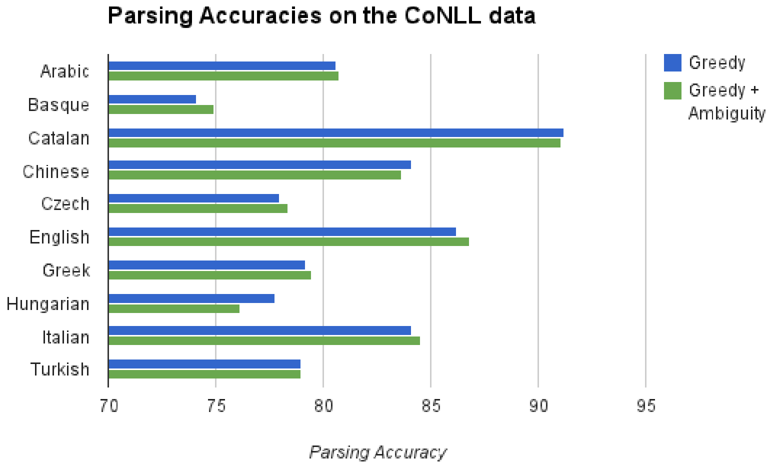
    conf ← initialize(sentence)
    while not conf.IsFinal() do
        predicted ← predict(w, ϕ(conf))
        action ← predicted
        if not is_allowed(predicted, conf, tree) then
            action ← highest scoring allowed action
            w.update(ϕ(conf), action, predicted)
        conf ← conf.apply(action)
return w
```

Some numbers: training with spurious ambiguity



avg: 0.25 max: 0.5

Some numbers: training with spurious ambiguity



avg: 0.03 max: 0.8

Some numbers: training with spurious ambiguity

mostly beneficial.

Some numbers: training with spurious ambiguity

but we are not done yet!

Another look at training, take 2

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Another look at training, take 2

oracle

Always following a correct action.

At training, parser never sees the result of incorrect actions.

o

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    action ← predicted
    if not is_allowed(predicted, conf, tree) **then**
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So what?

Always taking an allowed action is bad!

Training is attempting to learn the optimal action for a configuration

So what?

Always taking an allowed action is bad!

Training is attempting to learn the optimal action for a configuration, **assuming that all previous actions were correct!**

So what?

Always taking an allowed action is bad!

Training is attempting to learn the optimal action for a configuration, **assuming that all previous actions were correct!**

At parsing time, we may make a mistake

Once we err once in parsing time, the training assumptions no longer hold:

- We may reach a configuration we haven't seen before.
- We may need to react differently to configurations we *have* seen before.

always try to make the training conditions
as similar as possible to the testing conditions!

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We need to expose the parser to configurations
that result from following incorrect actions,
and to the **optimal actions** to take in these
configurations.

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that result from following incorrect actions,
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configurations.

What's the optimal action?

The oracles so far

are well defined **only** for configurations which can **lead to the gold tree.**

What we really want

an oracle which is **well defined** and **optimal** for **every possible configuration.**

What does it mean to behave optimally after a mistake?

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A reasonable definition of optimality

- If gold-tree is reachable: allow actions leading to gold tree.
- If gold-tree is **not** reachable: allow actions leading to the **best reachable tree**.

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"Best reachable tree"

- a reachable tree with minimum hamming loss to gold tree.

$\Rightarrow$ under arc decomposition: a tree containing all the reachable arcs from the gold tree

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"Best reachable tree"

- a reachable tree with minimum hamming loss to gold tree.

$\Rightarrow$ under arc decomposition: a tree containing all the reachable arcs from the gold tree

Thanks to arc-decomposition

- A small tweak to our oracle will make it **behave optimally for any configuration**
- and return a cost for each action/configuration pair.

Actions' costs and optimal actions

The cost of an action *a* at a configuration *C*

The number of gold arcs that are reachable from *C* but cannot be reached after taking action *a*.

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$$lost\_arcs(action, conf) = reachable\_arcs(conf) \setminus reachable\_arcs(conf.apply(action)) \quad (1)$$

$$action\_cost(action, conf, gold) = |lost\_arcs(action, conf) \cap gold| \quad (2)$$

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Optimal actions have a cost of 0

There is always an optimal action.

Algorithm: Training with a dynamic oracle and exploration

$w \leftarrow 0$
for sentence,tree pair in corpus **do**
    conf $\leftarrow$ initialize(sentence)
    while not conf.IsFinal() **do**
        predicted $\leftarrow$ predict(w, ϕ(conf))
        action $\leftarrow$ highest scoring allowed action
        if action_cost(predicted, conf, tree)!= 0 **then**
            w.update(ϕ(conf), action, predicted)
        conf $\leftarrow$ conf.apply(action)
return w

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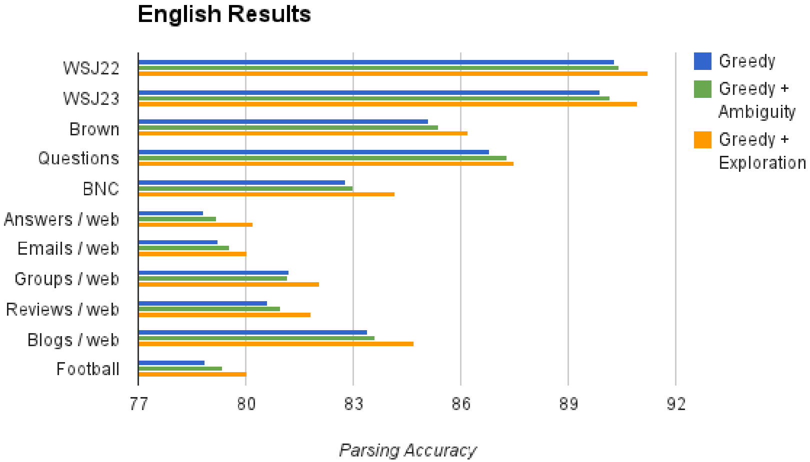
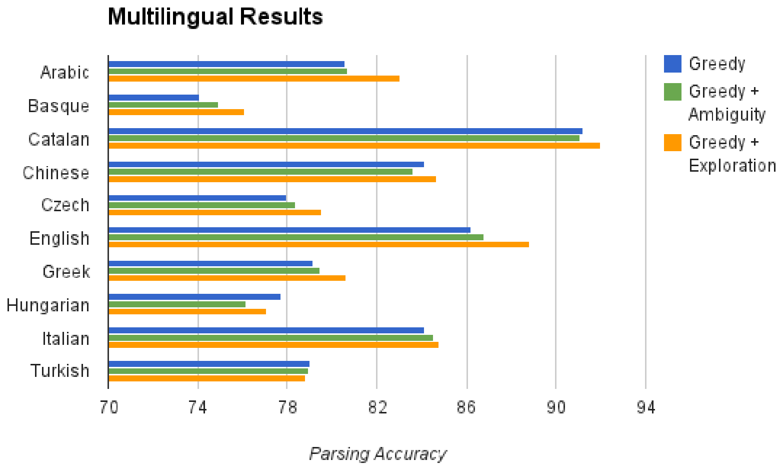
for sentence,tree pair in corpus **do**
  conf $\leftarrow$ initialize(sentence)
  while not conf.IsFinal() **do**
    predicted $\leftarrow$ predict(w, ϕ(conf))
    action $\leftarrow$ highest scoring allowed action
    if action_cost(predicted, conf, tree)!= 0 **then**
      w.update(ϕ(conf), action, predicted)
    sometimes
      conf $\leftarrow$ conf.apply(action)
    other times
      conf $\leftarrow$ conf.apply(predicted)
return w

Some numbers: training with exploration



avg: 1.1 max: 1.4

Some numbers: training with exploration



avg: 1.1 max: 2.6

Some numbers: training with exploration

Very meaningful improvements on (almost) all datasets.

Reachability + arc-decomposition: a strong tool

Concrete things we now have

- Able to calculate $lost\_arcs(action, conf)$.
- "Dynamic" oracle which is optimal for every configuration (and can work with partial evidence)
- Parsing algorithm for training with the dynamic oracle.
- More accurate deterministic parsing.

Take home:

Overall

- Better understanding $\Rightarrow$ better algorithms $\Rightarrow$ better results

Parser Users:

- Greedy parsers which are as-fast but more accurate than before.
- Ability to relate parsing mistakes to specific actions.

Parsing researchers:

- Stop using static-oracles. Our dynamic one is better.
- Training with spurious ambiguity can help.
- Do exploration when training whenever possible.
- A new way to reason about transition systems.

Extra

Some things we did not know (all related):

- How does an action affect the set of reachable structures?
  - It removes all structures containing the set of arcs which are “lost” by the action.
- What is the set of projective structures reachable from an arbitrary configuration?
  - All the projective structures which can be built from reachable arcs.
- What does a “SHIFT” mean?
  - Arc-Eager: “token on the buffer collected all its left modifiers, and is expecting a head to its right.”

For ML people

Does this remind you of **searn**? it should!

- Our "optimal everywhere" dynamic oracle is a good policy in the searn sense.
- Earlier attempts to use searn for parsing didn't work.
  - ⇒ They were missing the policy component.
- Now its available.