CS447: Natural Language Processing

http://courses.engr.illinois.edu/cs447

Lecture 17: Dependency Grammar

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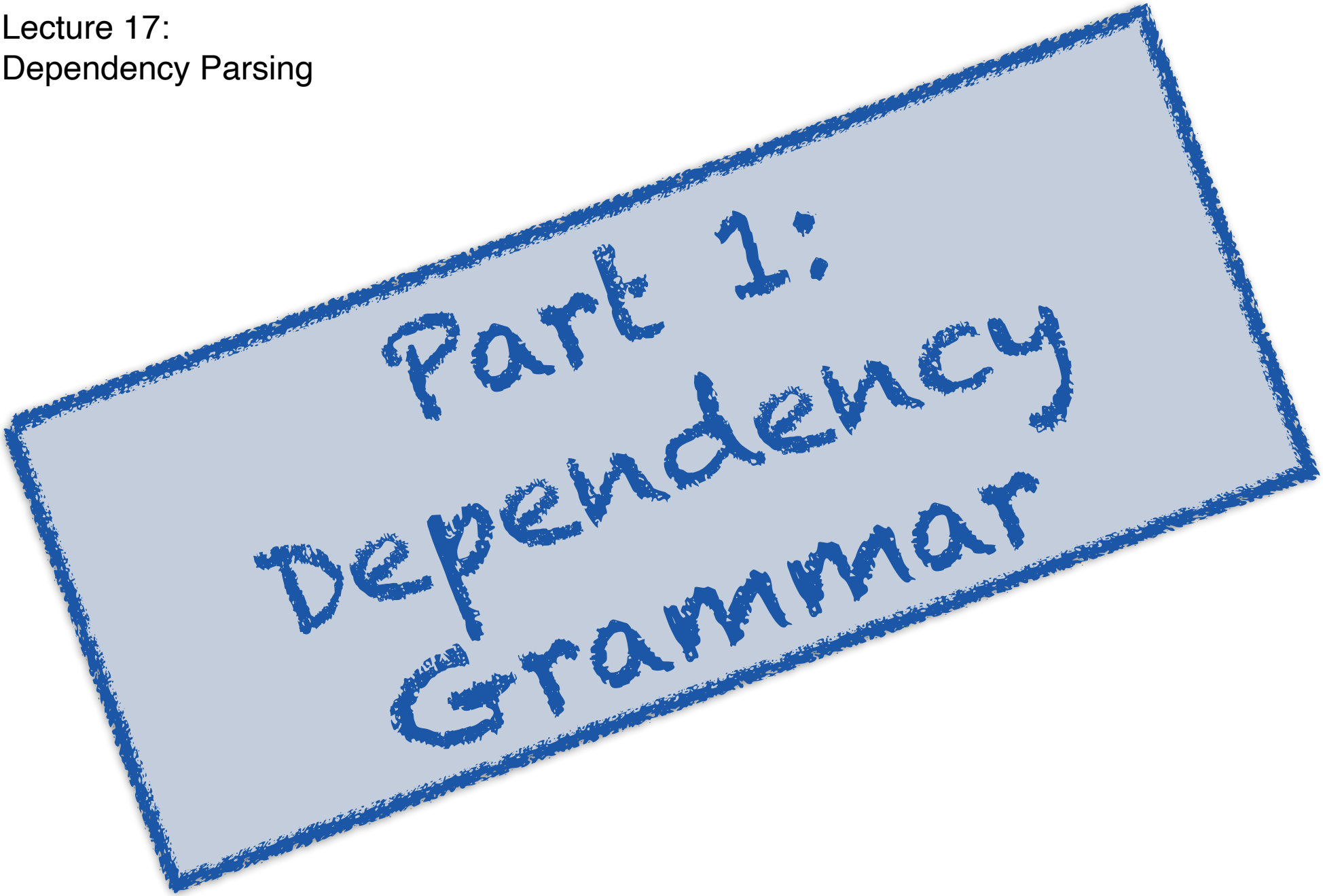
Lecture 17:
Dependency Parsing



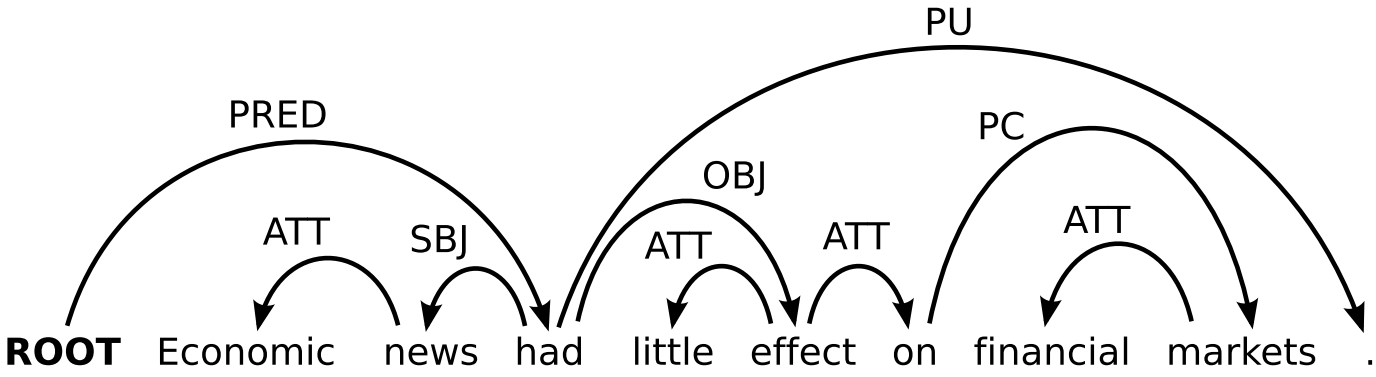
Today's lecture

Part 1: Dependency Grammar

Part 2: Dependency Treebanks

Part 3: Dependency Parsing

A dependency parse



Dependencies are (labeled) asymmetrical binary relations between two lexical items (words).

had —OBJ—> *effect* [*effect* is the object of *had*]

effect —ATT—> *little* [*little* is an attribute of *effect*]

We typically assume a special ROOT token as word 0

The popularity of Dependency Parsing

Currently the main paradigm for syntactic parsing.

Dependencies are easier to use and interpret
for downstream tasks than phrase-structure trees.

For languages with free word order, dependencies
are more natural than phrase-structure grammars

Dependency treebanks exist for many languages.

The Universal Dependencies project has dependency treebanks for dozens of languages that use a similar annotation standard.

Dependency grammar

Word-word dependencies are a component of many (most/all?) grammar formalisms.

Dependency grammar assumes that syntactic structure consists *only* of dependencies.

Many variants. Modern DG began with Tesniere (1959).

DG is often used for **free word order languages**.

DG is **purely descriptive** (not generative like CFGs etc.), but some formal equivalences are known.

Dependency trees

Dependencies form a graph over the words in a sentence.

This graph is **connected** (every word is a node) and (typically) **acyclic** (no loops).

Single-head constraint:
Every node has at most **one incoming edge (each word has one parent)**

Together with connectedness, this implies that the graph is a **rooted tree**.

Different kinds of dependencies

Head-argument: *eat sushi*

Arguments may be obligatory, but can only occur once.
The head alone cannot necessarily replace the construction.

Head-modifier: *fresh sushi*

Modifiers are optional, and can occur more than once.
The head alone can replace the entire construction.

Head-specifier: *the sushi*

Between function words (e.g. prepositions, determiners)
and their arguments. Here, syntactic head ≠ semantic head

Coordination: *sushi and sashimi*

Unclear where the head is.

There isn't one right dependency grammar

Some constructions can be represented in many different ways.
Different treebanks use different conventions:

Prepositional phrases (sushi [with wasabi])
Use the lexical head (the noun) as head (sushi→wasabi, wasabi→with),
or the functional head (thepreposition) (sushi→with, with→wasabi)

Verb clusters, complex tenses (I [will have done] this)
Which verb is the head? The main verb (done), or the auxiliaries?

Coordination (eat [sushi and sashimi], [sell and buy] shares)

eat→and, and→sushi, and→sashimi
or (e.g.) eat→sushi, sushi→and, sushi→sashimi, etc.

Relative clauses (the cat [that I thought I saw])
These include non-local dependencies (saw-cat) [future lecture]

NB: Some constructions (e.g. coordination, relative clauses) break the assumption that each word has only one parent, and dependency trees cannot represent them correctly.

From CFGs to dependencies

Assume each CFG rule has **one head child** (bolded)

The other children are **dependents** of the head.

S	→ NP **VP**	**VP** is head, NP is a dependent
VP	→ **V** NP NP	**V** is head, both NPs are dependents
NP	→ DT **NOUN**	
NOUN	→ ADJ **N**	

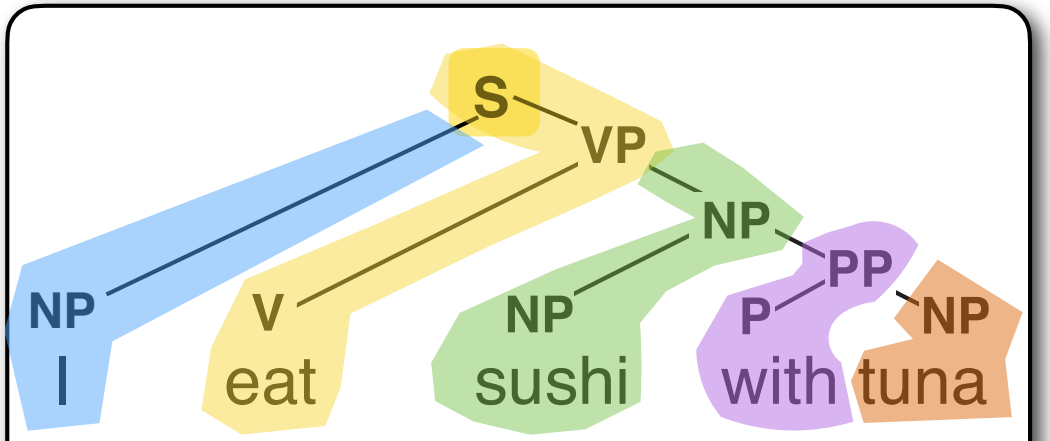
The **headword** of a constituent is the terminal that is reached by recursively following the head child.

(here, V is the head word of S, and N is the head word of NP).

If in rule XP → **X** Y, X is head child and Y dependent, the headword of Y depends on the headword of X.

The **maximal projection** of a terminal *w* is the highest nonterminal in the tree that *w* is headword of.
Here, Y is a maximal projection.

From CFGs to dependencies



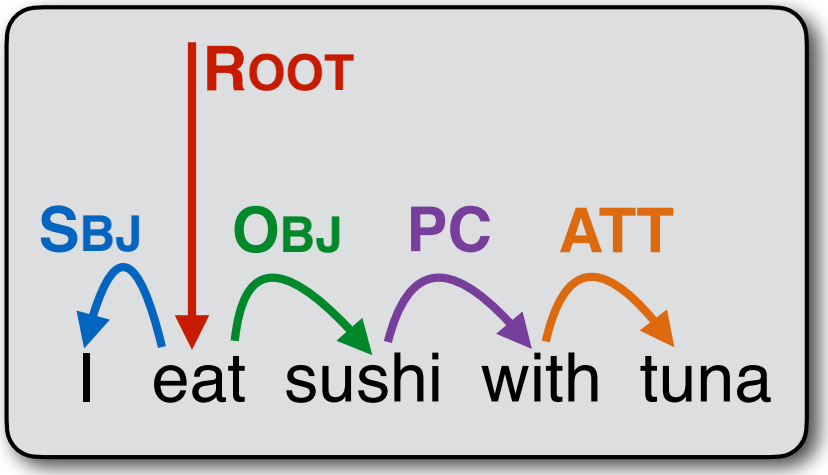
CFG (bold = head child):

S → NP **VP**

VP → **V** NP

NP → **NP** PP

PP → **P** NP



Start at the **root** of the tree (S)

Follow the **head path** ('**spine**' of the tree) to the **head word** of the sentence ('eat').

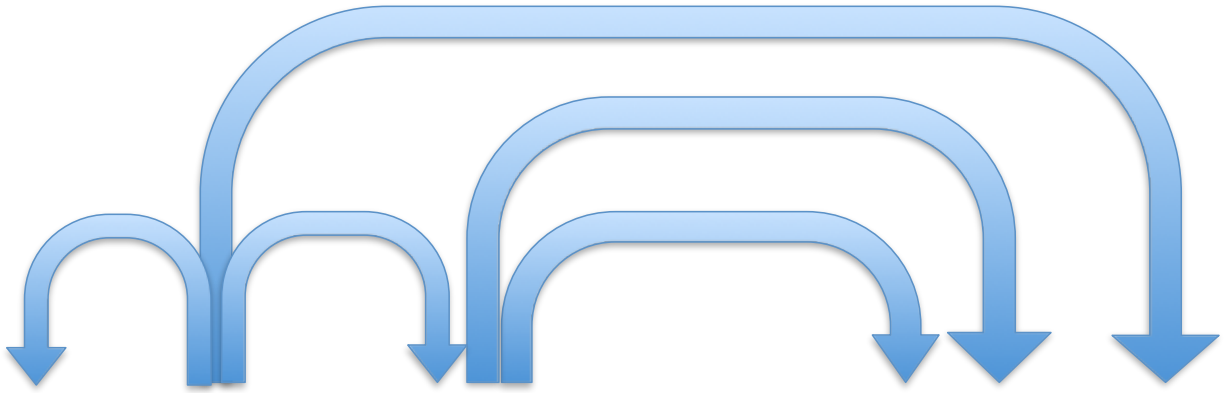
Add a ROOT dependency to this word.

For all other **maximal projections**: follow their head paths to get their head words and add the corresponding dependencies

Context-free grammars

CFGs capture only **nested** dependencies

- The dependency graph is a **tree**
- The dependencies **do not cross**

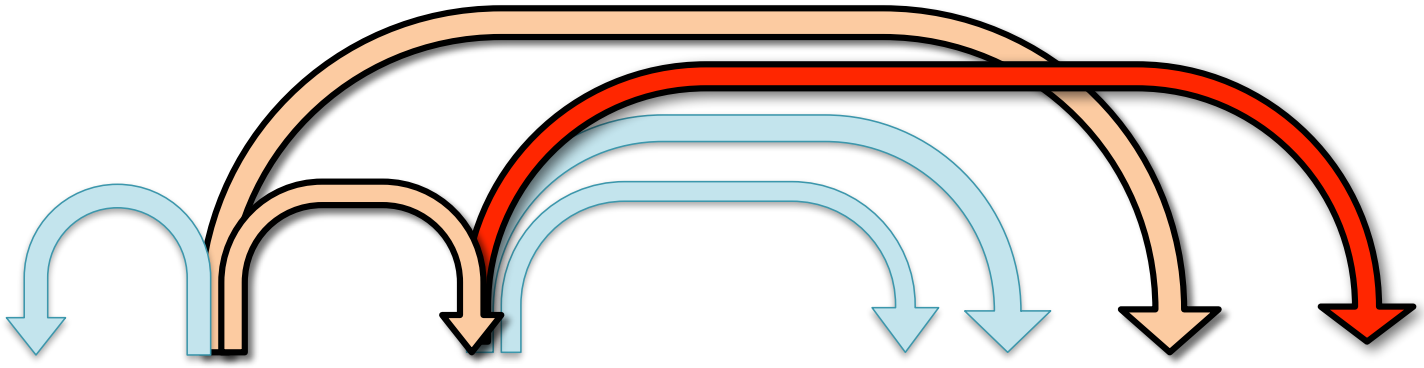


Beyond CFGs: Nonprojective dependencies

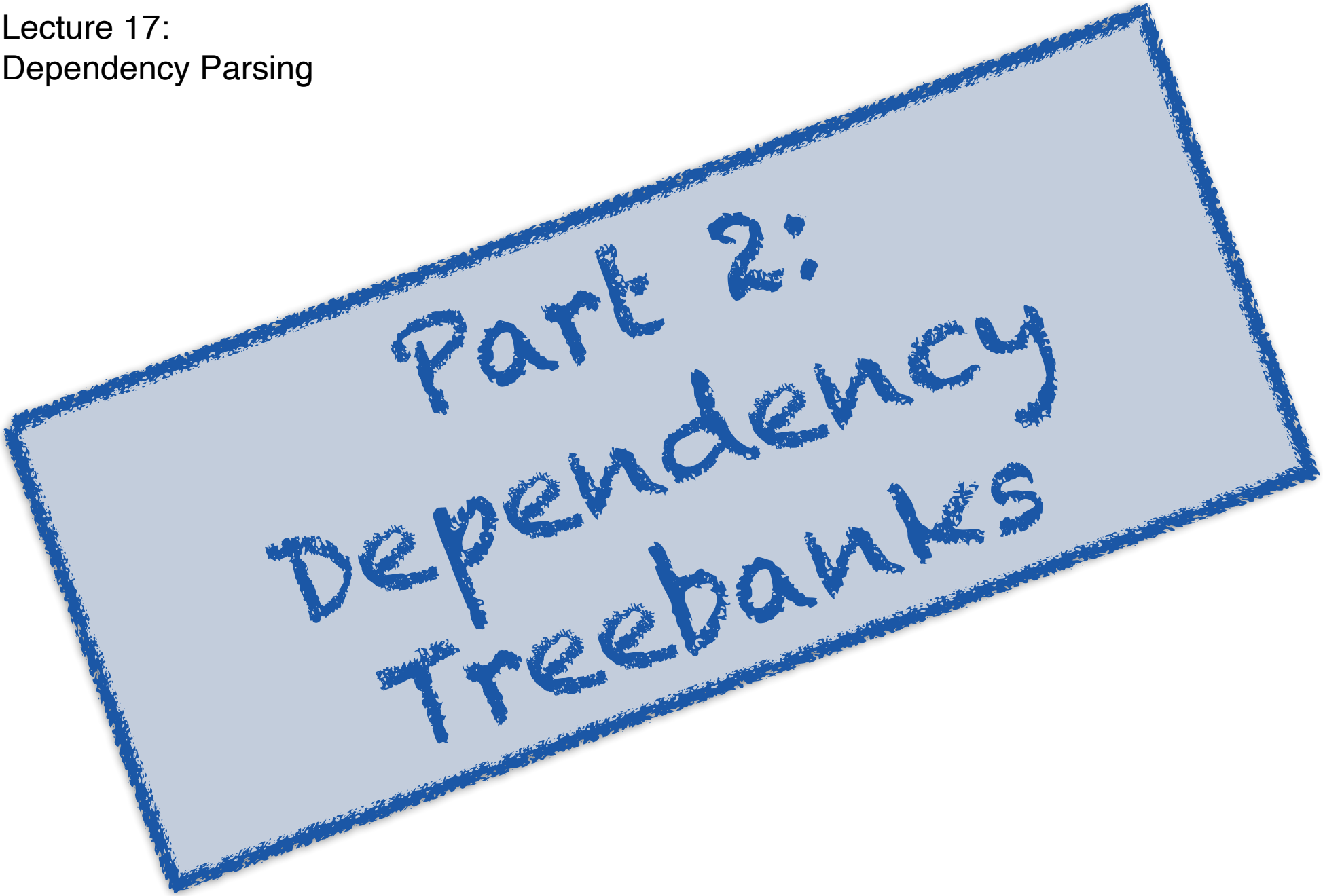
Dependencies: tree with crossing branches

Arise in the following constructions

- (Non-local) **scrambling** (free word order languages)
  Die Pizza *hat Klaus* ***versprochen*** *zu* ***bringen***
- **Extraposition** (*The* ***guy*** *is* ***coming*** ***who is wearing a hat****)*
- **Topicalization** *(****Cheeseburgers****, I* ***thought*** *he* ***likes****)*



Lecture 17:
Dependency Parsing



Dependency Treebanks

Dependency treebanks exist for many languages:

- Czech
- Arabic
- Turkish
- Danish
- Portuguese
- Estonian
- ....

Phrase-structure treebanks (e.g. the Penn Treebank) can also be translated into dependency trees (although there might be noise in the translation)

The Prague Dependency Treebank

2M words, three levels of annotation:

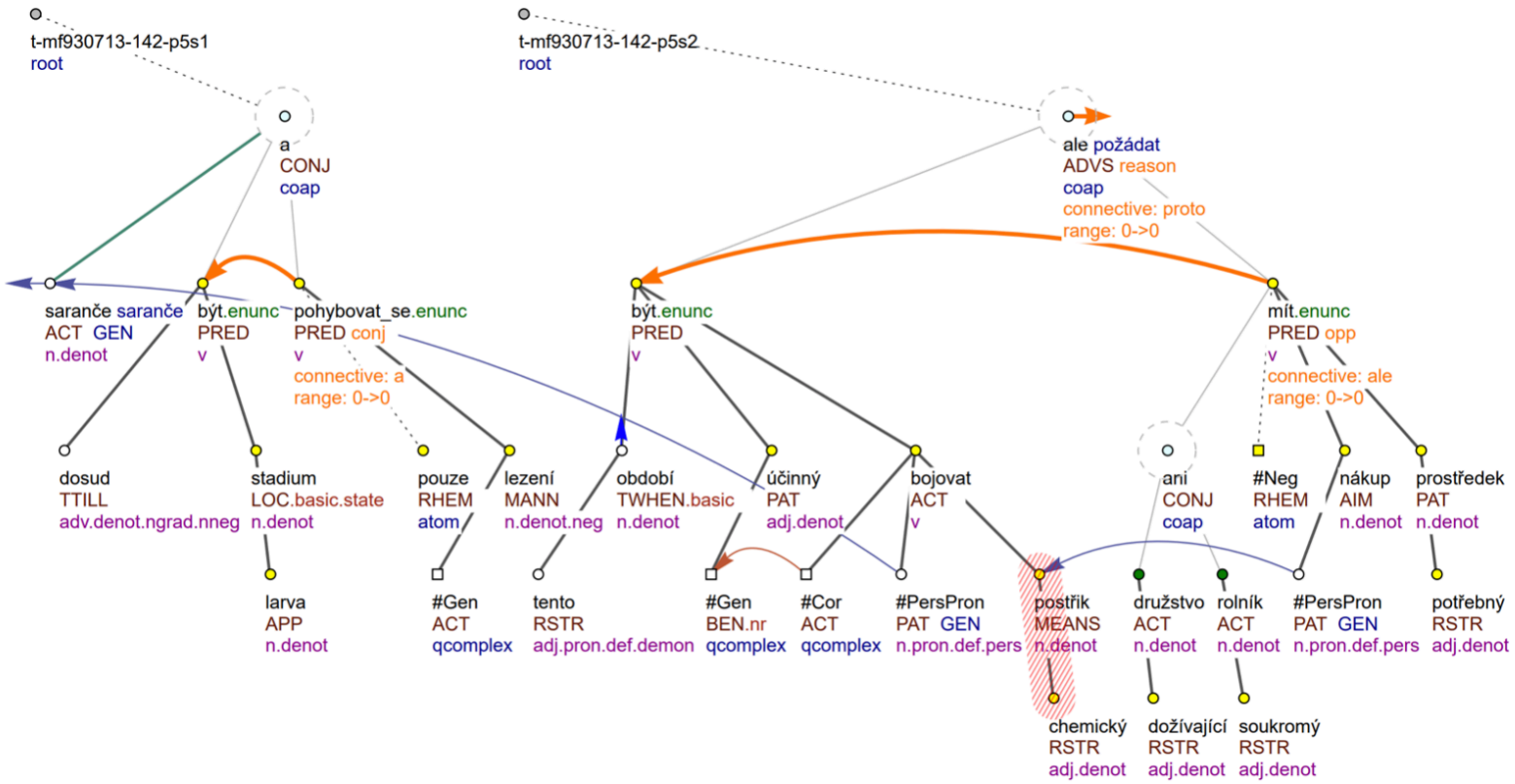
morphological: Lemma (dictionary form) + detailed analysis
(15 categories with many possible values = 4,257 tags)

surface-syntactic ("analytical"):
Labeled dependency tree encoding grammatical functions
(subject, object, conjunct, etc.)

semantic ("tectogrammatical"):
Labeled dependency tree for predicate-argument structure,
information structure, coreference
(39 labels: agent, patient, origin, effect, manner, etc….)

https://ufal.mff.cuni.cz/pdt3.5

Example sentences (PDT3.5)



Sarančata jsou doposud ve stadiu larev a pohybují se pouze lezením. V tomto období je účinné bojovat proti nim chemickými postřiky, ale dožívající družstva ani soukromí rolníci nemají na jejich nákup potřebné prostředky.

Example sentences from PDT 3.5, with tectogrammatical annotation including coreference links (blue and brown arrows), MWEs (red stripes) and discourse annotation (orange arrows and attributes/lables). Lit.: *Grasshoppers are still in the larvae stadium, crawling only. At this time of the year, it is efficient to fight them using chemicals, but neither the ailing cooperatives nor private farmers can afford them.*

METU-Sabanci Turkish Treebank

Turkish is an agglutinative language
with free word order.

Rich morphological annotations

Dependencies (next slide) are at the morpheme level

- iyileştiriliyorken
  - (literally) while it is being caused to become good
  - while it is being improved
- iyi+Adj ^DB+Verb+Become^DB+Verb+Caus
  ^DB+Verb+Pass+Pos+Pres^DB+Adverb+While

Very small -- about 5000 sentences

example from Kemal Oflazer's talk at Rochester, April 2007]

METU-Sabanci Turkish Treebank

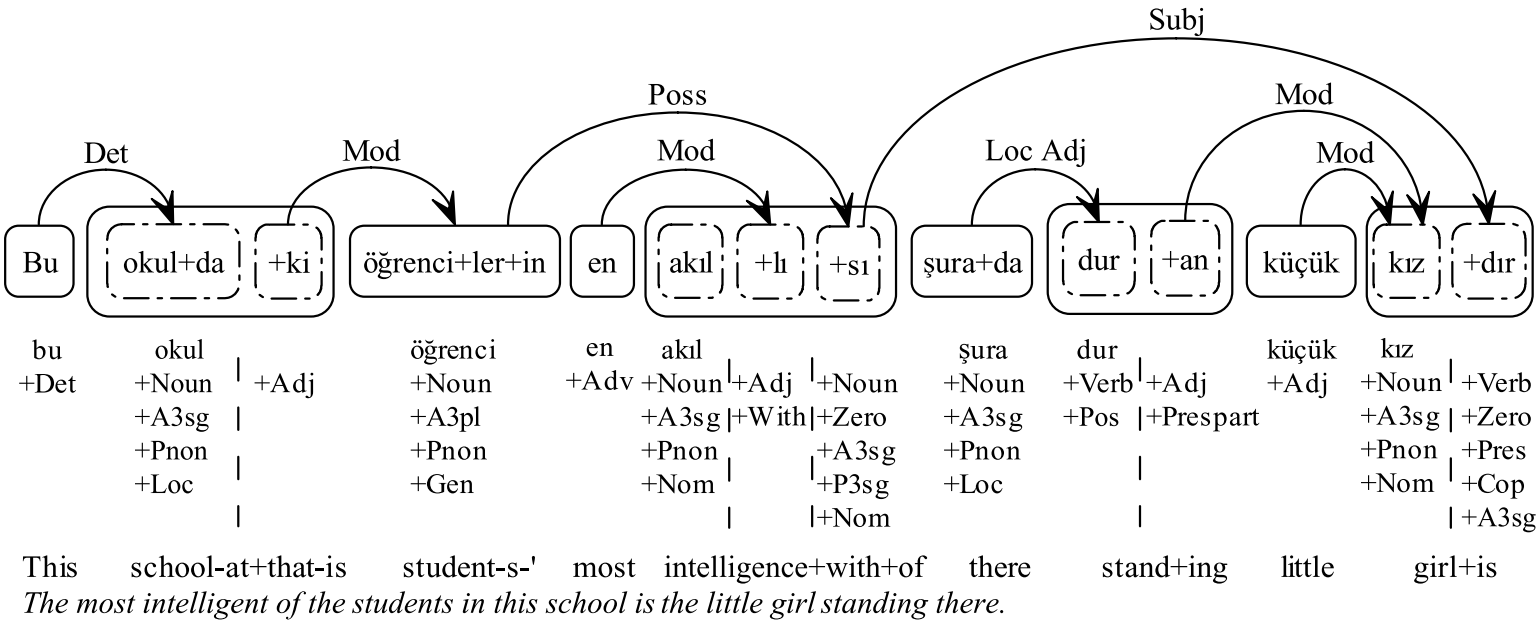


Figure 1
Dependency links in an example Turkish sentence.
'+'s indicate morpheme boundaries. The rounded rectangles show words, and IGs within words that have more than one IG are indicated by the dashed rounded rectangles. The inflectional features of each IG as produced by the morphological analyzer are listed below the IG.

Eryigit, Nivre, and Oflazer, Dependency Parsing of Turkish, CL 2008

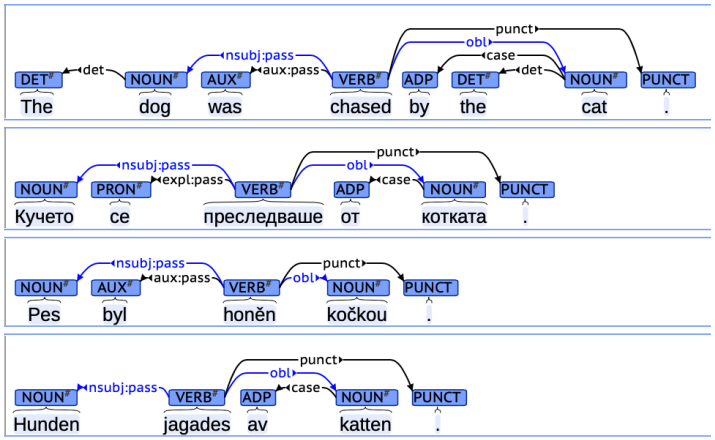
Universal Dependencies

37 syntactic relations, intended to be applicable to all languages ("universal"), with slight modifications for each specific language, if necessary.

http://universaldependencies.org

Example: "*the dog was chased by the cat*"
in English, Bulgarian, Czech and Swedish:

All languages have dependencies corresponding to
(*chased*, nsubj-pass, *dog*)
(*chased*, obj, *cat*)



Universal Dependency Relations

Nominal core arguments: `nsubj` (nominal subject, incl. `nsubj-pass` (nominal subject in passive), `obj` (direct object), `iobj` (indirect object)

Clausal core arguments: `csubj` (clausal subject), `ccomp` (clausal object ["complement"])

Non-core ("oblique") dependents: `obl` (oblique nominal argument or adjunct, e.g. for tools etc.), `advcl` (adverbial clause modifier), `aux` (auxiliary verb), `cop` (copula), `det` (determiner)

Nominal dependents: `nmod` (nominal modifier), `amod` (adjectival modifier), `appos` (appositional modifier)

Function words: `case` (case markers, prepositions), `det` (determiners),

Coordination: `cc` (coordinating conjunction), `conj` (conjunct)

Multiword Expressions: `compound` (within compound nouns), `flat` (dates, complex names, etc.),

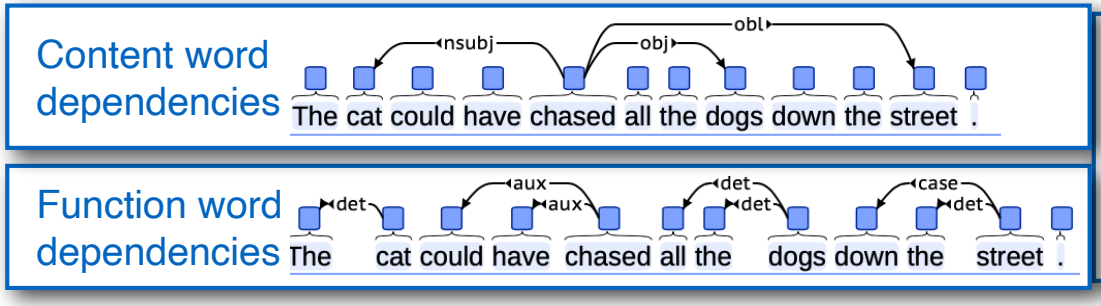
Other: `root` (from ROOT to the head of the sentence), `dep` (catch-all label), `punct` (to punctuation marks)

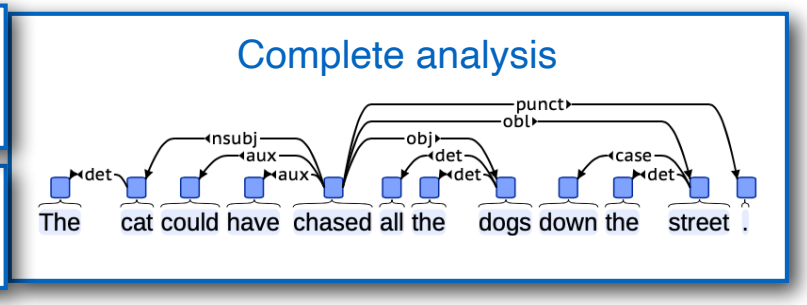
UD conventions: Primacy of content words

https://universaldependencies.org/u/overview/syntax.html

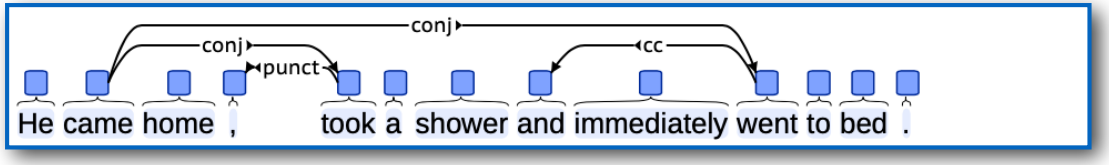
Dependency relations hold primarily between content words
(which vary less across languages than function words)

Function words (prepositions, copulas, auxiliaries, determiners)
attach to the most closely related content word,
and typically don't have dependents





In **coordination**, the first conjunct (*came*) is head, and
the coordination (*and*) and subsequent conjuncts (*took, went*)
depend on the first conjunct:



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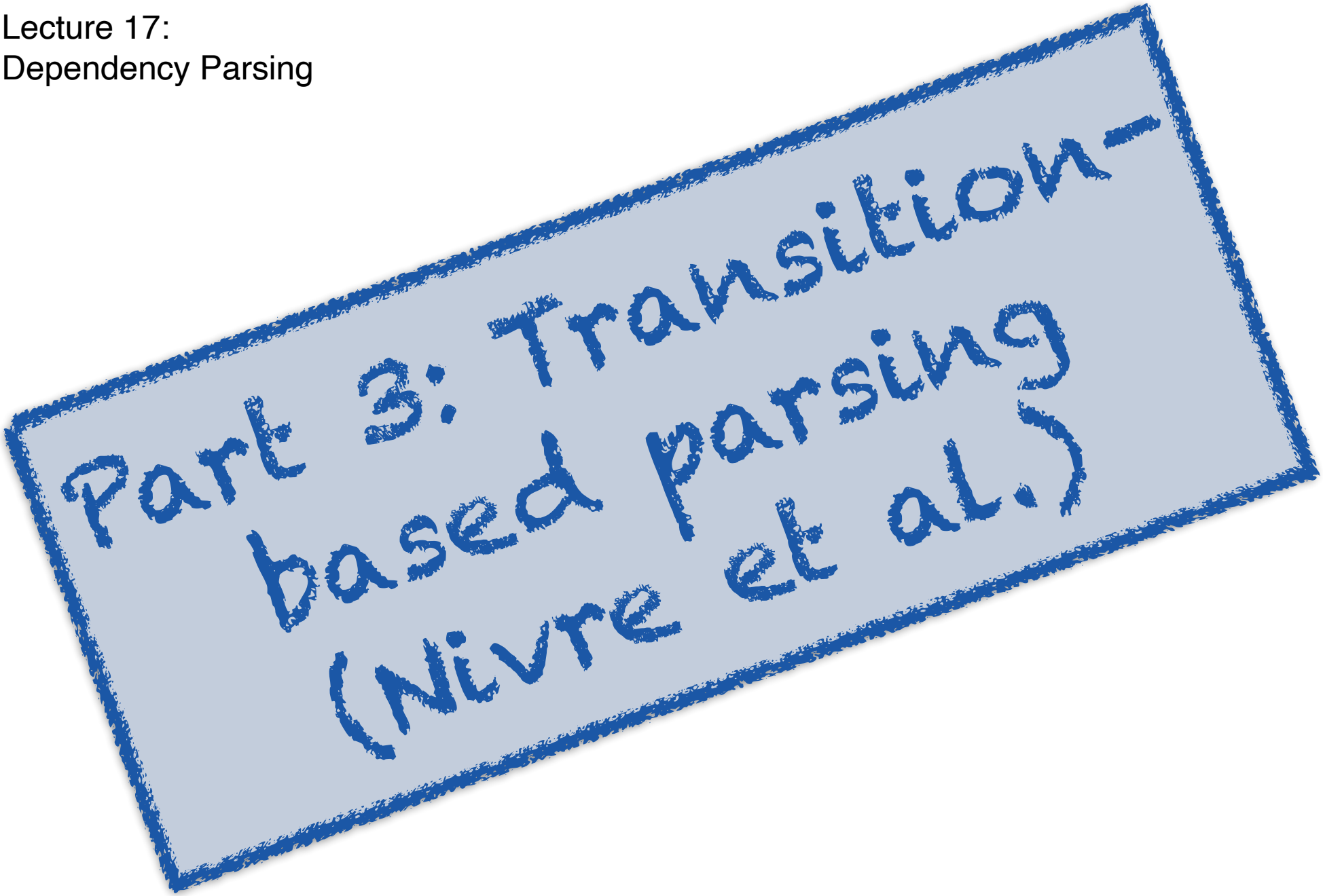
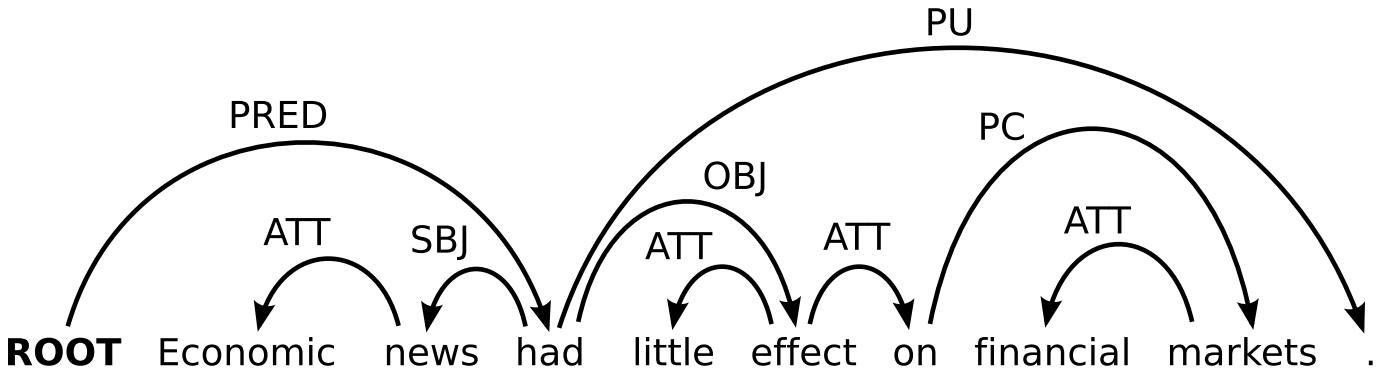


A dependency parse



Dependencies are (labeled) asymmetrical binary relations between two lexical items (words).

Parsing algorithms for DG

'Transition-based' parsers:

Learn a sequence of actions to parse sentences

Models:

State = stack of partially processed items
+ queue/buffer of remaining tokens
+ set of dependency arcs that have been found already

Transitions (actions) = add dependency arcs; stack/queue operations

'Graph-based' parsers:

Learn a model over dependency graphs

Models:

a function (typically sum) of local attachment scores

For dependency trees, you can use a minimum spanning tree algorithm

Transition-based parsing: assumptions

This algorithm works for **projective dependency trees**.

Dependency tree:

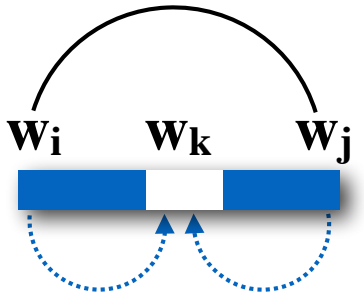
Each word has a single parent
(Each word is a dependent of [is attached to] one other word)

Projective dependencies:

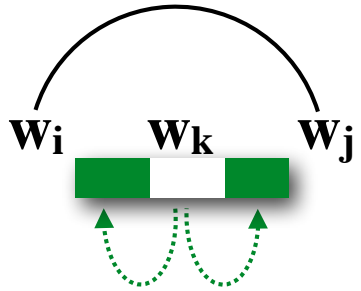
There are **no crossing dependencies**.

For any i, j, k with $i < k < j$: if there is a dependency between w_i and w_j, the parent of w_k is a word w_l between (possibly including) i and j: $i \leq l \leq j$, while any child w_m of w_k has to occur between (excluding) i and j: $i<m<j$

the parent of w_k:
one of $w_i \ldots w_j$



any child of w_k:
one of $w_{i+1} \ldots w_{j-1}$



Transition-based parsing

Transition-based shift-reduce parsing processes the sentence $S = w_0 w_1 ... w_n$ from left to right.

Unlike CKY, it constructs a **single tree**.

Notation:

w_0 is a special ROOT token.

$V_S = \{w_0, w_1, ..., w_n\}$ is the vocabulary of the sentence

R is a set of dependency relations

The parser uses three data structures:

σ: a **stack** of partially processed words $w_i \in V_S$

β: a **buffer** of remaining input words $w_i \in V_S$

A: a **set of dependency arcs** $(w_i, r, w_j) \in V_S \times R \times V_S$

Parser configurations (σ, β, A)

The **stack σ** is a list of **partially processed** words

We push and pop words onto/off of σ.

$\sigma|w$: w is on top of the stack.

Words on the stack are not (yet) attached to any other words.

Once we attach w, w can't be put back onto the stack again.

The **buffer β** is the **remaining input** words

We read words from β (left-to-right) and push them onto σ

$w|\beta$: w is on top of the buffer.

The **set of arcs A** defines the current tree.

We can add new arcs to A by attaching the word on top of the stack to the word on top of the buffer, or vice versa.

Parser configurations (σ, β, A)

We start in the **initial configuration** ($[w_0]$, $[w_1, \ldots, w_n]$, $\{\}$)
(Root token, Input Sentence, Empty tree)

We can **attach the first word** (w_1) **to the root** token w_0,
or we **can push** w_1 **onto the stack.**

(w_0 is the only token that can't get attached to any other word)

We want to end in the **terminal configuration** ($[]$, $[]$, A)
(Empty stack, Empty buffer, Complete tree)

Success!
We have **read all of the input** words (empty buffer) and have **attached all input words** to some other word (empty stack)

Transition-based parsing

We process the sentence $S = w_0 w_1 ... w_n$
from left to right ("**incremental parsing**")

In the parser configuration $(\sigma|w_i, w_j|\beta, A)$:

- w_i is on top of the stack. w_i may have some children
- w_j is on top of the buffer. w_j may have some children
- w_i precedes w_j ($i < j$)

We have to either **attach w_i to w_j**, **attach w_j to w_i**, or decide there is **no dependency between w_i and w_j**

NB: If we reach $(\sigma|w_i, w_j|\beta, A)$, **all words w_k** with $i < k < j$ have **already been attached to a parent w_m** with $i \leq m \leq j$

Parser actions

(σ, β, A): Parser configuration with stack σ, buffer β, set of arcs A

(w, r, w'): Dependency with head w, relation r and dependent w'

SHIFT: Push the next input word w_i from the buffer β onto the stack σ

$$(\sigma, w_i|\beta, A) \Rightarrow (\sigma|w_i, \beta, A)$$

LEFT-ARC$_r$: $\ldots\ w_i \ldots w_j \ldots$ (dependent *precedes* head)

Attach dependent w_i (top of stack σ) to head w_j (top of buffer β) with relation r from w_j to w_i. Pop w_i off the stack σ.

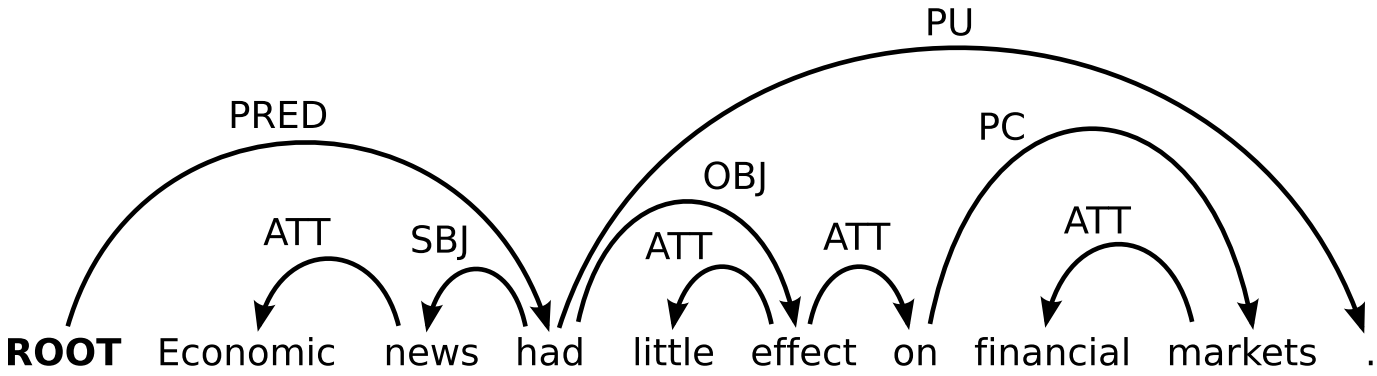
$$(\sigma|w_i, w_j|\beta, A) \Rightarrow (\sigma, w_j|\beta, A \cup \{(w_j, r, w_i)\})$$

RIGHT-ARC$_r$: $\ldots w_i \ldots w_j \ldots$ (dependent *follows* head)

Attach dependent w_j (top of buffer β) to head w_i (top of stack σ) with relation r from w_i to w_j. Move w_i back to the buffer β

$$(\sigma|w_i, w_j|\beta, A) \Rightarrow (\sigma, w_i|\beta, A \cup \{(w_i, r, w_j)\})$$

An example sentence & parse



Economic news had little effect on financial markets .

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Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	Ø)

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Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	Ø)
SH ⇒	([ROOT, Economic],	[news, . . . , .],	Ø)

Economic news had little effect on financial markets .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	∅)
SH ⇒	([ROOT, Economic],	[news, . . . , .],	∅)
LA_{ATT} ⇒	([ROOT],	[news, . . . , .],	$A_1 = \{(\text{news, ATT, Economic})\}$)

Economic **news** **had** little effect on financial markets .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	∅)
SH ⇒	([ROOT, Economic],	[news, . . . , .],	∅)
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LA_{SBJ} ⇒	([ROOT],	[had, . . . , .],	$A_2 = A_1 \cup \{(\text{had, SBJ, news})\}$)

Economic news **had** **little** effect on financial markets .

Transition	Configuration		
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SH ⇒	([ROOT, had],	[little, . . . , .],	A_2)

Economic news had **little** **effect** on financial markets .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	$\emptyset$)
SH $\Rightarrow$	([ROOT, Economic],	[news, . . . , .],	$\emptyset$)
$\text{LA}_{\text{ATT}} \Rightarrow$	([ROOT],	[news, . . . , .],	$A_1 = \{(\text{news}, \text{ATT}, \text{Economic})\}$)
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SH $\Rightarrow$	([ROOT, had],	[little, . . . , .],	A_2)
SH $\Rightarrow$	([ROOT, had, little],	[effect, . . . , .],	A_2)

Economic news **had little effect** on financial markets .

Transition	Configuration		
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$\text{LA}_{\text{ATT}} \Rightarrow$	([ROOT, had],	[effect, . . . , .],	$A_3 = A_2 \cup \{(\text{effect}, \text{ATT}, \text{little})\}$)

Economic news **had** little **effect** on financial markets .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	$\emptyset$)
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Economic news had little **effect** **on** financial markets .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	∅)
SH ⇒	([ROOT, Economic],	[news, . . . , .],	∅)
LA_{ATT} ⇒	([ROOT],	[news, . . . , .],	$A_1 = \{(\text{news}, \text{ATT}, \text{Economic})\}$)
SH ⇒	([ROOT, news],	[had, . . . , .],	A_1)
LA_{SBJ} ⇒	([ROOT],	[had, . . . , .],	$A_2 = A_1 \cup \{(\text{had}, \text{SBJ}, \text{news})\}$)
SH ⇒	([ROOT, had],	[little, . . . , .],	A_2)
SH ⇒	([ROOT, had, little],	[effect, . . . , .],	A_2)
LA_{ATT} ⇒	([ROOT, had],	[effect, . . . , .],	$A_3 = A_2 \cup \{(\text{effect}, \text{ATT}, \text{little})\}$)
SH ⇒	([ROOT, had, effect],	[on, . . . , .],	A_3)

Economic news had little effect **on financial** markets .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	∅)
SH ⇒	([ROOT, Economic],	[news, . . . , .],	∅)
LA_{ATT} ⇒	([ROOT],	[news, . . . , .],	$A_1 = \{(news, ATT, Economic)\}$)
SH ⇒	([ROOT, news],	[had, . . . , .],	A_1)
LA_{SBJ} ⇒	([ROOT],	[had, . . . , .],	$A_2 = A_1 \cup \{(had, SBJ, news)\}$)
SH ⇒	([ROOT, had],	[little, . . . , .],	A_2)
SH ⇒	([ROOT, had, little],	[effect, . . . , .],	A_2)
LA_{ATT} ⇒	([ROOT, had],	[effect, . . . , .],	$A_3 = A_2 \cup \{(effect, ATT, little)\}$)
SH ⇒	([ROOT, had, effect],	[on, . . . , .],	A_3)
SH ⇒	([ROOT, . . . on],	[financial, markets, .],	A_3)

Economic news had little effect on **financial markets** .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	∅)
SH ⇒	([ROOT, Economic],	[news, . . . , .],	∅)
LA_{ATT} ⇒	([ROOT],	[news, . . . , .],	$A_1 = \{(\text{news, ATT, Economic})\}$)
SH ⇒	([ROOT, news],	[had, . . . , .],	A_1)
LA_{SBJ} ⇒	([ROOT],	[had, . . . , .],	$A_2 = A_1 \cup \{(\text{had, SBJ, news})\}$)
SH ⇒	([ROOT, had],	[little, . . . , .],	A_2)
SH ⇒	([ROOT, had, little],	[effect, . . . , .],	A_2)
LA_{ATT} ⇒	([ROOT, had],	[effect, . . . , .],	$A_3 = A_2 \cup \{(\text{effect, ATT, little})\}$)
SH ⇒	([ROOT, had, effect],	[on, . . . , .],	A_3)
SH ⇒	([ROOT, . . . on],	[financial, markets, .],	A_3)
SH ⇒	([ROOT, . . . , financial],	[markets, .],	A_3)

Economic news had little effect **on financial markets** .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	∅)
SH ⇒	([ROOT, Economic],	[news, . . . , .],	∅)
LA_{ATT} ⇒	([ROOT],	[news, . . . , .],	$A_1 = \{(news, ATT, Economic)\}$)
SH ⇒	([ROOT, news],	[had, . . . , .],	A_1)
LA_{SBJ} ⇒	([ROOT],	[had, . . . , .],	$A_2 = A_1 \cup \{(had, SBJ, news)\}$)
SH ⇒	([ROOT, had],	[little, . . . , .],	A_2)
SH ⇒	([ROOT, had, little],	[effect, . . . , .],	A_2)
LA_{ATT} ⇒	([ROOT, had],	[effect, . . . , .],	$A_3 = A_2 \cup \{(effect, ATT, little)\}$)
SH ⇒	([ROOT, had, effect],	[on, . . . , .],	A_3)
SH ⇒	([ROOT, . . . on],	[financial, markets, .],	A_3)
SH ⇒	([ROOT, . . . , financial],	[markets, .],	A_3)
LA_{ATT} ⇒	([ROOT, . . . on],	[markets, .],	$A_4 = A_3 \cup \{(markets, ATT, financial)\}$)

Economic news had little effect **on** financial **markets** .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	∅)
SH ⇒	([ROOT, Economic],	[news, . . . , .],	∅)
LA_{ATT} ⇒	([ROOT],	[news, . . . , .],	$A_1 = \{(news, ATT, Economic)\}$)
SH ⇒	([ROOT, news],	[had, . . . , .],	A_1)
LA_{SBJ} ⇒	([ROOT],	[had, . . . , .],	$A_2 = A_1 \cup \{(had, SBJ, news)\}$)
SH ⇒	([ROOT, had],	[little, . . . , .],	A_2)
SH ⇒	([ROOT, had, little],	[effect, . . . , .],	A_2)
LA_{ATT} ⇒	([ROOT, had],	[effect, . . . , .],	$A_3 = A_2 \cup \{(effect, ATT, little)\}$)
SH ⇒	([ROOT, had, effect],	[on, . . . , .],	A_3)
SH ⇒	([ROOT, . . . on],	[financial, markets, .],	A_3)
SH ⇒	([ROOT, . . . , financial],	[markets, .],	A_3)
LA_{ATT} ⇒	([ROOT, . . . on],	[markets, .],	$A_4 = A_3 \cup \{(markets, ATT, financial)\}$)

Economic news had little **effect** **on** financial **markets** .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	∅)
SH ⇒	([ROOT, Economic],	[news, . . . , .],	∅)
LA_{ATT} ⇒	([ROOT],	[news, . . . , .],	$A_1 = \{(news, ATT, Economic)\}$)
SH ⇒	([ROOT, news],	[had, . . . , .],	A_1)
LA_{SBJ} ⇒	([ROOT],	[had, . . . , .],	$A_2 = A_1 \cup \{(had, SBJ, news)\}$)
SH ⇒	([ROOT, had],	[little, . . . , .],	A_2)
SH ⇒	([ROOT, had, little],	[effect, . . . , .],	A_2)
LA_{ATT} ⇒	([ROOT, had],	[effect, . . . , .],	$A_3 = A_2 \cup \{(effect, ATT, little)\}$)
SH ⇒	([ROOT, had, effect],	[on, . . . , .],	A_3)
SH ⇒	([ROOT, . . . on],	[financial, markets, .],	A_3)
SH ⇒	([ROOT, . . . , financial],	[markets, .],	A_3)
LA_{ATT} ⇒	([ROOT, . . . on],	[markets, .],	$A_4 = A_3 \cup \{(markets, ATT, financial)\}$)
RA_{PC} ⇒	([ROOT, had, effect],	[on, .],	$A_5 = A_4 \cup \{(on, PC, markets)\}$)

Economic news had little **effect** **on** financial markets .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	∅)
SH ⇒	([ROOT, Economic],	[news, . . . , .],	∅)
LA_{ATT} ⇒	([ROOT],	[news, . . . , .],	$A_1 = \{(news, ATT, Economic)\}$)
SH ⇒	([ROOT, news],	[had, . . . , .],	A_1)
LA_{SBJ} ⇒	([ROOT],	[had, . . . , .],	$A_2 = A_1 \cup \{(had, SBJ, news)\}$)
SH ⇒	([ROOT, had],	[little, . . . , .],	A_2)
SH ⇒	([ROOT, had, little],	[effect, . . . , .],	A_2)
LA_{ATT} ⇒	([ROOT, had],	[effect, . . . , .],	$A_3 = A_2 \cup \{(effect, ATT, little)\}$)
SH ⇒	([ROOT, had, effect],	[on, . . . , .],	A_3)
SH ⇒	([ROOT, . . . on],	[financial, markets, .],	A_3)
SH ⇒	([ROOT, . . . , financial],	[markets, .],	A_3)
LA_{ATT} ⇒	([ROOT, . . . on],	[markets, .],	$A_4 = A_3 \cup \{(markets, ATT, financial)\}$)
RA_{PC} ⇒	([ROOT, had, effect],	[on, .],	$A_5 = A_4 \cup \{(on, PC, markets)\}$)

Economic news **had** little **effect** **on** financial markets .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	$\emptyset$)
SH $\Rightarrow$	([ROOT, Economic],	[news, . . . , .],	$\emptyset$)
$\text{LA}_{\text{ATT}} \Rightarrow$	([ROOT],	[news, . . . , .],	$A_1 = \{(\text{news}, \text{ATT}, \text{Economic})\}$)
SH $\Rightarrow$	([ROOT, news],	[had, . . . , .],	A_1)
$\text{LA}_{\text{SBJ}} \Rightarrow$	([ROOT],	[had, . . . , .],	$A_2 = A_1 \cup \{(\text{had}, \text{SBJ}, \text{news})\}$)
SH $\Rightarrow$	([ROOT, had],	[little, . . . , .],	A_2)
SH $\Rightarrow$	([ROOT, had, little],	[effect, . . . , .],	A_2)
$\text{LA}_{\text{ATT}} \Rightarrow$	([ROOT, had],	[effect, . . . , .],	$A_3 = A_2 \cup \{(\text{effect}, \text{ATT}, \text{little})\}$)
SH $\Rightarrow$	([ROOT, had, effect],	[on, . . . , .],	A_3)
SH $\Rightarrow$	([ROOT, . . . on],	[financial, markets, .],	A_3)
SH $\Rightarrow$	([ROOT, . . . , financial],	[markets, .],	A_3)
$\text{LA}_{\text{ATT}} \Rightarrow$	([ROOT, . . . on],	[markets, .],	$A_4 = A_3 \cup \{(\text{markets}, \text{ATT}, \text{financial})\}$)
$\text{RA}_{\text{PC}} \Rightarrow$	([ROOT, had, effect],	[on, .],	$A_5 = A_4 \cup \{(\text{on}, \text{PC}, \text{markets})\}$)
$\text{RA}_{\text{ATT}} \Rightarrow$	([ROOT, had],	[effect, .],	$A_6 = A_5 \cup \{(\text{effect}, \text{ATT}, \text{on})\}$)

Economic news **had** little **effect** on financial markets .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	∅)
SH ⇒	([ROOT, Economic],	[news, . . . , .],	∅)
LA_{ATT} ⇒	([ROOT],	[news, . . . , .],	$A_1 = \{(news, ATT, Economic)\}$)
SH ⇒	([ROOT, news],	[had, . . . , .],	A_1)
LA_{SBJ} ⇒	([ROOT],	[had, . . . , .],	$A_2 = A_1 \cup \{(had, SBJ, news)\}$)
SH ⇒	([ROOT, had],	[little, . . . , .],	A_2)
SH ⇒	([ROOT, had, little],	[effect, . . . , .],	A_2)
LA_{ATT} ⇒	([ROOT, had],	[effect, . . . , .],	$A_3 = A_2 \cup \{(effect, ATT, little)\}$)
SH ⇒	([ROOT, had, effect],	[on, . . . , .],	A_3)
SH ⇒	([ROOT, . . . on],	[financial, markets, .],	A_3)
SH ⇒	([ROOT, . . . , financial],	[markets, .],	A_3)
LA_{ATT} ⇒	([ROOT, . . . on],	[markets, .],	$A_4 = A_3 \cup \{(markets, ATT, financial)\}$)
RA_{PC} ⇒	([ROOT, had, effect],	[on, .],	$A_5 = A_4 \cup \{(on, PC, markets)\}$)
RA_{ATT} ⇒	([ROOT, had],	[effect, .],	$A_6 = A_5 \cup \{(effect, ATT, on)\}$)

Economic news **had** little **effect** on financial markets .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	∅)
SH ⇒	([ROOT, Economic],	[news, . . . , .],	∅)
LA_{ATT} ⇒	([ROOT],	[news, . . . , .],	$A_1 = \{(news, ATT, Economic)\}$)
SH ⇒	([ROOT, news],	[had, . . . , .],	A_1)
LA_{SBJ} ⇒	([ROOT],	[had, . . . , .],	$A_2 = A_1 \cup \{(had, SBJ, news)\}$)
SH ⇒	([ROOT, had],	[little, . . . , .],	A_2)
SH ⇒	([ROOT, had, little],	[effect, . . . , .],	A_2)
LA_{ATT} ⇒	([ROOT, had],	[effect, . . . , .],	$A_3 = A_2 \cup \{(effect, ATT, little)\}$)
SH ⇒	([ROOT, had, effect],	[on, . . . , .],	A_3)
SH ⇒	([ROOT, . . . on],	[financial, markets, .],	A_3)
SH ⇒	([ROOT, . . . , financial],	[markets, .],	A_3)
LA_{ATT} ⇒	([ROOT, . . . on],	[markets, .],	$A_4 = A_3 \cup \{(markets, ATT, financial)\}$)
RA_{PC} ⇒	([ROOT, had, effect],	[on, .],	$A_5 = A_4 \cup \{(on, PC, markets)\}$)
RA_{ATT} ⇒	([ROOT, had],	[effect, .],	$A_6 = A_5 \cup \{(effect, ATT, on)\}$)
RA_{OBJ} ⇒	([ROOT],	[had, .],	$A_7 = A_6 \cup \{(had, OBJ, effect)\}$)

Economic news **had** little effect on financial markets .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	∅)
SH ⇒	([ROOT, Economic],	[news, . . . , .],	∅)
LA_{ATT} ⇒	([ROOT],	[news, . . . , .],	$A_1 = \{(news, ATT, Economic)\}$)
SH ⇒	([ROOT, news],	[had, . . . , .],	A_1)
LA_{SBJ} ⇒	([ROOT],	[had, . . . , .],	$A_2 = A_1 \cup \{(had, SBJ, news)\}$)
SH ⇒	([ROOT, had],	[little, . . . , .],	A_2)
SH ⇒	([ROOT, had, little],	[effect, . . . , .],	A_2)
LA_{ATT} ⇒	([ROOT, had],	[effect, . . . , .],	$A_3 = A_2 \cup \{(effect, ATT, little)\}$)
SH ⇒	([ROOT, had, effect],	[on, . . . , .],	A_3)
SH ⇒	([ROOT, . . . on],	[financial, markets, .],	A_3)
SH ⇒	([ROOT, . . . , financial],	[markets, .],	A_3)
LA_{ATT} ⇒	([ROOT, . . . on],	[markets, .],	$A_4 = A_3 \cup \{(markets, ATT, financial)\}$)
RA_{PC} ⇒	([ROOT, had, effect],	[on, .],	$A_5 = A_4 \cup \{(on, PC, markets)\}$)
RA_{ATT} ⇒	([ROOT, had],	[effect, .],	$A_6 = A_5 \cup \{(effect, ATT, on)\}$)
RA_{OBJ} ⇒	([ROOT],	[had, .],	$A_7 = A_6 \cup \{(had, OBJ, effect)\}$)
SH ⇒	([ROOT, had],	[.],	A_7)

Economic news **had** little effect on financial markets .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	∅)
SH ⇒	([ROOT, Economic],	[news, . . . , .],	∅)
LA_{ATT} ⇒	([ROOT],	[news, . . . , .],	$A_1 = \{(news, ATT, Economic)\}$)
SH ⇒	([ROOT, news],	[had, . . . , .],	A_1)
LA_{SBJ} ⇒	([ROOT],	[had, . . . , .],	$A_2 = A_1 \cup \{(had, SBJ, news)\}$)
SH ⇒	([ROOT, had],	[little, . . . , .],	A_2)
SH ⇒	([ROOT, had, little],	[effect, . . . , .],	A_2)
LA_{ATT} ⇒	([ROOT, had],	[effect, . . . , .],	$A_3 = A_2 \cup \{(effect, ATT, little)\}$)
SH ⇒	([ROOT, had, effect],	[on, . . . , .],	A_3)
SH ⇒	([ROOT, . . . on],	[financial, markets, .],	A_3)
SH ⇒	([ROOT, . . . , financial],	[markets, .],	A_3)
LA_{ATT} ⇒	([ROOT, . . . on],	[markets, .],	$A_4 = A_3 \cup \{(markets, ATT, financial)\}$)
RA_{PC} ⇒	([ROOT, had, effect],	[on, .],	$A_5 = A_4 \cup \{(on, PC, markets)\}$)
RA_{ATT} ⇒	([ROOT, had],	[effect, .],	$A_6 = A_5 \cup \{(effect, ATT, on)\}$)
RA_{OBJ} ⇒	([ROOT],	[had, .],	$A_7 = A_6 \cup \{(had, OBJ, effect)\}$)
SH ⇒	([ROOT, had],	[.],	A_7)
RA_{PU} ⇒	([ROOT],	[had],	$A_8 = A_7 \cup \{(had, PU, .)\}$)

Economic news **had** little effect on financial markets .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	∅)
SH ⇒	([ROOT, Economic],	[news, . . . , .],	∅)
LA_{ATT} ⇒	([ROOT],	[news, . . . , .],	$A_1 = \{(news, ATT, Economic)\}$)
SH ⇒	([ROOT, news],	[had, . . . , .],	A_1)
LA_{SBJ} ⇒	([ROOT],	[had, . . . , .],	$A_2 = A_1 \cup \{(had, SBJ, news)\}$)
SH ⇒	([ROOT, had],	[little, . . . , .],	A_2)
SH ⇒	([ROOT, had, little],	[effect, . . . , .],	A_2)
LA_{ATT} ⇒	([ROOT, had],	[effect, . . . , .],	$A_3 = A_2 \cup \{(effect, ATT, little)\}$)
SH ⇒	([ROOT, had, effect],	[on, . . . , .],	A_3)
SH ⇒	([ROOT, . . . on],	[financial, markets, .],	A_3)
SH ⇒	([ROOT, . . . , financial],	[markets, .],	A_3)
LA_{ATT} ⇒	([ROOT, . . . on],	[markets, .],	$A_4 = A_3 \cup \{(markets, ATT, financial)\}$)
RA_{PC} ⇒	([ROOT, had, effect],	[on, .],	$A_5 = A_4 \cup \{(on, PC, markets)\}$)
RA_{ATT} ⇒	([ROOT, had],	[effect, .],	$A_6 = A_5 \cup \{(effect, ATT, on)\}$)
RA_{OBJ} ⇒	([ROOT],	[had, .],	$A_7 = A_6 \cup \{(had, OBJ, effect)\}$)
SH ⇒	([ROOT, had],	[.],	A_7)
RA_{PU} ⇒	([ROOT],	[had],	$A_8 = A_7 \cup \{(had, PU, .)\}$)
RA_{PRED} ⇒	([ ],	[ROOT],	$A_9 = A_8 \cup \{(ROOT, PRED, had)\}$)

Economic news had little effect on financial markets .

Transition	Configuration		
	([ROOT],	[Economic, . . . , .],	∅)
SH ⇒	([ROOT, Economic],	[news, . . . , .],	∅)
LA_{ATT} ⇒	([ROOT],	[news, . . . , .],	$A_1 = \{(news, ATT, Economic)\}$)
SH ⇒	([ROOT, news],	[had, . . . , .],	A_1)
LA_{SBJ} ⇒	([ROOT],	[had, . . . , .],	$A_2 = A_1 \cup \{(had, SBJ, news)\}$)
SH ⇒	([ROOT, had],	[little, . . . , .],	A_2)
SH ⇒	([ROOT, had, little],	[effect, . . . , .],	A_2)
LA_{ATT} ⇒	([ROOT, had],	[effect, . . . , .],	$A_3 = A_2 \cup \{(effect, ATT, little)\}$)
SH ⇒	([ROOT, had, effect],	[on, . . . , .],	A_3)
SH ⇒	([ROOT, . . . on],	[financial, markets, .],	A_3)
SH ⇒	([ROOT, . . . , financial],	[markets, .],	A_3)
LA_{ATT} ⇒	([ROOT, . . . on],	[markets, .],	$A_4 = A_3 \cup \{(markets, ATT, financial)\}$)
RA_{PC} ⇒	([ROOT, had, effect],	[on, .],	$A_5 = A_4 \cup \{(on, PC, markets)\}$)
RA_{ATT} ⇒	([ROOT, had],	[effect, .],	$A_6 = A_5 \cup \{(effect, ATT, on)\}$)
RA_{OBJ} ⇒	([ROOT],	[had, .],	$A_7 = A_6 \cup \{(had, OBJ, effect)\}$)
SH ⇒	([ROOT, had],	[.],	A_7)
RA_{PU} ⇒	([ROOT],	[had],	$A_8 = A_7 \cup \{(had, PU, .)\}$)
RA_{PRED} ⇒	([ ],	[ROOT],	$A_9 = A_8 \cup \{(ROOT, PRED, had)\}$)
SH ⇒	([ROOT],	[ ],	A_9)

Transition-based parsing in practice

Which action should the parser take
in the current configuration?

We also need a **parsing model** that assigns a score to each possible action given a current configuration.

- **Possible actions:**
  SHIFT, and for any relation r: LEFT-ARC$_r$, or RIGHT-ARC$_r$
- **Possible features of the current configuration**:
  The **top {1,2,3} words** on the **buffer** and on the **stack**, their **POS tags**, distances between the words, etc.

We can learn this model from a dependency treebank.

A neural dependency parser

(Chen and Manning, 2014)

https://www.aclweb.org/anthology/D14-1082.pdf

Predict the next action in a transition-based parser with a **feedforward network** (with one hidden layer)

Input: Parser configurations (stack, buffer, arcs) represented as a (fixed-sized) list of features.

- Each feature captures words, POS-tags and/or arc labels at specific positions in the stack and buffer
- Words, POS-tags, arc labels: *d*-dimensional embeddings

Output: With L dependency labels, softmax over $(1+ 2L)$ actions

(SHIFT, plus 2 actions per label $l \in L$: LEFT-ARC$_l$, RIGHTARC$_l$,)