Computational Linguistics

9A

CSC 2501 / 485
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9A. Mildly Context-Sensitive Grammar Formalisms

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Based on slides by David Smith, Dan Klein, Stephen Clark and Eva Banik

Combinatory Categorial Grammar

Combinatory Categorial Grammar (CCG)

- Categorial grammar (CG) is one of the oldest grammar formalisms

- *Combinatory* Categorial Grammar now well established and computationally well founded (Steedman, 1996, 2000)
  - Account of syntax; semantics; prodody and information structure; automatic parsers; generation

Combinatory Categorial Grammar (CCG)

- CCG is a lexicalized grammar
- An elementary syntactic structure – for CCG a lexical category – is assigned to each word in a sentence

  walked: S\NP "give me an NP to my left and I return a sentence"
- A small number of rules define how categories can combine
  - Rules based on the combinators from Combinatory Logic

CCG Lexical Categories

- Atomic categories: S , N , NP , PP , . . . (not many more)
- Complex categories are built recursively from atomic categories and slashes, which indicate the directions of arguments

- Complex categories encode subcategorisation information

  - intransitive verb: S \NP *walked*

  - transitive verb: (S \NP)/NP *respected*
  - ditransitive verb: ((S \NP)/NP)/NP *gave*
- Complex categories can encode modification
  - PP nominal: (NP \NP)/NP
  - PP verbal: ((S \NP)\(S \NP))/NP

Simple CCG Derivation

$$
\begin{array}{cccc}
\mathit{interleukin-10} & \mathit{inhibits} & \mathit{production} & \\
\cline{1-1}\cline{2-2}\cline{3-3}
NP & (S\backslash NP)/NP & NP & \\
\cline{2-3}
 & \multicolumn{2}{c}{S\backslash NP} & > \\
\hline
\multicolumn{3}{c}{S} & <
\end{array}
$$

$>$ forward application

$<$ backward application

Function Application Schemata

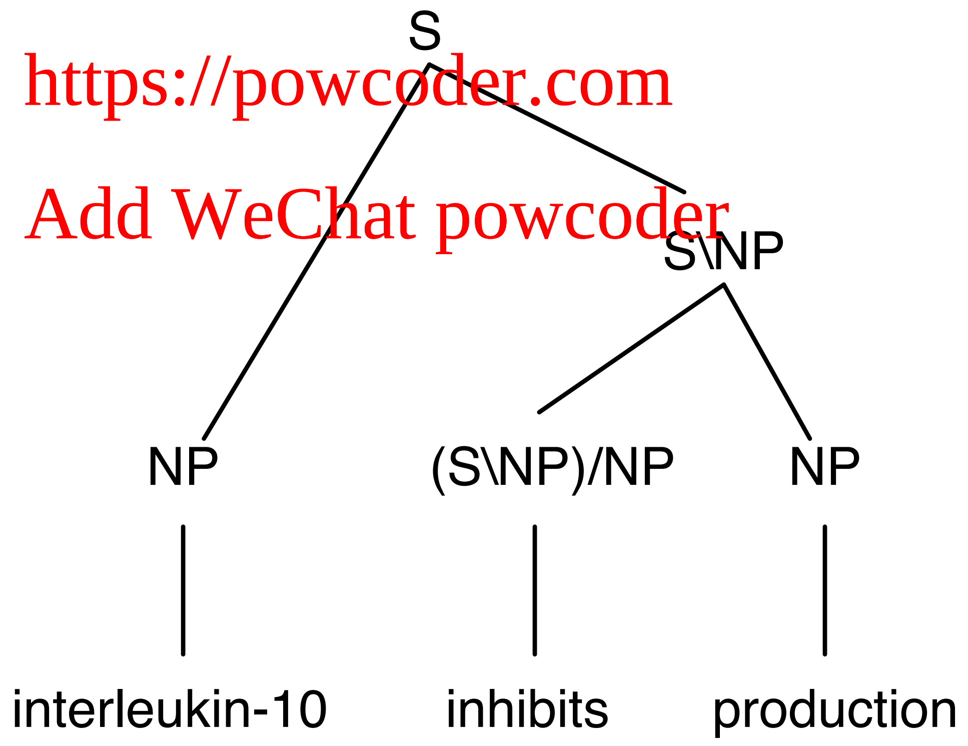
- Forward ($>$) and backward ($<$) application:

$$X/Y \quad Y \quad \Rightarrow \quad X \qquad (>)$$

$$Y \quad X\backslash Y \quad \Rightarrow \quad X \qquad (<)$$

Classical Categorial Grammar

- ‘Classical’ Categorial Grammar only has application rules
- Classical Categorial Grammar is context free



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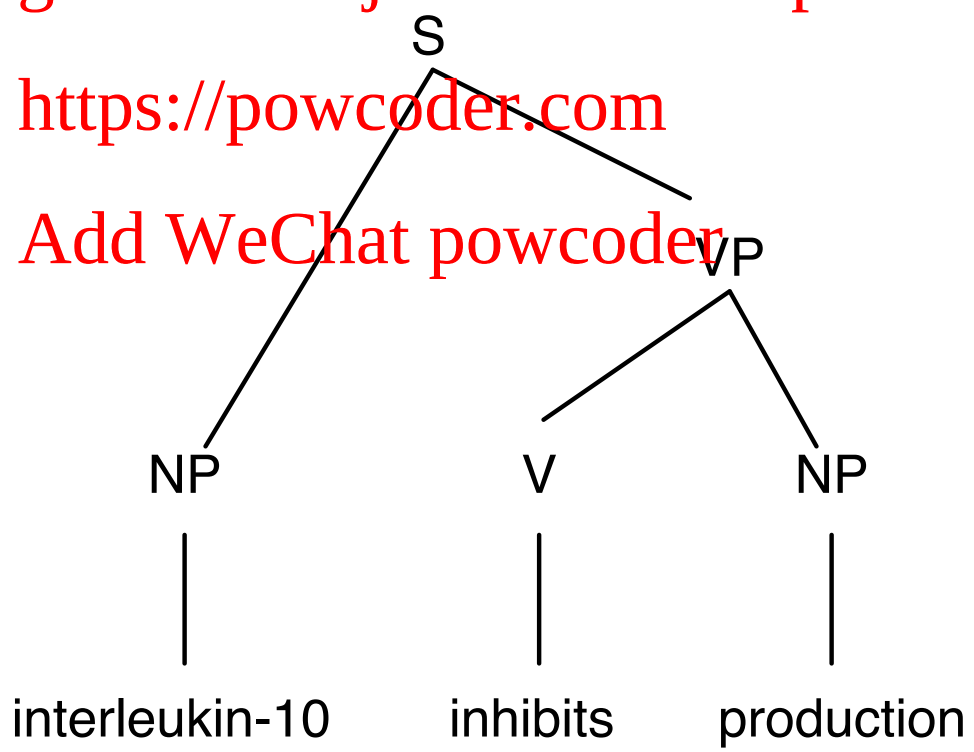


Extraction out of a Relative Clause

$$\begin{array}{ccccc} \mathit{The} & \mathit{company} & \mathit{which} & \mathit{Microsoft} & \mathit{bought} \\ \hline NP/N & N & (NP\backslash NP)/(S/NP) & NP & (S\backslash NP)/NP \end{array}$$

Extraction out of a Relative Clause

$$\begin{array}{ccccc}
\mathit{The} & \mathit{company} & \mathit{which} & \mathit{Microsoft} & \mathit{bought} \\
\overline{NP/N} & \overline{N} & \overline{(NP\backslash NP)/(S/NP)} & \overline{NP} & \overline{(S\backslash NP)/NP} \\
 & & & \overline{\qquad\qquad}{>}\mathbf{T} & \\
 & & & S/(S\backslash NP) &
\end{array}$$

$>\mathbf{T}$ type-raising

Extraction out of a Relative Clause

$$\begin{array}{ccccc}
\textit{The} & \textit{company} & \textit{which} & \textit{Microsoft} & \textit{bought} \\
\hline
NP/N & N & (NP\backslash NP)/(S/NP) & NP & (S\backslash NP)/NP \\
\cline{4-4}
 & & & S/(S\backslash NP) \quad {>}\mathbf{T} & \\
\cline{4-5}
 & & & \multicolumn{2}{c}{S/NP \quad {>}\mathbf{B}}
\end{array}$$

$>$ **T** type-raising
$>$ **B** forward composition

Extraction out of a Relative Clause

$$\begin{array}{ccccc}
\textit{The} & \textit{company} & \textit{which} & \textit{Microsoft} & \textit{bought}\\
\overline{NP/N} & \overline{N} & \overline{(NP\backslash NP)/(S/NP)} & \overline{NP} & \overline{(S\backslash NP)/NP}\\
 & & & \overline{S/(S\backslash NP)}^{>\mathbf{T}} & \\
 & & & \multicolumn{2}{c}{\overline{S/NP}^{>\mathbf{B}}}\\
 & & \multicolumn{3}{c}{\overline{NP\backslash NP}^{>}}
\end{array}$$

Extraction out of a Relative Clause

$$\begin{array}{ccccc}
\mathit{The} & \mathit{company} & \mathit{which} & \mathit{Microsoft} & \mathit{bought} \\
\hline
NP/N & N & (NP\backslash NP)/(S/NP) & NP & (S\backslash NP)/NP \\
\cline{1-2}\cline{4-4}
\multicolumn{2}{c}{NP \quad >} & & S/(S\backslash NP) \quad >\mathbf{T} & \\
\cline{4-5}
 & & & \multicolumn{2}{c}{S/NP \quad >\mathbf{B}} \\
\cline{3-5}
 & & \multicolumn{3}{c}{NP\backslash NP \quad >} \\
\cline{1-5}
\multicolumn{5}{c}{NP \quad <}
\end{array}$$

Forward Composition and Type-Raising

- Forward composition ($>_{\mathbf{B}}$):

$$X/Y \quad Y/Z \quad \Rightarrow \quad X/Z \qquad (>_{\mathbf{B}})$$

- Type-raising ($\mathbf{T}$):

$$X \quad \Rightarrow \quad T/(T\backslash X) \qquad (>_{\mathbf{T}})$$
$$X \quad \Rightarrow \quad T\backslash(T/X) \qquad (<_{\mathbf{T}})$$

- Extra combinatory rules increase the weak generative power to mild context -sensitivity

“Non-constituents” in CCG – Right Node Raising

$$\begin{array}{cccccc}
Google & sells & but & Microsoft & buys & shares \\
\overline{NP} & \overline{(S\backslash NP)/NP} & \overline{conj} & \overline{NP} & \overline{(S\backslash NP)/NP} & \overline{NP} \\
\overline{S/(S\backslash NP)}^{>\mathbf{T}} & & & \overline{S/(S\backslash NP)}^{>\mathbf{T}} & &
\end{array}$$

$> \mathbf{T}$ type-raising

"Non-constituents" in CCG – Right Node Raising

$$\begin{array}{cccccc}
\mathit{Google} & \mathit{sells} & \mathit{but} & \mathit{Microsoft} & \mathit{buys} & \mathit{shares} \\
\hline
NP & (S\backslash NP)/NP & conj & NP & (S\backslash NP)/NP & NP \\
\overline{S/(S\backslash NP)}^{>\mathbf{T}} & & & \overline{S/(S\backslash NP)}^{>\mathbf{T}} & & \\
\multicolumn{2}{c}{\overline{S/NP}^{>\mathbf{B}}} & & \multicolumn{2}{c}{\overline{S/NP}^{>\mathbf{B}}} &
\end{array}$$

$>$ **T**	type-raising
$>$ **B**	forward composition

“Non-constituents” in CCG – Right Node Raising

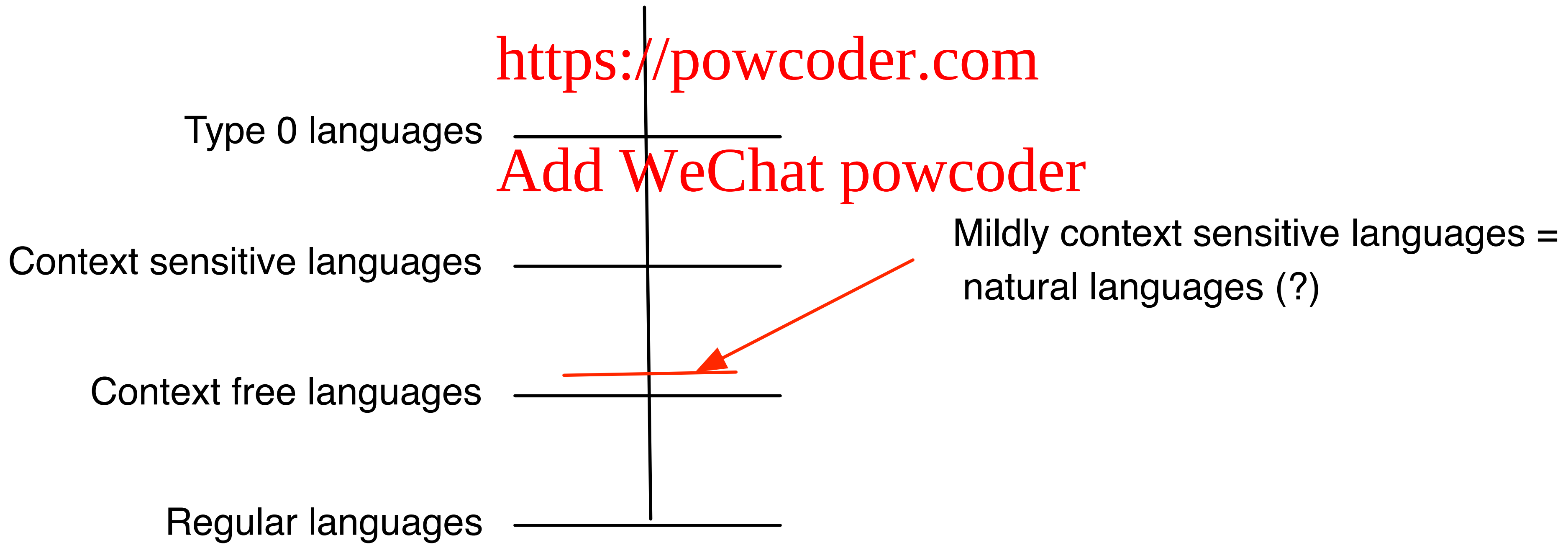
$$\begin{array}{cccccc}
Google & sells & but & Microsoft & buys & shares \\
\hline
NP & (S\backslash NP)/NP & conj & NP & (S\backslash NP)/NP & NP \\
\cline{1-1}\cline{4-4}
S/(S\backslash NP)\ {>}\mathbf{T} & & & S/(S\backslash NP)\ {>}\mathbf{T} & & \\
\cline{1-2}\cline{4-5}
\multicolumn{2}{c}{S/NP\ {>}\mathbf{B}} & & \multicolumn{2}{c}{S/NP\ {>}\mathbf{B}} & \\
\cline{1-5}
\multicolumn{5}{c}{S/NP\ {<}\Phi{>}} &
\end{array}$$

"Non-constituents" in CCG – Right Node Raising

$$
\begin{array}{cccccc}
\mathit{Google} & \mathit{sells} & \mathit{but} & \mathit{Microsoft} & \mathit{buys} & \mathit{shares} \\
\hline
NP & (S\backslash NP)/NP & conj & NP & (S\backslash NP)/NP & \color{blue}{NP} \\
\overline{S/(S\backslash NP)}^{>\mathbf{T}} & & & \overline{S/(S\backslash NP)}^{>\mathbf{T}} & & \\
\multicolumn{2}{c}{\overline{\qquad S/NP \qquad}^{>\mathbf{B}}} & & \multicolumn{2}{c}{\overline{\qquad S/NP \qquad}^{>\mathbf{B}}} & \\
\multicolumn{5}{c}{\overline{\qquad\qquad S/\color{blue}{NP} \qquad\qquad}^{<\Phi>}} & \\
\multicolumn{6}{c}{\overline{\qquad\qquad\qquad S \qquad\qquad\qquad}^{>}}
\end{array}
$$

Combinatory Categorial Grammar

- CCG is *mildly* context sensitive
- Natural language is provably non-context free
- Constructions in Dutch and Swiss German (Shieber, 1985) require more than context free power for their analysis
    - these have *crossing* dependencies (which CCG can handle)


Type 0 languages
Context sensitive languages
Context free languages
Regular languages
Mildly context sensitive languages = natural languages (?)

CCG Semantics

- Categories encode argument sequences
- Parallel syntactic combinator operations and lambda calculus semantic operations

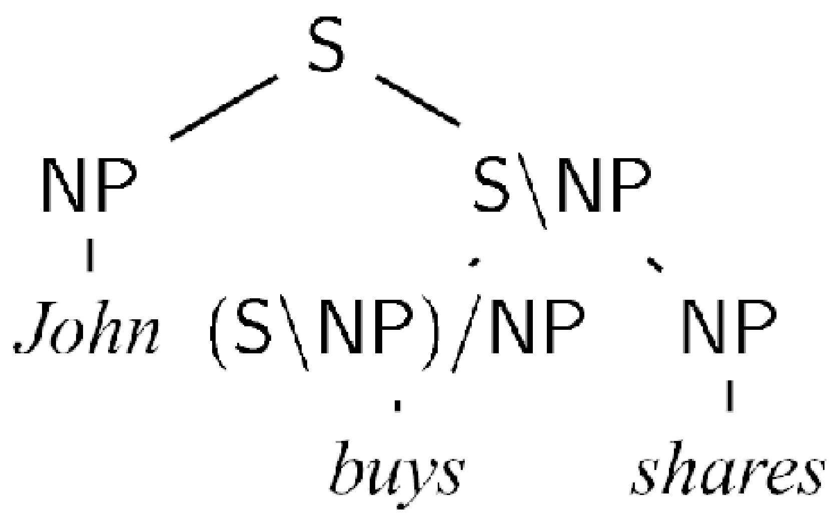
$John \vdash \mathrm{NP} : john'$

$shares \vdash \mathrm{NP} : shares'$

$buys \vdash (\mathrm{S}\backslash\mathrm{NP})/\mathrm{NP} : \lambda x.\lambda y.buys'xy$

$sleeps \vdash \mathrm{S}\backslash\mathrm{NP} : \lambda x.sleeps'x$

$well \vdash (\mathrm{S}\backslash\mathrm{NP})\backslash(\mathrm{S}\backslash\mathrm{NP}) : \lambda f.\lambda x.well'(fx)$



CCG Semantics

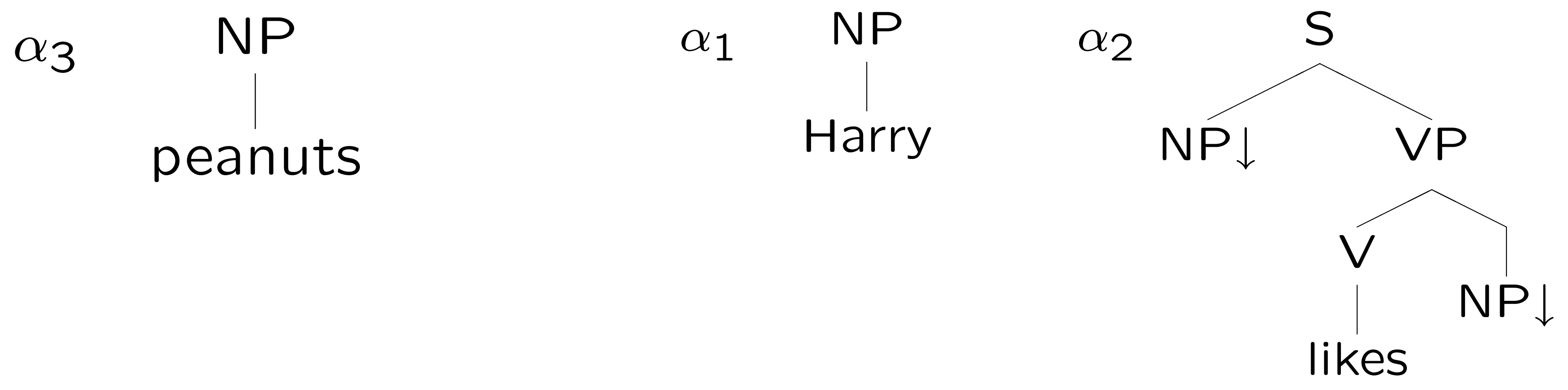
Left arg.	Right arg.	Operation	Result
X/Y : f	Y : a	Forward application	X : f(a)
Y : a	X\Y : f	Backward application	X : f(a)
X/Y : f	Y/Z : g	Forward composition	X/Z : λx.f(g(x))
X : a		Type raising	T/(T\X) : λf.f(a)

etc.

Tree Adjoining Grammar

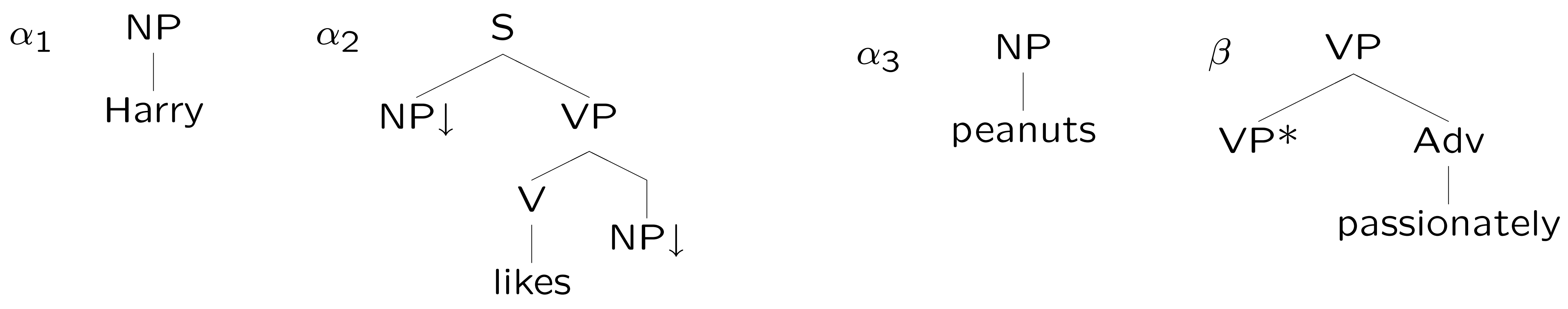
TAG Building Blocks

- Elementary trees (of many depths)
- Substitution at ↓
- Tree *Substitution* Grammar equivalent to CFG

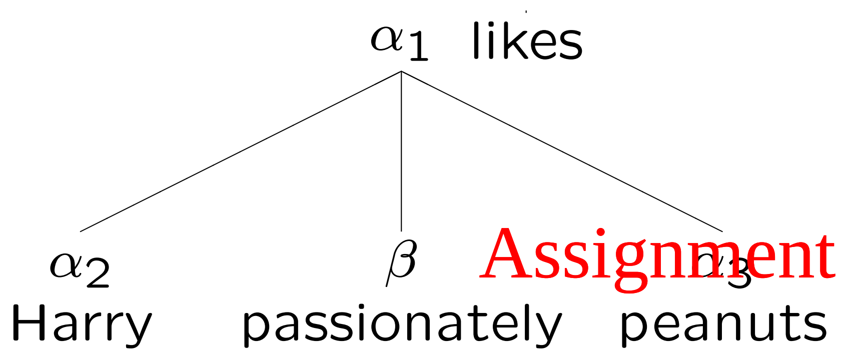


TAG Building Blocks

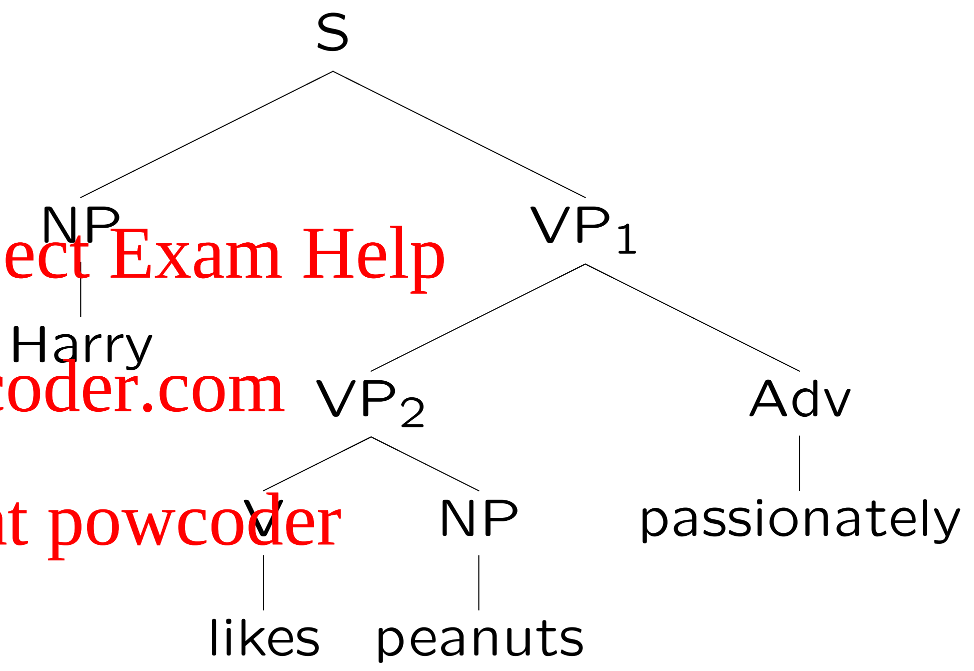
- Auxiliary trees for *adjunction*
- Adds extra power beyond CFG



Derivation Tree



Derived Tree



Semantics

$Harry(x) \wedge likes(e, x, y) \wedge peanuts(y) \wedge passionately(e)$