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# Abstract Categorical Grammars as a Model of the Syntax-Semantics Interface for TAG

Sylvain Pogodalla

`sylvain.pogodalla@inria.fr`  
LORIA/INRIA Nancy-Grand Est, Nancy, France

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Umeå, Sweden  
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# Overview

## 1 Introduction

- Motivations
- Mathematical Notions

## 2 Abstract Categorical Grammars

- Definitions and Notations
- Properties
- ACG as a Model for the Syntax-Semantics Interface

## 3 TAG as ACG

- Substitution and Adjunction as Function Application
- Generalized Derivation Trees
- Semantic Construction
- TAG Encoding

## 4 Discussion

# Abstract Categorical Grammars (de Groote 2001)

## Main Features

- ACG is a (grammatical) **framework**
- An ACG  $\mathcal{G}$  generates **two** languages:
  - ▶ The **abstract** language  $\mathcal{A}(\mathcal{G})$
  - ▶ The **object** language  $\mathcal{O}(\mathcal{G})$

**Abstract language:** Admissible *structures*

**Object language:** *Realizations* of the admissible structures

- Both languages are the same objects: sets of (linear)  $\lambda$ -terms

# Affiliations (I)

## A type-theoretic view on grammars and grammatical composition

- Finite set of atomic types (e.g., np, s, n, etc.)
- Type formation rules (e.g.,  $np \rightarrow s$  is a type)
- Grammatical composition follows typing rules (e.g.,  $np, np \rightarrow s \vdash s$ ,  $np \leftarrow n, n \vdash np$ )

## Applications

Grammatical formalisms:

- AB and classical categorial grammars (Ajdukiewicz 1935; Bar-Hillel 1953): **directed application**
- Lambek grammars (Lambek 1958): **hypothetical reasoning**
- Formulas-as-types and proofs-as-terms (Howard 1980; Benthem 1986) to provide Lambek Grammars with Montague semantics

# Types and Signatures

## Definition (Implicative types)

*Implicative types* built upon  $A$  are  $\mathcal{T}_A ::= A \mid \mathcal{T}_A \multimap \mathcal{T}_A \mid \mathcal{T}_A \rightarrow \mathcal{T}_A$

## Definition (Higher-Order Signatures)

A *higher-order signature*  $\Sigma$  is a triple  $\Sigma = \langle A, C, \tau \rangle$  where:

- $A$  is a finite set of atomic types;
- $C$  is a finite set of constants;
- $\tau : C \rightarrow \mathcal{T}_A$  is a function assigning types to constants.

## Example

- $A = \{\text{np}, \text{n}, \text{s}\}$
- $C = \{c_{\text{John}}, c_{\text{sleeps}}, \dots\}$
- $\tau(c_{\text{John}}) = \text{np}$ ,  $\tau(c_{\text{sleeps}}) = \text{np} \multimap \text{s}$ , ...

# Terms

## Definition ( $\lambda$ -Terms $\Lambda(\Sigma)$ )

$X$  an infinite countable set of  $\lambda$ -variables and  $\Sigma = \langle A, C, \tau \rangle$  a signature.  $\Lambda(\Sigma)$  consists of:

- $c \in C$
- $x \in X$
- $\lambda^{\circ}x.t$  ( $x$  occurs free in  $t$  exactly once);
- $\lambda x.t$
- $(t u)$

## $\beta$ -conversion

$$(\lambda^{\circ}x.t) u \rightarrow_{\beta} t[u/x]$$

# Type System

## Definition (Typing Judgment)

$\Gamma; \Delta \vdash_{\Sigma} t : \alpha$  where:

- $\Gamma$  is a finite *set* of non-linear variable typing declarations of the form  $x : \beta$ ;
- $\Delta$  is a finite *multi-set* of linear variable typing declarations of the form  $x : \beta$ .

## Typing rules

$$\begin{array}{c}
 \frac{}{\Gamma; \Delta \vdash_{\Sigma} c : \tau(c)} \text{ (const.)} \\
 \frac{}{\Gamma; x : \alpha \vdash_{\Sigma} x : \alpha} \text{ (lin. var.)} \quad \frac{}{\Gamma, x : \alpha; \vdash_{\Sigma} x : \alpha} \text{ (var.)} \\
 \frac{\Gamma; \Delta \vdash_{\Sigma} t : \beta}{\Gamma, x : \alpha; \Delta \vdash_{\Sigma} t : \beta} \text{ (weak.)} \\
 \frac{\Gamma; \Delta, x : \alpha \vdash_{\Sigma} t : \beta}{\Gamma; \Delta \vdash_{\Sigma} \lambda^{\circ} x. t : \alpha \rightarrow \beta} \text{ (lin. abs.)} \quad \frac{\Gamma; \Delta_1 \vdash_{\Sigma} t : \alpha \rightarrow \beta \quad \Gamma; \Delta_2 \vdash_{\Sigma} u : \alpha}{\Gamma; \Delta_1, \Delta_2 \vdash_{\Sigma} (tu) : \beta} \text{ (lin. app.)} \\
 \frac{\Gamma, x : \alpha; \Delta \vdash_{\Sigma} t : \beta}{\Gamma; \Delta \vdash_{\Sigma} \lambda x. t : \alpha \rightarrow \beta} \text{ (abs.)} \quad \frac{\Gamma; \Delta \vdash_{\Sigma} t : \alpha \rightarrow \beta \quad \Gamma; \vdash_{\Sigma} u : \alpha}{\Gamma; \Delta \vdash_{\Sigma} (tu) : \beta} \text{ (app.)}
 \end{array}$$



# Notations

- $\lambda x. \lambda y. t = \lambda x y. t$
- $((t u) v) w = t u v w$
- $\alpha \rightarrow (\beta \rightarrow (\gamma \rightarrow \delta)) = \alpha \rightarrow \beta \rightarrow \gamma \rightarrow \delta$
- infix notation: if  $+$  is a constant,  $(+ f) g = f + g$

# Example: The Vocabulary of Strings $\Sigma_{strings}$

 $\Sigma_{strings}$ 

- Types**
- $o$  is the unique atomic type
  - $\sigma = o \multimap o$  the type of strings (defined)
- Constants**
- $John, sleeps, a, b, \dots : \sigma$
  - $\# : o$
  - we define
    - ▶ an infix operator  $+ = \lambda^o f g. \lambda^o z. f(g z) : \sigma \multimap \sigma \multimap \sigma$
    - ▶  $\epsilon = \lambda^o x. x : \sigma$

## Example ( $\epsilon$ is neutral for $+$ )

$$\begin{aligned}
 a + \epsilon &= + a \epsilon \\
 &= (\lambda^o f g. \lambda^o z. f(g z)) a \epsilon \\
 &\rightarrow_{\beta} (\lambda^o g. \lambda^o z. a(g z)) \epsilon \\
 &\rightarrow_{\beta} \lambda^o z. a(\epsilon z) \\
 &\rightarrow_{\beta} \lambda^o z. a z \\
 &= a
 \end{aligned}$$

# Example

## Remark

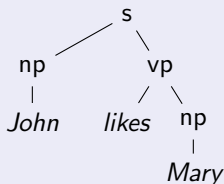
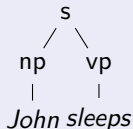
$$\begin{aligned}
 (t + u) z &= ((\lambda^{\circ} f \ g. \lambda^{\circ} z'. f (g \ z')) t \ u) z \\
 &\rightarrow_{\beta} (\lambda^{\circ} z'. t (u \ z')) z \\
 &\rightarrow_{\beta} t (u \ z)
 \end{aligned}$$

## Example (Associativity of +)

$$\begin{aligned}
 f + (g + h) &= (\lambda^{\circ} f' \ g'. \lambda^{\circ} z. f' (g' \ z)) f (g + h) \\
 &\rightarrow_{\beta} \lambda^{\circ} z. f ((g + h) \ z) \\
 &\rightarrow_{\beta} \lambda^{\circ} z. f (g (h \ z)) \\
 (f + g) + h &= (\lambda^{\circ} f' \ g'. \lambda^{\circ} z. f' (g' \ z)) (f + g) h \\
 &\rightarrow_{\beta} \lambda^{\circ} z. (f + g)(h \ z) \\
 &= \lambda^{\circ} z. f(g(h \ z))
 \end{aligned}$$

# Example: The Vocabulary of Trees $\Sigma_{trees}$

## Trees Built on a Ranked Alphabet


 $s_2 (np_1 \text{ John}) (vp_2 \text{ likes } (np_1 \text{ Mary}))$ 

 $s_2 (np_1 \text{ John}) (vp_1 \text{ sleeps})$ 

## Alphabet

- $s$  of arity 2 (non-terminal)
- $np$  of arity 1 (non-terminal)
- $vp?$   $vp_1$  of arity 1 and  $vp_2$  of arity 2 (non-terminals)
- $John$  of arity 0 (terminal)

## (Higher-Order) Signature

- $s_2 : \tau \multimap \tau \multimap \tau$
- $np_1 : \tau \multimap \tau$
- $vp_1 : \tau \multimap \tau$ ,  $vp_2 : \tau \multimap \tau \multimap \tau$
- $John : \tau$

## Affiliations (II)

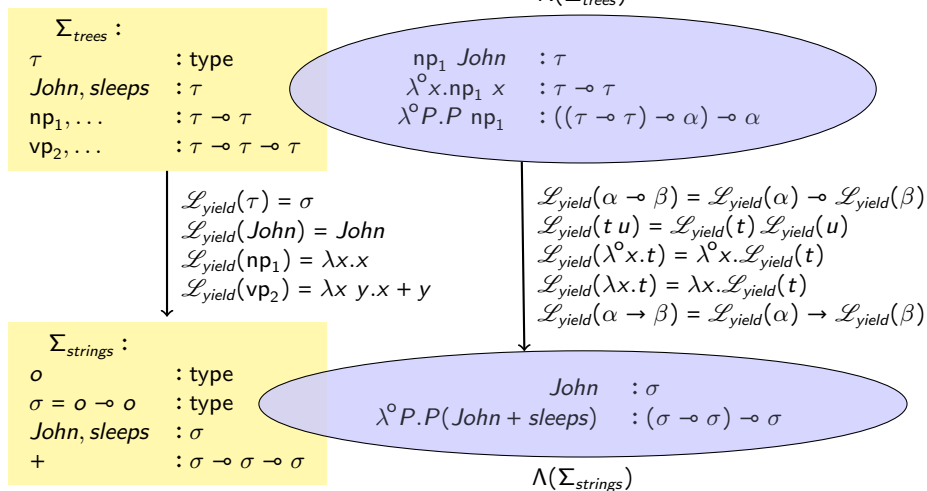
### Two levels for the grammatical architecture (Curry 1961)

- Tectogrammatics: “the study of [abstract] grammatical structure in itself” (e.g., the derivations)
- Phenogrammatics: “the study of the way [abstract] phrases are represented by expressions” (e.g., the yields)

The combinatorial properties of words (e.g., transitive verbs expect two np) are not described at the same place as their combinations are (e.g., SVO, SOV, etc.). The functorial types can be **undirected**.

### Applications

- Type theoretical grammar and GF (Ranta 1994; Ranta 2004)
- Labeled categorial systems (Oehrle 1994; Oehrle 1995),
- $\lambda$ -grammars (Muskens 2001; Muskens 2003)
- etc.

Relating  $\Lambda(\Sigma_{trees})$  to  $\Sigma_{strings}$  with  $\mathcal{L}_{yield}$ 

# Abstract Categorical Grammars

## Definition (Lexicon)

$\Sigma_1 = \langle A_1, C_1, \tau_1 \rangle$  and  $\Sigma_2 = \langle A_2, C_2, \tau_2 \rangle$  are two higher-order signatures.

A *lexicon*  $\mathcal{L} = \langle F, G \rangle$  from  $\Sigma_1$  to  $\Sigma_2$  is such that:

- $F : \mathcal{T}_{A_1} \rightarrow \mathcal{T}_{A_2}$  is an homomorphism
- $G : \Lambda(\Sigma_1) \rightarrow \Lambda(\Sigma_2)$  is an homomorphism
- $F$  and  $G$  are such that **for all  $c \in C_1$ ,  $\vdash_{\Sigma_2} G(c) : F(\tau_1(c))$  is provable.**

Notation: We use  $\mathcal{L}$  instead of  $F$  or  $G$ .

# Abstract Categorical Grammars

(de Groote 2001)

## Definition (Abstract Categorical Grammar)

An *abstract categorical grammar* is a quadruple  $\mathcal{G} = \langle \Sigma_1, \Sigma_2, \mathcal{L}, s \rangle$  where:

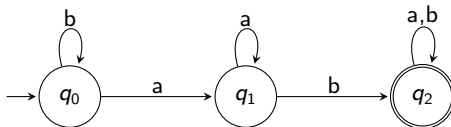
- $\Sigma_1$  and  $\Sigma_2$  are higher-order signatures
- $\mathcal{L} : \Sigma_1 \rightarrow \Sigma_2$  is a lexicon.
- $s \in \mathcal{T}_{A_1}$  is the *distinguished type* of the grammar.

Notations:

$$\left. \begin{array}{l} \mathcal{L}(\alpha) = \beta \\ \mathcal{G}(\alpha) = \beta \\ \alpha := \beta \\ \llbracket \alpha \rrbracket = \beta \end{array} \right\} \text{all denote that the interpretation of } \alpha \text{ is } \beta$$



# FSA Example



A signature  $\Sigma_{FSA}$  for transitions to  $q_2$

Atomic Types  $q_0$ ,  $q_1$ , and  $q_2$

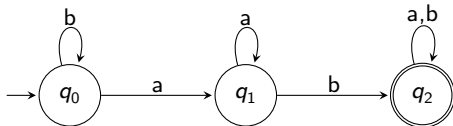
Constants  $\delta_{q_0,a} : q_1 \multimap q_0$   $\delta_{q_1,a} : q_1 \multimap q_1$   $\delta_{q_2,a} : q_2 \multimap q_2$   
 $\delta_{q_0,b} : q_0 \multimap q_0$   $\delta_{q_1,b} : q_2 \multimap q_1$   $\delta_{q_2,b} : q_2 \multimap q_2$   
 $F : q_2$

$$\delta_{q_0,a} \left( \overbrace{\delta_{q_1,a}}^{q_1} \left( \overbrace{\delta_{q_1,b}}^{q_1} F \right) \right) : q_0$$

## Remark

$q_2$  is reachable from  $q_i$  iff there exists  $t : q_i \in \Lambda(\Sigma_{FSA})$

## FSA Example (cont'd)



$$\Sigma_{FSA} : \begin{array}{lll} \delta_{q_0,a} : q_1 \multimap q_0 & \delta_{q_1,a} : q_1 \multimap q_1 & \delta_{q_2,a} : q_2 \multimap q_2 \\ \delta_{q_0,b} : q_0 \multimap q_0 & \delta_{q_1,b} : q_2 \multimap q_1 & \delta_{q_2,b} : q_2 \multimap q_2 \\ F : q_2 \end{array}$$

$$\Sigma_{strings} : \begin{array}{ll} a, b & : o \multimap o \\ \# & : o \end{array}$$

The  $\mathcal{G}_{FSA}$  ACGType interpretation  $q_0, q_1, q_2 :=_{FSA} o$ 

Constant interpretation

$$\begin{array}{lll} \delta_{q_0,a} & :=_{FSA} \lambda z. a z & \delta_{q_1,a} & :=_{FSA} a & \delta_{q_2,a} & :=_{FSA} a \\ \delta_{q_0,b} & :=_{FSA} b & \delta_{q_1,b} & :=_{FSA} b & \delta_{q_2,b} & :=_{FSA} b \\ F & :=_{FSA} \# \end{array}$$
Distinguished type  $q_0$ 

$$\begin{aligned} \llbracket \delta_{q_1,b} F \rrbracket_{FSA} &= \llbracket \delta_{q_1,b} \rrbracket_{FSA} \llbracket F \rrbracket_{FSA} & \delta_{q_1,a}(\delta_{q_1,b} F) & :=_{FSA} a(b \#) \\ &= b \# & \delta_{q_0,a}(\delta_{q_1,a}(\delta_{q_1,b} F)) & :=_{FSA} a(a(b \#)) \end{aligned}$$

# Languages of an ACG

## Definition (Abstract and Object Languages)

Let  $\mathcal{G} = \langle \Sigma_1, \Sigma_2, \mathcal{L}, s \rangle$  be an ACG.

The *abstract language* is defined by

$$\mathcal{A}(\mathcal{G}) = \{t \in \Lambda(\Sigma_1) \mid \vdash_{\Sigma_1} t : s \text{ is derivable}\}$$

The *object language* is defined by

$$\mathcal{O}(\mathcal{G}) = \{u \in \Lambda(\Sigma_2) \mid \exists t \in \mathcal{A}(\mathcal{G}) \text{ s.t. } u = \mathcal{L}(t)\}$$

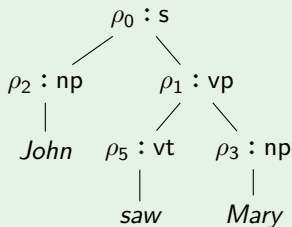
## ACG parsing

- $u \in \Lambda(\Sigma_2)$
- Does  $t \in \Lambda(\Sigma_1)$  exist such that  $\mathcal{L}(t) = u$ ?

## CFG into ACG Encoding

## Example (CFG)

$\rho_0 : s \rightarrow np\ vp$   
 $\rho_1 : vp \rightarrow vt\ np$   
 $\rho_2 : np \rightarrow John$   
 $\rho_3 : np \rightarrow Mary$   
 $\rho_4 : vp \rightarrow left$   
 $\rho_5 : vt \rightarrow saw$



$\Sigma_{Rules}$		$\Sigma_{Strings}$	
$np, vp, vt, s$	: atomic types	$\sigma$	
$\rho_0$	: $np \multimap vp \multimap s$	$\lambda xy. x + y$	: $\sigma \multimap \sigma \multimap \sigma$
$\rho_1$	: $vt \multimap np \multimap vp$	$\lambda xy. x + y$	: $\sigma \multimap \sigma \multimap \sigma$
$\rho_2$	: $np$	<i>John</i>	: $\sigma$
$\rho_3$	: $np$	<i>Mary</i>	: $\sigma$
$\rho_4$	: $vp$	<i>left</i>	: $\sigma$
$\rho_5$	: $vt$	<i>saw</i>	: $\sigma$

## CFG into ACG Encoding (cont'd)

## CFG as ACG

$\Sigma_{Rules}$		$\Sigma_{Strings}$	
np, vp, vt, s	: atomic types	$:=_{CFG}$	$\sigma$
$\rho_0$	: np $\multimap$ vp $\multimap$ s	$:=_{CFG}$	$\lambda xy.x + y : \sigma \multimap \sigma \multimap \sigma$
$\rho_1$	: vt $\multimap$ np $\multimap$ vp	$:=_{CFG}$	$\lambda xy.x + y : \sigma \multimap \sigma \multimap \sigma$
$\rho_2$	: np	$:=_{CFG}$	<i>John</i> : $\sigma$
$\rho_3$	: np	$:=_{CFG}$	<i>Mary</i> : $\sigma$
$\rho_4$	: vp	$:=_{CFG}$	<i>left</i> : $\sigma$
$\rho_5$	: vt	$:=_{CFG}$	<i>saw</i> : $\sigma$

$$\begin{aligned}
 \mathcal{L}_{CFG}(\rho_0 \rho_2 (\rho_1 \rho_5 \rho_3) : s) &= (\lambda xy.x + y) John((\lambda xy.x + y) saw Mary) \\
 &\rightarrow_{\beta} (\lambda y. John + y)((\lambda y. saw + y) Mary) \\
 &\rightarrow_{\beta} (\lambda y. John + y)(saw + Mary) \\
 &\rightarrow_{\beta} John + (saw + Mary)
 \end{aligned}$$

# About Linearity

Can we generate  $\{\omega\omega \mid \omega \in L\}$ ? **Yes**

Example ( $L$  is the language of any sequence of  $a$ 's and  $b$ 's)

$s'$	: type	$:=_{Dup}$	$\sigma$
$s$	: type	$:=_{Dup}$	$(\sigma \multimap \sigma \multimap \sigma) \multimap \sigma$
$\varepsilon$	: s	$:=_{Dup}$	$\lambda f.f \in \epsilon$
$A$	: $s \multimap s$	$:=_{Dup}$	$\lambda^{\circ} f.\lambda^{\circ} g.f(\lambda^{\circ} x y.g(a+x)(a+y))$
$B$	: $s \multimap s$	$:=_{Dup}$	$\lambda^{\circ} f.\lambda^{\circ} g.f(\lambda^{\circ} x y.g(b+x)(b+y))$
$C$	: $s \multimap s'$	$:=_{Dup}$	$\lambda^{\circ} f.f(\lambda^{\circ} x y.x+y)$

$$C(A(B(B\varepsilon))) : s' :=_{Dup} a + b + b + a + b + b : \sigma$$

# ACG Hierarchy

## Definition (Order)

The order  $\text{ord}(\tau)$  of a type  $\tau \in \mathcal{T}_A$  is inductively defined as:

- $\text{ord}(a) = 1$  if  $a \in A$
- $\text{ord}(\alpha \multimap \beta) = \text{ord}(\alpha \rightarrow \beta) = \max(1 + \text{ord}(\alpha), \text{ord}(\beta))$  otherwise

Ex:

- $\text{ord}(\text{np} \multimap \text{s}) = 2$
- $\text{ord}((\sigma \multimap \sigma \multimap \sigma) \multimap \sigma) = 4$  ( $\sigma = o \multimap o$  is not atomic!)

## Definition (Order and complexity of an ACG; ACG hierarchy)

- The *order* of an ACG is the maximum of the orders of its abstract constants.
- The *complexity* of an ACG is the maximum of the orders of the realizations of its atomic types.

# ACG: Formal Properties

(Groote and Pogodalla 2004; Salvati 2006; Kanazawa and Salvati 2007; Kanazawa 2009),  
(Salvati 2007; Kanazawa 2007; Kanazawa 2008; Kanazawa 2017)

## Generative Power

	String language	Tree language
$ACG_{(1,n)}$	finite	finite
$ACG_{(2,1)}$	regular	regular
$ACG_{(2,2)}$	context-free	linear context-free
$ACG_{(2,3)}$	non-duplicating macro well-nested multiple context-free	$\subset$ 1-visit attribute grammar
$ACG_{(2,4)}$	mildly context-sensitive (multiple context-free)	hyperedge replacement gram.
$ACG_{(2,4+n)}$	$ACG_{(2,4)}$	$ACG_{(2,4)}$
$ACG_{(3,n)}$	MELL decidability	MELL decidability

## Complexity

- $ACG_{(2,n)}$  parsing is polynomial, equivalent to datalog querying
- Reduces to best cases with standard techniques (magic set rewriting) with correct prefix Earley algorithms



# Higher Order Logic as an Object Language

## The $\Sigma_{logic}$ vocabulary

Types  $e, t$

Constants Logical constants

$\wedge$  :  $t \multimap t \multimap t$

$\Rightarrow$  :  $t \multimap t \multimap t$

$\exists$  :  $(e \multimap t) \multimap t$

$\vee$  :  $t \multimap t \multimap t$

$\neg$  :  $t \multimap t$

$\forall$  :  $(e \multimap t) \multimap t$

Non-logical constants

john :  $e$

sleep :  $e \multimap t$

seem :  $e \multimap (e \multimap t) \multimap t$

WHO :  $(e \multimap t) \multimap t$

love, chase :  $e \multimap e \multimap t$

seemingly, usually :  $t \multimap t$

claim, think :  $e \multimap t \multimap t$

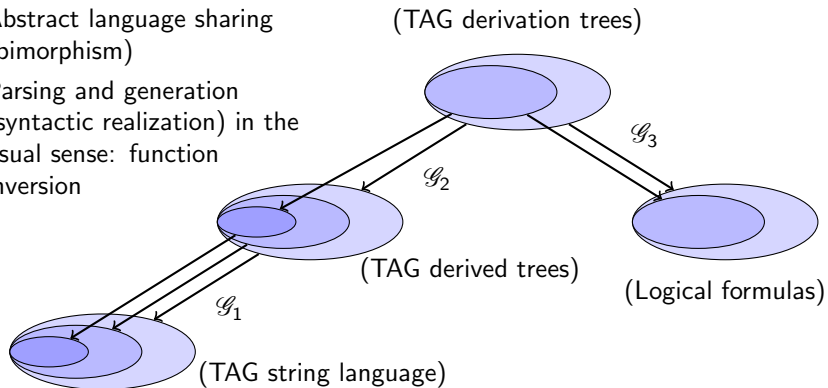
big, black, dog, cat :  $e \multimap t$

**ACG parsing** works exactly the same, whatever the object language

# ACG Architecture

## Composition Ability

- Functional composition
- Abstract language sharing (bimorphism)
- Parsing and generation (syntactic realization) in the usual sense: function inversion

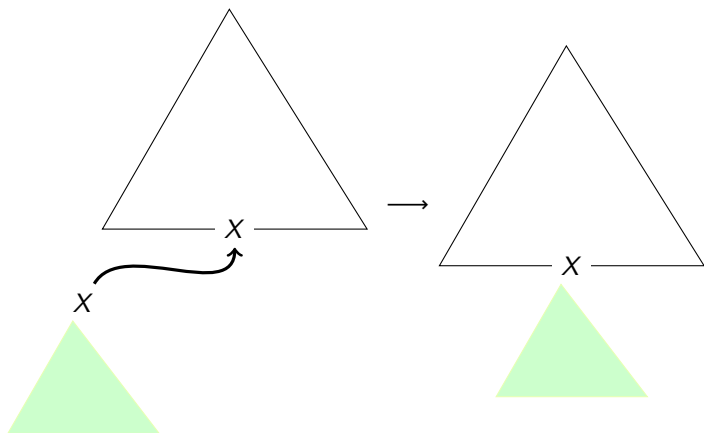


# Tree Adjoining Grammars

## Main features

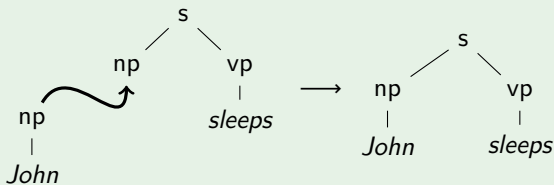
- Tree grammars with two operations
  - ▶ Substitution
  - ▶ Adjunction
- $L(\text{CFG}) \not\subseteq L(\text{TAG}) \not\subseteq L(\text{WnMCFG})$
- Allows for an *extended domain of locality* (Joshi 1994): locally specify (syntactic and semantic) dependencies between parts that can occur arbitrarily far from each other at the surface level at the end of a derivation

# Substitution



# Substitution as Functional Application

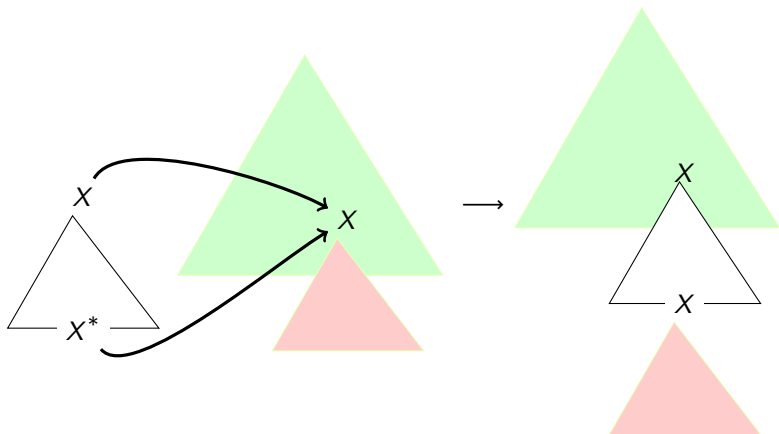
## Example



$$\left( \lambda^{\circ} x. \begin{array}{c} s \\ / \quad \backslash \\ x \quad \text{vp} \\ \quad \quad | \\ \quad \quad \text{sleeps} \end{array} \right) \left( \begin{array}{c} \text{np} \\ | \\ \text{John} \end{array} \right) \rightarrow_{\beta} \begin{array}{c} s \\ / \quad \backslash \\ \text{np} \quad \text{vp} \\ | \quad \quad | \\ \text{John} \quad \text{sleeps} \end{array}$$

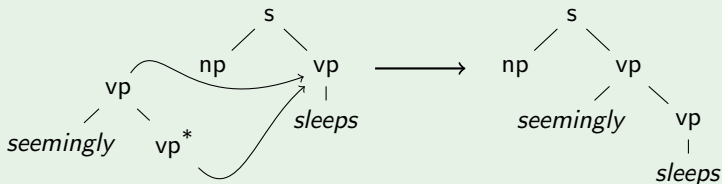
$$(\lambda^{\circ} x. s_2 x (\text{vp}_1 \text{sleeps})) (\text{np}_1 \text{John}) \rightarrow_{\beta} s_2 (\text{np}_1 \text{John}) (\text{vp}_1 \text{sleeps})$$

# Adjunction



# Auxiliary Trees as Functions

## Example



$$\left( \lambda^{\circ}x. \begin{array}{c} \text{vp} \\ / \quad \backslash \\ \text{seemingly} \quad x \end{array} \right) \text{vp} \begin{array}{c} | \\ \text{sleeps} \end{array} \rightarrow_{\beta} \begin{array}{c} \text{vp} \\ / \quad \backslash \\ \text{seemingly} \quad \text{vp} \\ | \\ \text{sleeps} \end{array}$$

$$\left( \lambda a. \text{np} \begin{array}{c} / \quad \backslash \\ \text{s} \quad a \left( \begin{array}{c} \text{vp} \\ | \\ \text{sleeps} \end{array} \right) \end{array} \right) \left( \lambda^{\circ}x. \begin{array}{c} \text{vp} \\ / \quad \backslash \\ \text{seemingly} \quad x \end{array} \right)$$





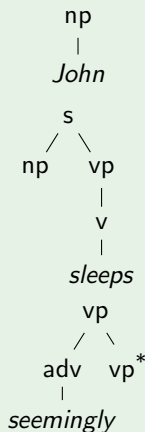
# Terms (of $\Lambda(\Sigma_{trees})$ ) for TAG Operations

$$\gamma_{John} = np_1 \text{ John} : \tau$$

$$\gamma_{sleeps} = \lambda^{\circ} S a s.S (s_2 s (a (vp_1 (v_1 \text{ sleeps})))) \\ : (\tau \multimap \tau) \multimap (\tau \multimap \tau) \multimap \tau \multimap \tau$$

$$\gamma_{seemingly} = \lambda^{\circ} a v.a (vp_2 (\text{adv}_1 \text{ seemingly}) v) \\ : (\tau \multimap \tau) \multimap \tau \multimap \tau$$

$$I = \lambda^{\circ} X.X : \tau \multimap \tau$$



$$\gamma_{sleeps} I (\gamma_{seemingly} I) \gamma_{John} \rightarrow_{\beta} s_2 (np_1 \text{ John}) (vp_2 (\text{adv}_1 \text{ seemingly}) (vp_1 (v_1 \text{ sleeps})))$$

$$\gamma_{sleeps} I (\gamma_{seemingly} I) \gamma_{John} :=_{\text{yield}} \text{John} + \text{seemingly} + \text{sleeps}$$

## So far...

- A vocabulary for strings  $\Sigma_{strings}$
- A vocabulary for trees  $\Sigma_{trees}$
- Yield of a tree as an ACG  $\mathcal{G}_{yield}$
- TAG operations on trees as applications of terms of  $\Lambda(\Sigma_{trees})$

**PB:** Not only TAG derived trees (e.g.,  $\gamma_{seemingly} I : \tau \multimap \tau$  and  $\gamma_{John} : \tau$ )

## TAG as ACG (1st part)

## Category Induced Constraints

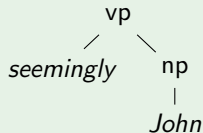
- The site of an adjunction has the same category as the root (and foot) node of the auxiliary tree
- The site of a substitution has the same category as the root node of the substituted tree

$\Sigma_{derivations}$		$\Lambda(\Sigma_{trees})$	
$c_{John}$	: np	$\gamma_{John}$	: $\mathcal{T}$
$c_{seemingly}$	: $(vp \multimap vp) \multimap vp \multimap vp$	$\gamma_{seemingly}$	: $(\mathcal{T} \multimap \mathcal{T}) \multimap \mathcal{T} \multimap \mathcal{T}$
np, vp, s...	: types		$\mathcal{T}$
$l_{vp}$	: $vp \multimap vp$	$l$	: $\mathcal{T} \multimap \mathcal{T}$

## Example

$c_{seemingly} l_{vp} c_{John}$  is not well-typed

There is no  $t : vp \in \Lambda(\Sigma_{derivations})$  such that  $t :=_{derived\ trees}$



## Control on the Derived Trees

$$\mathcal{G}_{\text{derived trees}} = \langle \Sigma_{\text{derivations}}, \Sigma_{\text{trees}}, \mathcal{L}_{\text{derived trees}}, \mathcal{S} \rangle$$

$$c_{\text{seemingly}} : (\text{vp} \multimap \text{vp}) \multimap \text{vp} \multimap \text{vp} \quad :=_{\text{derived trees}} \lambda^{\circ} a x . a \left( \begin{array}{c} s \\ / \quad \backslash \\ \text{seemingly} \quad x \end{array} \right)$$

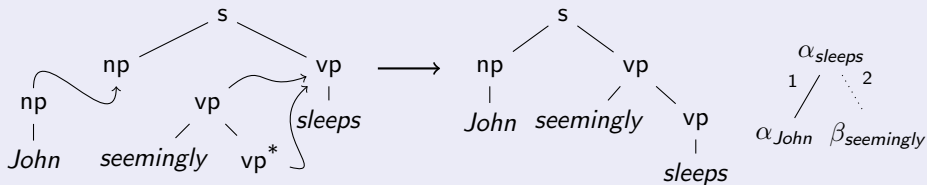
$$c_{\text{sleeps}} : (\text{s} \multimap \text{s}) \multimap (\text{vp} \multimap \text{vp}) \multimap \text{np} \multimap \text{s} \quad :=_{\text{derived trees}} \lambda^{\circ} S a s . S \left( \begin{array}{c} s \\ / \quad \backslash \\ s \quad \left( \begin{array}{c} s \\ / \quad \backslash \\ \text{vp} \\ | \\ \text{sleeps} \end{array} \right) \end{array} \right)$$

$$l_{\text{vp}} : \text{vp} \multimap \text{vp}$$

$$c_{\text{likes}} l_s (c_{\text{seemingly}} l_{\text{vp}}) c_{\text{John}} : \text{s} \quad :=_{\text{derived trees}} \begin{array}{c} s \\ / \quad \backslash \\ \text{np} \quad \text{vp} \\ | \quad / \quad \backslash \\ \text{John} \text{ seemingly} \quad \text{vp} \\ | \\ \text{sleeps} \end{array}$$

## TAG Derivation Trees as Abstract Terms

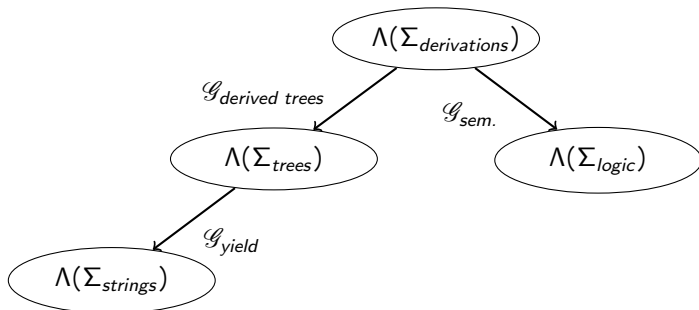
Derivation tree: to record the operations



$$\begin{array}{l}
 C_{sleeps} \ I_s \ (C_{seemingly} \ I_{vp}) \ C_{John} \\
 \\
 C_{likes} \\
 \\
 = \ I_s \begin{array}{c} \begin{array}{ccc} C_{likes} & & \\ \swarrow & | & \searrow \\ 0 & 1 & 2 \\ C_{seemingly} & & C_{John} \\ | & & \\ 0 & & \\ I_{vp} & & \end{array} \end{array} \\
 \\
 : \underbrace{(s \multimap s)}_0 \multimap \underbrace{(vp \multimap vp)}_2 \multimap \underbrace{np}_1 \multimap s
 \end{array}$$

## TAG as ACG

## Intermediate Picture



# Building a Semantic Representation

## $\Sigma_{derivations}$

$C_{John}$	: np
$C_{seemingly}$	: (vp $\multimap$ vp) $\multimap$ vp $\multimap$ vp
$C_{sleeps}$	: (s $\multimap$ s) $\multimap$ (vp $\multimap$ vp) $\multimap$ np $\multimap$ s
$I_{vp}$	: vp $\multimap$ vp

## $\Sigma_{logic}$

$\wedge, \vee, \Rightarrow$	: $t \multimap t \multimap t$
$\neg$	: $t \multimap t$
$\exists, \forall$	: $(e \rightarrow t) \multimap t$
john	: e
sleep	: $e \multimap t$
seemingly	: $t \multimap t$

## A standard interpretation *à la* Montague

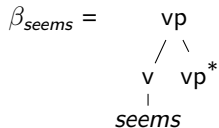
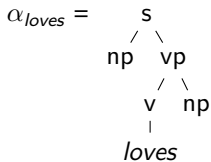
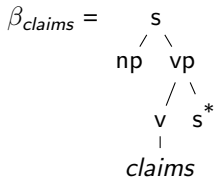
s	:= <sub>sem.</sub> t	np	:= <sub>sem.</sub> (e $\rightarrow$ t) $\multimap$ t
vp	:= <sub>sem.</sub> e $\rightarrow$ t	n	:= <sub>sem.</sub> e $\rightarrow$ t
$I_s$	:= <sub>sem.</sub> $\lambda^{\circ}x.x$	$C_{John}$	:= <sub>sem.</sub> $\lambda^{\circ}P.Pj$
$I_{vp}$	:= <sub>sem.</sub> $\lambda^{\circ}x.x$	$C_{seemingly}$	:= <sub>sem.</sub> $\lambda^{\circ}aP.a(\lambda x.seemingly (P x))$
		$C_{likes}$	:= <sub>sem.</sub> $\lambda^{\circ}S a s.S (s (a (\lambda x.seems x)))$

$$C_{sleeps} I_s (C_{seemingly} I_{vp}) C_{John} :=_{sem.} \text{seemingly (sleep j)}$$

# Long-Distance Dependencies

## Example

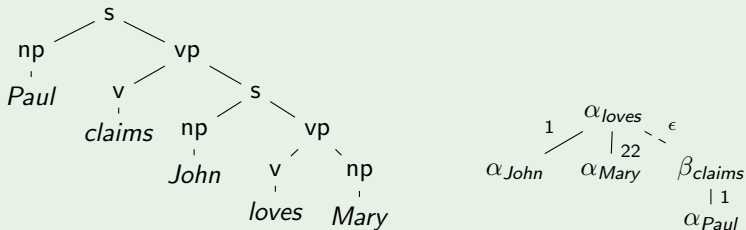
- (1) Paul claims John loves Mary
- (2) Paul claims John seems to love Mary
- (3) Who does Peter think Paul claims John seems to love





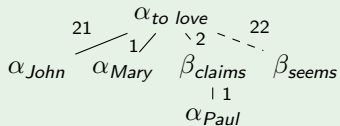
# Long-Distance Dependencies

## Example (Paul claims John loves Mary)



claim paul (love john mary)

## Example (Paul claims John seems to love Mary)



claim paul (seem john ( $\lambda x$ .love x mary))

# Long-Distance Dependencies

## The ACG Way

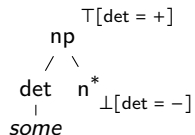
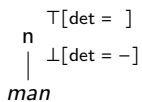
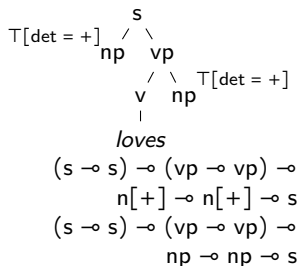
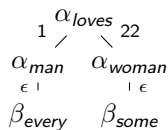
$$\begin{aligned}
 c_{claims} &:=_{sem.} \lambda^{\circ} adv_s adv_{vp} subj \textit{comp}.adv_s (subj (adv_{vp} (\lambda x. claim\ x\ \textit{comp}))) \\
 c_{seems} &:=_{sem.} \lambda^{\circ} mod \textit{pred}.mod (\lambda x. seem\ x\ \textit{pred}) \\
 c_{loves} &:=_{sem.} \lambda^{\circ} adv_s adv_{vp} subj obj.adv_s (subj (adv_{vp} (\lambda x. obj (\lambda y. love\ x\ y)))) \\
 c_{to\ love} &:=_{sem.} \lambda^{\circ} adv_s adv_{vp} obj subj.adv_s (subj (adv_{vp} (\lambda x. obj (\lambda y. love\ x\ y))))
 \end{aligned}$$

See the demo!

$$c_{loves} (c_{claims} I_s I_{vp} c_{Paul}) I_{vp} c_{John} c_{Mary} :=_{sem.} \textit{claim paul (love john mary)}$$

$$\begin{aligned}
 c_{to\ love} (c_{claims} I_s I_{vp} c_{Paul}) (c_{seems} I_{vp}) c_{Mary} c_{John} \\
 :=_{sem.} \textit{claim paul (seem john (\lambda x. love\ x\ mary))}
 \end{aligned}$$

## Quantification

(4) *every man loves some woman* $\forall x.\text{man}(x) \Rightarrow \exists y.\text{woman}(x) \wedge \text{love}(x, y)$  $n[-] \multimap n[+]$  $n \multimap \text{np}$  $(n[-] \multimap n[+]) \multimap n[+]$  $(n \multimap \text{np}) \multimap \text{np}$ 

# A Note on Feature Structures

- The ACG way corresponds to specifying adjunction constraints by *enumeration*
- Vijay-Shanker and Joshi (1988, p. 718):

*“... if we think of the auxiliary tree as corresponding to functions over feature structures (by  $\lambda$ -abstracting the variable corresponding to the feature structure for the tree that will appear below the foot node). Adjunction corresponds to applying this function to the feature structure corresponding to the subtree below the node where [it] takes place.”*

# Quantification

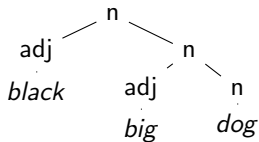
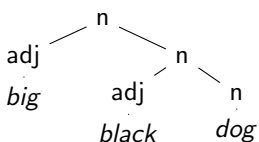
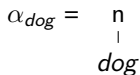
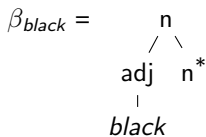
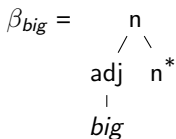
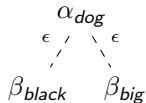
## The ACG Way

Constants of $\Sigma_{derivations}$	By $\mathcal{G}_{derived\ trees}$	By $\mathcal{G}_{sem.}$
$c_{man} : (n \multimap np) \multimap np$	$\lambda^{\circ} d.d (n_1 man)$	$\lambda^{\circ} Q.Q \text{ man}$
$c_{some} : n \multimap np$	$\lambda^{\circ} n.np_2 (\text{det}_1 \text{ some}) n$	$\lambda^{\circ} P Q.\exists x.(P x) \wedge (Q x)$
$c_{every} : n \multimap np$	$\lambda^{\circ} n.np_2 (\text{det}_1 \text{ every}) n$	$\lambda^{\circ} P Q.\forall x.(P x) \Rightarrow (Q x)$

$$c_{loves} I_s I_{vp} (c_{man} c_{every}) (c_{woman} c_{some}) :=_{sem.}$$

$$\forall x.(\text{man } x) \Rightarrow (\exists y.(\text{woman } y) \wedge (\text{love } x y))$$

## Multiple Modification

(5) *big black dog* $\text{black}(x) \wedge \text{big}(x) \wedge \text{dog}(x)$ (6) *black big dog* $\text{black}(x) \wedge \text{big}(x) \wedge \text{dog}(x)$  $\alpha_{\text{dog}}$   
|  
 $\epsilon$  $\beta_{\text{black}}$   
|  
 $\epsilon$  $\beta_{\text{big}}$  $\alpha_{\text{dog}}$   
|  
 $\epsilon$  $\beta_{\text{big}}$   
|  
 $\epsilon$  $\beta_{\text{black}}$ 

# Multiple Adjunction

The ACG way

$$\begin{aligned}
 c_{big} & : (n \multimap np) \multimap n \multimap np :=_{sem.} \lambda^{\circ} Q n.Q (\lambda x.(n x) \wedge (big x)) \\
 c_{black} & : (n \multimap np) \multimap n \multimap np :=_{sem.} \lambda^{\circ} Q n.Q (\lambda x.(n x) \wedge (black x)) \\
 c_{dog} & : (n \multimap np) \multimap np :=_{sem.} \lambda^{\circ} Q.Q dog
 \end{aligned}$$

$$\begin{aligned}
 \lambda^{\circ} D.c_{dog} (c_{black} (c_{big} D)) & :=_{sem.} \lambda^{\circ} D.D (\lambda x.((big x) \wedge (black x)) \wedge (dog x)) \\
 \lambda^{\circ} D.c_{dog} (c_{big} (c_{black} D)) & :=_{sem.} \lambda^{\circ} D.D (\lambda x.((black x) \wedge (big x)) \wedge (dog x))
 \end{aligned}$$

## Etc.

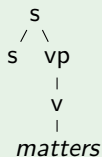
- Control verbs
- Idioms (based on Kobele 2012):  
 $c_{kicked\ the\ bucket} :=_{derived\ trees} \llbracket \lambda^o s\ a\ subj.\ c_{kicked}\ s\ a\ subj\ (c_{bucket}\ c_{the}) \rrbracket_{derived\ trees}$
- Subordinate Conjunctions
- Discourse connectives their syntax-semantics interface (Danlos, Maskharashvili, and Pogodalla 2016; Maskharashvili 2016)

Demo with:

- The ACG toolkit (<http://calligramme.loria.fr/acg#Software>)
- Signatures, lexicons, and scripts available from my web page (<http://members.loria.fr/sylvain.pogodalla>)

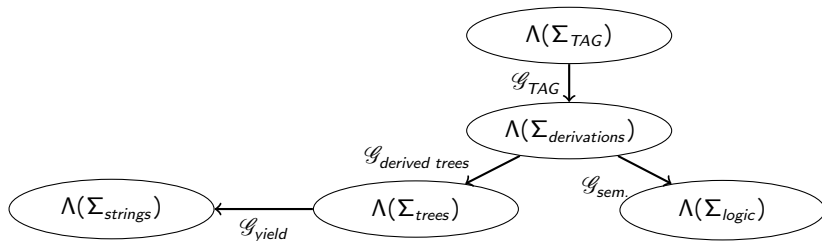


## TAG as ACG: Completing the Encoding

Example (*To arrive on time matters*)

$$c_{matters} : (vp \multimap vp) \multimap s \multimap s$$

- Not 2nd-order!
- $c_{matters} \upharpoonright_{vp} : s \multimap s$  has the type of an auxiliary tree. Overgeneration



$$\mathcal{G}_{TAG} = \langle \Sigma_{TAG}, \Sigma_{derivations}, \mathcal{L}_{TAG}, \mathcal{S} \rangle$$

(de Groote 2002)

Types and constants of  $\Sigma_{TAG}$

$np, s, \dots$

$vp_A$

$s_A$

$n_A$

$C_{sleeps} : s_A \multimap vp_A \multimap np \multimap s$

$C_{seemingly} : vp_A \multimap vp_A$

$I_s : s_A$

$I_{vp} : vp_A$

$C_{matters} : vp_A \multimap s \multimap s$

Their interpretations in  $\Lambda(\Sigma_{derivations})$

$np, s, \dots$

$vp \multimap vp$

$s \multimap s$

$n \multimap np$

$C_{sleeps} : (s \multimap s) \multimap (vp \multimap vp) \multimap np \multimap s$

$C_{seemingly} : (vp \multimap vp) \multimap vp \multimap vp$

$I_s : s \multimap s$

$I_{vp} : vp \multimap vp$

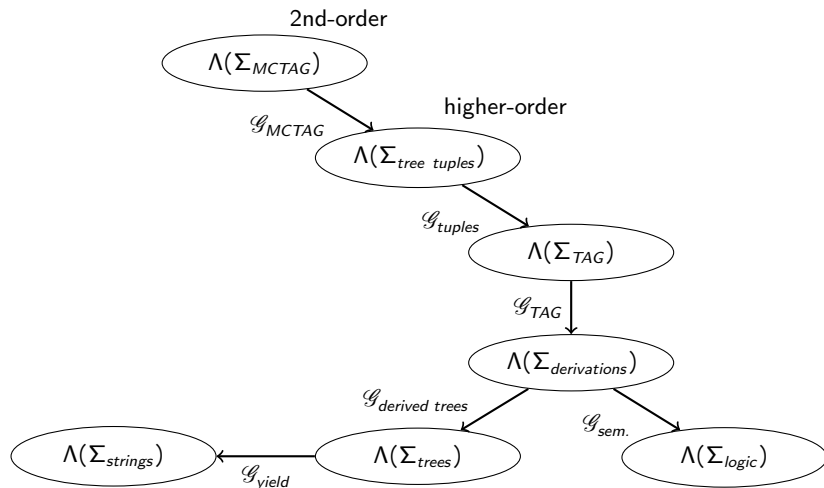
$C_{matters} : (vp \multimap vp) \multimap s \multimap s$

$\mathcal{G}_{TAG}$  is 2nd-order:

- Parsing results apply
- Both from strings and from logical formulas! See the demo

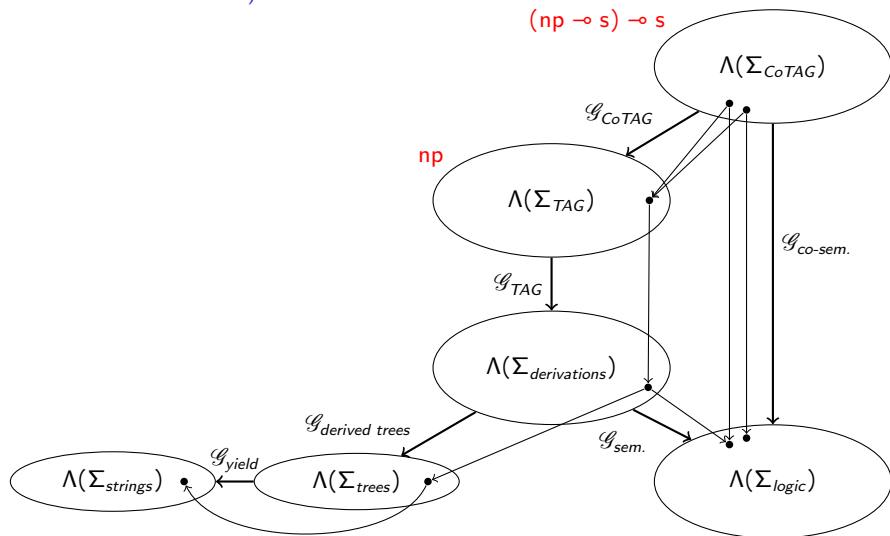
# Playing with the ACG Architecture

Multi-Component TAG (MCTAG Weir 1988)



# Playing with the ACG Architecture

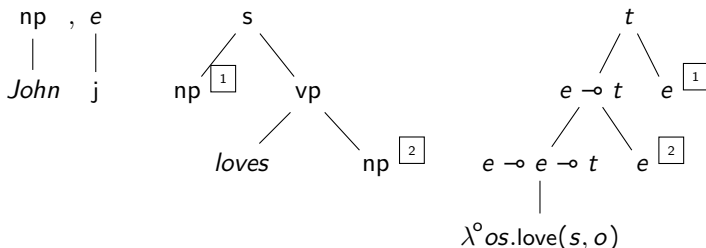
Scope Ambiguity: CoTAG (Barker 2010) as Type-raising (Pogodalla 2007b; Pogodalla 2007a; Kobele and Michaelis 2012)



## Related Approaches

Synchronous TAG (Nesson and Shieber 2006; Nesson 2009)

Syntactic and semantic derivations are performed synchronously:



- Need to interpret the semantic tree as  $love(j, m)$
- How to go from a logical formula  $f$  ( $\beta$ -reduced) to some possible semantic tree that gets interpreted as  $f$ ?
- Similar with Interpreted Regular Tree Grammars (Koller and Kuhlmann 2011; Koller and Kuhlmann 2012)

## Related Approaches

Semantics by Feature Unification (Gardent and Kallmeyer 2003; Kallmeyer and Romero 2004; Kallmeyer and Romero 2008)

### Principles:

- Semantic features are added (typically  $[Ind = x]$ ,  $[P = l]$  where  $l$  is the label of some logical formula)
- A representation language specifying the relations between the labels is used to plug together the logical formulas

### Limitations:

- No control on whether a feature that is asked at some node will be provided by another node (no static typing)
- Need to handle variable naming on-line (no  $\alpha$ -conversion)
- The lack of functional application requires using labels (first-order unification)
- How to inverse the process?

# Conclusion

## ACGs

- Flexible framework
- Interesting computational properties
- Modularity by composition, and type-checking
- Provides a unified way to extend other formalisms
- Reversible
- Integrate well with type-theoretic base semantic modelling (discourse dynamics, intensionalization, etc.)

## Work in progress

- Tractable 3rd-order fragments
- Logical equivalence (theoretically and practically)
- Optimization
- Semantics conservativity

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