Syntactic Formalisms for Parsing Natural Languages

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Parsing with CCG

Outline

- Categorial Grammar is
  - : a lexicalized theory of grammar along with other theories of grammar such as HPSG, TAG, LFG, ...
  - : linguistically and computationally attractive
    $\longrightarrow$ language invariant combination rules, high efficient parsing

Main idea in CG and *application operation*

- All natural language consists of <u>operators</u> and of <u>operands</u>.
  - Operator (functor) and operand (argument)
  - Application: (operator(operand))
  - Categorial type: typed operator and operand

1. A-B categorial system

The product of the directional adaptation by Bar-Hillel (1953) of Ajdukiewicz's calculus of syntactic connection (Ajdukiewicz, 1935)

Definition 1 (AB categories).
Given A, a finite set of *atomic categories*, the **set of categories C** is the smallest set such that:

- $A \subseteq C$
- $(X\backslash Y), (X/Y) \in C$ *if* $X, Y \in C$

1. A-B categorial system

- **Categories** (type): primitive categories and derivative categories
  - Primitive: S for sentence, N for nominal phrase
  - Derivative: $S/N, N/N, (S\backslash N)/N, NN/N, S/S \ldots$
- Forward($>$) and backward ($<$) **functional application**

$$\begin{array}{ll} a.\ X/Y\ Y \Rightarrow X & (>) \\ b.\ Y\ X\backslash Y \Rightarrow X & (<) \end{array}$$

1. A-B categorial system

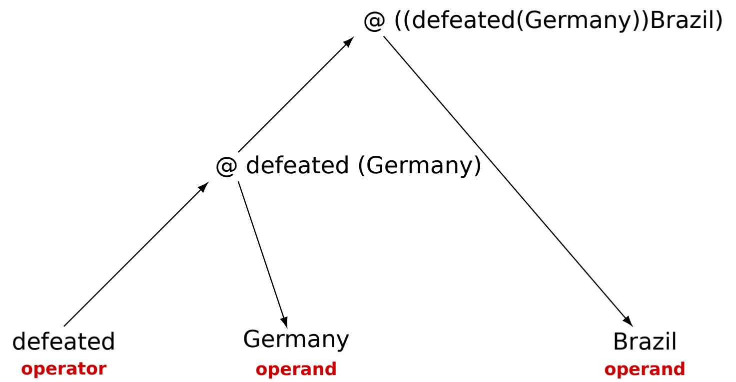
- **Calculus on types** in CG are analogue to **algebraic operations**

$$x/y\ y \rightarrow x \quad \approx \quad 3/5 * 5 = 3$$

$$\begin{array}{ccc} \textit{Brazil} & \textit{defeated} & \textit{Germany} \\ \hline n & (s\backslash n)/n & n \\ & \multicolumn{2}{c}{\overline{\qquad s\backslash n \qquad}{>}} \\ \multicolumn{3}{c}{\overline{\qquad\qquad s \qquad\qquad}{<}} \end{array}$$

1. A-B categorial system

Applicative tree of *Brazil defeated Germany*



Limitation of AB system

1. Relative construction

   a. team$_i$ that t$_i$ defeated Germany
   b. team$_i$ that Brazil defeated t$_i$
   a'. that $(n\backslash n)/(s\backslash n)$ team [that]$_{(n\backslash n)/(s\backslash n)}$ [defeated Germany]$_{s\backslash n}$
   b'. that $(n\backslash n)/(s/n)$ team [that]$_{(n\backslash n)/(s/n)}$ [Brazil defeated]$_{s/n}$

team	that	Brazil	defeated
	$(n\backslash n)/(s/n)$	n	$(s\backslash n)/n$
		←	(?)

3. Many others complex phenomena
   - Coordination, object extraction, phrasal verbs, ...
4. AB's generative power is too weak – *context-free*

2. Lambek calculus (Lambek, 1958, 1961)

the calculus of **syntactic types**
still *context-free*

The axioms of Lambek calculus are the following:

1. $x \rightarrow x$
2. $(xy)z \rightarrow x(yz) \rightarrow (xy)z$ (the axioms 1, 2 with inference rules, 3, 4, 5)
3. If $xy \rightarrow z$ then $x \rightarrow z/y$, if $xy \rightarrow z$ then $y \rightarrow x\backslash z$;
4. If $x \rightarrow z/y$ then $xy \rightarrow z$, if $y \rightarrow x\backslash z$ then $xy \rightarrow z$;
5. If $x \rightarrow y$ and $y \rightarrow z$ then $x \rightarrow z$.

2. Lambek calculus (Lambek, 1958, 1961)

The rules obtained from the previous axioms are the following:

1. Hypothesis: if x and y are types, then x/y and $y\backslash x$ are types.
2. Application rules : $(x/y)y \rightarrow x, y(y\backslash x) \rightarrow x$
   ex: *Poor John works.*
3. *Associativity rule :* $(x\backslash y)/z \leftrightarrow x\backslash(y/z)$
   ex: John likes Jane.
4. Composition rules : $(x/y)(y/z) \rightarrow x/z, (x\backslash y)(y\backslash z) \rightarrow x\backslash z$
   ex: *He likes him.*
   $s/(n\backslash s)n\backslash s/n$
5. *Type-raising rules :* $x \rightarrow y/(x/y), x \rightarrow (y/x)\backslash y$

3. Combinatory Categorial Grammar

- Developed originally by M. Steedman (1988, 1990, 2000, ...)
- Combinatory Categorial Grammar (CCG) is a grammar formalism equivalent to Tree Adjoining Grammar, i.e.
  - it is lexicalized
  - it is parsable in polynomial time (See Vijay-Shanker and Weir, 1990)
  - it can capture cross-serial dependencies
- Just like TAG, CCG is used for grammar writing
- CCG is especially suitable for statistical parsing

3. Combinatory Categorial Grammar

- several of the **combinators which Curry and Feys** (1958) use to define **the λ-calculus** and applicative systems in general are of considerable syntactic interest (Steedman, 1988)
- The relationships of these combinators to terms of the λ-calculus are defined by the following equivalences (Steedman, 2000b):

$$a.\mathbf{B}fg \equiv \lambda x.f(gx) \text{ ... composition}$$
$$b.\mathbf{T}x \equiv \lambda f.fx \text{ ... type-raising}$$
$$c.\mathbf{S}fg \equiv \lambda x.fx(gx) \text{ ... substitution}$$

CCG categories

- Atomic categories: S, N, NP, PP, TV...
- Complex categories are built recursively from atomic categories and slashes
- Example complex categories for verbs:
  - intransitive verb: $S\backslash NP$ walked
  - transitive verb: $(S\backslash NP)/NP$ respected
  - ditransitive verb: $((S\backslash NP)/NP)/NP$ gave

Lexical categories in CCG

- An elementary syntactic structure – a lexical category – is assigned to each word in a sentence, eg:

  walked: $S\backslash NP$ ‘give me an NP to my left and I return a sentence’
- Think of the lexical category for a verb as a function: NP is the argument, S the result, and the slash indicates the direction of the argument

The typed lexicon item

- The CCG lexicon assigns categories to words, i.e. it specifies which categories a word can have.
- Furthermore, the lexicon specifies the semantic counterpart of the syntactic rules, e.g.:

  love $(S\backslash NP)/NP \lambda x \lambda y.\text{loves}' xy$
- Combinatory rules determine what happens with the category and the semantics on combination

The typed lexicon item

- Attribution of types to lexical items: examples

Predicate

ex: is as an identificator of nominal

as an *operator of predication* from a nominal $\longrightarrow (S\backslash NP)/NP$

from an adjective $\longrightarrow (S\backslash NP)/(N/N)$

from an adverb $\longrightarrow (S\backslash NP)/(S\backslash NP)\backslash(S\backslash NP)$

from a preposition $\longrightarrow (S\backslash NP)/((S\backslash NP)\backslash(S\backslash NP)/NP)$

ex: verbs

- unary $(S\backslash NP)$
- binary $(S\backslash NP)/NP$
- ternary $(S\backslash NP)/NP/NP$

The typed lexicon item

Adverbs

Adverb of verb

$(S\backslash NP)/(S\backslash NP)$

$(S\backslash NP)/NP/(S\backslash NP)/NP$

Adverb of adverb

$(S\backslash NP)/(S\backslash NP)/(S\backslash NP)/(S\backslash NP)$

$(S\backslash NP)/NP/(S\backslash NP)/NP/(S\backslash NP)/NP/(S\backslash NP)/NP$

Adverb of adjective

$(N/N)/(N/N)$

$(N\backslash N)/(N\backslash N)$

Adverb of proposition

S/S

Adverb: operator of determination of type (X/X)

The typed lexicon item

Preposition

Prep. 1: constructor of adverbial phrase

$(S\backslash NP)\backslash(S\backslash NP)/NP$

$(S/S)/NP$

$(S/S)/N$

Prep. 2: constructor of adjectival phrase

$(N\backslash N)/NP$

$(N\backslash N)/N$

Preposition: constructor of determination of type (X/X)

Dictionary of typed words

Syntactic categories	Syntactic types	Lexical entries
Nom.	N	*Olivia, apple...*
Completed nom.	NP	*an apple, the school*
Pron.	NP	*She, he...*
Adj.	$(N/N), (N\backslash N)$	***pretty** woman,...*
Adv.	$(N/N)/(N/N)$, $(S\backslash NP)\backslash(S\backslash NP)...$	***very** delicious,...*
Vb	$(S\backslash NP), (S\backslash NP)/NP...$	*run, give...*
Prep.	$(S\backslash NP)\backslash(S\backslash NP)/NP$, $(NP\backslash NP)/NP...$	*run in the park, book of John, ...*
Relative	$(S\backslash NP)/S...$	*I believe that...*

Combinatorial categorial rules

- Functional application $(>, <)$
- Functional composition $(> \mathbf{B}, < \mathbf{B})$
- Type-raising $(< \mathbf{T}, > \mathbf{T})$
- Distribution $(< \mathbf{S}, > \mathbf{S})$
- Coordination $(< \Phi, > \Phi)$

Functional application (FA)

$X/Y : f \quad Y : a \Rightarrow X : fa$ (forward functional application, $>$)

$Y : a \quad X\backslash Y : f \Rightarrow X : fa$ (backward functional application, $<$)

- Combine a function with its argument:

$NP \; S\backslash NP$

S

Mary sleeps → (sleeps (Mary))

$NP \; (S\backslash NP)/NP \; NP$

$S\backslash NP$ → (likes (Mary))

S

John likes Mary → ((likes (Mary))John)

- Direction of the slash indicates position of the argument with respect to the function

Derivation in CCG

- The combinatorial rule used in each derivation step is usually indicated on the right of the derivation line
- Note especially what happens with the semantic information

John *loves* *Mary*

$NP : John' \quad (S\backslash NP)/NP : \lambda x \lambda y.loves'xy \quad NP : Mary'$

$S\backslash NP : \lambda y.loves'Mary'y \quad >$

$S : loves'Mary'John' \quad <$

Function composition (FC)

Generalized forward composition $(> \boldsymbol{Bn})$

$$X/Y : f \qquad Y/Z : g \quad \Rightarrow_B \quad X/Z : \lambda x.f(gx) \qquad (> B)$$

- Functional composition composes two complex categories (two functions):

$$(S\backslash NP)/PP \quad (PP/NP) \Rightarrow_B (S\backslash NP)/NP$$
$$S/(S\backslash NP) \quad (S\backslash NP)/NP \Rightarrow_B S/NP$$

birds — like — bugs

$$\frac{\dfrac{\dfrac{\dfrac{\text{birds}}{NP}}{S/(S\backslash NP)}{>T} \quad \dfrac{\text{like}}{(S\backslash NP)/NP}}{S/NP}{>B} \quad \dfrac{\text{bugs}}{NP}}{S}{>}$$

Function composition (FC)

Generalized backward composition $(< \boldsymbol{Bn})$

$$Y\backslash Z : f \qquad X\backslash Y : g \Rightarrow_B X\backslash Z : x.f(gx) \qquad (< B)$$

The referee gave — *Unsal* — *a card* — *and* — *Rivaldo* — *the ball*

- *The referee gave*: $(s/np)/np$
- *Unsal*: np $\xrightarrow{<T}$ $(s/np)\backslash((s/np)/np)$
- *a card*: np $\xrightarrow{<T}$ $s\backslash(s/np)$
- Unsal a card $\xrightarrow{<B}$ $s\backslash((s/np)/np$
- *and*: $(X\backslash X)/X$
- *Rivaldo*: np $\xrightarrow{<T}$ $(s/np)\backslash((s/np)/np)$
- *the ball*: np $\xrightarrow{<T}$ $s\backslash(s/np)$
- Rivaldo the ball $\xrightarrow{<B}$ $s\backslash((s/np)/np$
- Unsal a card and Rivaldo the ball $\xrightarrow{<\Phi>}$ $s\backslash((s/np)/np$
- The referee gave … $\xrightarrow{<}$ s

Type-raising (T)

Forward type-raising $(> \boldsymbol{T})$

$$X : a \Rightarrow T/(T\backslash X) : \lambda f.fa \qquad (> T)$$

- Type-raising turns an argument into a function (e.g. for case assignment)

$$NP \Rightarrow S/(S\backslash NP) \text{ (nominative)}$$

$$\frac{\dfrac{\textit{birds}}{NP} \quad \dfrac{\textit{fly}}{S\backslash NP}}{S}{<} \qquad\qquad \frac{\dfrac{\dfrac{\textit{birds}}{NP}}{S/(S\backslash NP)}{>T} \quad \dfrac{\textit{fly}}{S\backslash NP}}{S}{>}$$

- This must be used *e.g. in the case of WH-questions*

Example of functional composition $(> \boldsymbol{B})$ and type-raising (T)

team — *that* — *I* — *thought* — *that* — *Brazil* — *defeated*

- *team*: n
- *that*: $(n\backslash n)/(s/np)$
- *I*: np $\xrightarrow{>T}$ $s/(s\backslash np)$
- *thought*: $(s\backslash np)/s$
- I thought $\xrightarrow{>B}$ s/s
- *that*: s/s
- *Brazil*: np $\xrightarrow{>T}$ $s/(s\backslash np)$
- *defeated*: $(s\backslash np)/np$
- Brazil defeated $\xrightarrow{>B}$ s/np
- that Brazil defeated $\xrightarrow{>B}$ s/np
- I thought that Brazil defeated $\xrightarrow{>B}$ s/np
- that I thought that Brazil defeated $\xrightarrow{>}$ $n\backslash n$
- team that I thought that Brazil defeated $\xrightarrow{<}$ n

Example of functional composition ($> B$) and type-raising (T)

Backward type-raising ($< \boldsymbol{T}$)

$$X : a \Rightarrow T\backslash(T/X) : \lambda f.fa \qquad (< T)$$

- Type-raising turns an argument into a function (e.g. for case assignment)

$$NP \Rightarrow (S\backslash NP)\backslash((S\backslash NP)/NP) \text{ (accusative)}$$

The referee gave	*Unsal*	*a card*	*and*	*Rivaldo*	*the ball*
$(s/np)/np$	np	np	$(X\backslash X)/X$	np	np
	$<T$: $(s/np)\backslash((s/np)/np)$	$<T$: $s\backslash(s/np)$		$<T$: $(s/np)\backslash((s/np)/np)$	$<T$: $s\backslash(s/np)$
	$<B$: $s\backslash((s/np)/np)$			$<B$: $s\backslash((s/np)/np)$	
	$<\Phi>$: $s\backslash((s/np)/np)$				
$<$: s					

Coordination (&)

$$X \; CONJ \; X \Rightarrow_{\Phi} X \qquad (Coordination(\Phi))$$

give	*a dog*	*a bone*	*and*	*a policeman*	*a flower*
$(VP/NP)/NP$	$<T$: $(VP/NP)\backslash((VP/NP)/NP)$	$<T$: $VP\backslash(VP/NP)$	conj	$<T$: $(VP/NP)\backslash((VP/NP)/NP)$	$<T$: $VP\backslash(VP/NP)$
	$<B$: $VP\backslash((VP/NP)/NP)$			$<B$: $VP\backslash((VP/NP)/NP)$	
	$<\&>$: $VP\backslash((VP/NP)/NP)$				
$<$: VP					

Substitution (S)

Forward substitution ($> \boldsymbol{S}$)

$$(X/Y)/Z \; Y/Z \Rightarrow_S X/Z$$

- Application to parasitic gap such as the following:

a. *team that I persuaded every detractor of to support*

team	that	I	persuaded	every detractor of	to support
	$(n\backslash n)/(s/np)$	np	$((s\backslash np)/(s\backslash np))/np$	np/np	$(s\backslash np)/np$
		$>T$: $s/(s\backslash np)$	$>B$: $((s\backslash np)/(s\backslash np))/np$		
			$>S$: $(s\backslash np)/np$		
		$>B$: s/np			
	$>$: $n\backslash n$				

Substitution (S)

Backward crossed substitution ($< \boldsymbol{S}\times$)

$$Y/Z \; (X\backslash Y)/Z \Rightarrow_S X/Z$$

- Application to parasitic gap such as the following:

a. *John watched without enjoying the game between Germany and Paraguay.*

b. game that John watched without enjoying

game that John [watched]$_{(s\backslash np)/np}$ [without enjoying]$_{((s\backslash np)\backslash(s\backslash np))/np}$

game	*that*	*John*	*watched*	*without enjoying*
	$(n\backslash n)/(s/np)$	np	$(s\backslash np)/np$	$((s\backslash np)\backslash(s\backslash np))/np$
		$>T$: $s/(s\backslash np)$	$<S_\times$: $(s\backslash np)/np$	
		$>B$: $s/(s\backslash np)$		
	$>$: $n\backslash n$			

Limit on possible rules

- The Principle of Adjacency:

Combinatory rules may only apply to entities which are linguistically realised and adjacent.

- The Principle of Directional Consistency:

All syntactic combinatory rules must be consistent with the directionality of the principal function. ex: $X\backslash Y \; Y \not=> X$

- The Principle of Directional Inheritance:

If the category that results from the application of a combinatory rule is a function category, then the slash defining directionality for a given argument in that category will be the same as the one defining directionality for the corresponding arguments in the input functions. ex: $X/Y \; Y/Z \not=> X\backslash Z$.

Semantic in CCG

- CCG offers a syntax-semantics interface.
- The lexical categories are augmented with an explicit identification of their semantic interpretation and the rules of functional application are accordingly expanded with an explicit semantics.
- Every syntactic category and rule has a semantic counterpart.
- The lexicon is used to pair words with syntactic categories and semantic interpretations:

$$love \; (S\backslash NP)/NP \Rightarrow \lambda x \lambda y.loves'xy$$

Semantic in CCG

- The semantic interpretation of all combinatory rules is fully determined by the **Principle of Type Transparency**:
  - **Categories**: All syntactic categories reflect the semantic type of the associated logical form.
  - **Rules**: All syntactic combinatory rules are type-transparent versions of one of a small number of semantic operations over functions including application, composition, and type-raising.

Semantic in CCG

proved $:= (S\backslash NP_{3s})/NP : \lambda x \lambda y.prove'xy$

- the semantic type of the reduction is the same as its syntactic type, here functional application.

$$\dfrac{\dfrac{Marcel}{NP_{3sm} : marcel'} \quad \dfrac{\dfrac{proved}{(S\backslash NP_{3s})/NP : \lambda x \lambda y.prove'xy} \quad \dfrac{completeness}{NP : completeness'}}{S\backslash NP_{3s} : \lambda y.prove'completeness'y}>}{S : prove'completeness'marcel'}<$$

Semantic in CCG

CCG with semantics : ***Mary will copy and file without reading these articles***

Mary will	*copy*	*and*	*file*	*without*	*reading*	*these articles*
S/VP :p.Mary'	VP/NP λp.will'	:copy' CONJ	:and' VP/NP	:file' (VP\VP)/VPing λp.λq.without'pq	VPing/NP :read'	NP :articles'

(VP\VP)/VPing :λx.λq.without'(read' x)q >B

VP/NP :λx.without'(read'x)(file'x) <S

VP/NP :λx.and'(without'(read'x)(file'x))(copy'x) $< \Phi >$

VP :and'(without')(read'articles')(file'articles'))(copy'articles') <

S :will'(and'(without')(read'articles')(file'articles'))(copy'articles'))mary' >

Parsing a sentence in CCG

Step 1: tokenization

Step 2: tagging the concatenated lexicon

Step 3:

- calculate on types attributed to the concatenated lexicons by applying the adequate combinatorial rules
- eliminate the applied combinators (we will see how to do on next week)

Step 4: finding the parsing results presented in the form of an operator/operand structure (predicate -argument structure)

Parsing a sentence in CCG

Example: *I requested and would prefer musicals*

STEP 1 : tokenization/lemmatization $\rightarrow$ *ex) POS Tagger, tokenizer, lemmatizer*

a. *I-requested-and-would-prefer-musicals*

b. *I-request-ed-and-would-prefer-musical-s*

STEP 2 : tagging the concatenated expressions $\rightarrow$ *ex) Supertagger, Inventory of typed words*

I	*NP*
Requested	$(S\backslash NP)/NP$
And	*CONJ*
Would	$(S\backslash NP)/VP$
Prefer	VP/NP
musicals	*NP*

Parsing a sentence in CCG

STEP 3 : categorial calculus

a. apply the type-raising rules $\longrightarrow$ *Subject Type-raising* $(>T)$
$NP : a \Rightarrow T/(T\backslash NP) : Ta$

b. apply the functional composition rules $\longrightarrow$ *Forward Composition:* $(>B)$
$X/Y : f \quad Y/Z : g \Rightarrow X/Z : Bfg$

c. apply the coordination rules $\longrightarrow$ *Coordination:* $(<\&>)$
$X\ conj\ X \Rightarrow X$

	I-	requested-	and-	would-	prefer-	musicals	
1/	NP	$(S\backslash NP)/NP$	CONJ	$(S\backslash NP)/VP$	VP/NP	NP	
2/	$S/(S\backslash NP)$	$(S\backslash NP)/NP$	CONJ	$(S\backslash NP)/VP$	VP/NP	NP	(>T)
3/	$S/(S\backslash NP)$	$(S\backslash NP)/NP$	CONJ	$(S\backslash NP)/NP$		NP	(>B)
4/	$S/(S\backslash NP)$	$(S\backslash NP)/NP$				NP	$(>\Phi)$
5/	$S/(S\backslash NP)$	$(S\backslash NP)/NP$				NP	(>B)
6/	S/NP					NP	(>)
7/				**S**			

Parsing a sentence in CCG

STEP 4 : semantic representation (predicate-argument structure)

I requested and would prefer musicals

1/ :i' :request' :and' : will' :prefer' : musicals'

2/ :λf.f I'

3/ : λx.λy.will'(prefer'x)y

4/ : λxλy.and'(will'(prefer'x)y)(request'xy)

5/ : λxλy.and'(will'(prefer'x)y)(request'xy)

6/ :λy.and'(would'(prefer' musicals')y)(request' musicals' y)

7/S: and'(will'(prefer' musicals') i')(request' musicals' i')

Variation of CCG : Multi-modal CCG (Baldridge, 2002)

- Modalized CCG system
- Combination of Categorial Type Logic (CTL, Morrill, 1994; Moortgat, 1997) into the CCG (Steedman, 2000)
- Rules restrictions by introducing the modalities: *, x, •, ◊
- Modalized functional composition rules

$$
\begin{array}{llll}
(> B) & X/_{\Diamond}Y \quad Y/_{\Diamond}Z & \Rightarrow & X/_{\Diamond}Z \\
(< B) & X\backslash_{\Diamond}Y \quad Y\backslash_{\Diamond}Z & \Rightarrow & X\backslash_{\Diamond}Z
\end{array}
$$

- Invite you to read the paper "*Multi-Modal CCG*" of (Baldridge and M.Kruijff, 2003)

The positions of several formalisms on the Chomsky hierarchy