Combinatory Categorial Grammar (CCG)

11-711 Algorithms for NLP

30 November 2017

(With thanks to Alan W Black)

Goals of CCG

- Simplify the (*combinatory*) rules
- Move complexity from rules to (*categorial*) lexical entries
- More tightly couple with semantics, particularly lambda calculus
- One-to-one relationship between syntactic and semantic constituents

Five (5) rules!

- Application:
  - Forward: A/B + B = A
  - Backward: B + A\B = A
- Composition:
  - A/B + B/C = A/C
- Coordination:
  - X CONJ X’ = X”
- Type raising:
  - A = X/(X\A)

John = np *(an argument category)*

Mary = np

likes = (s\np)/np *(a functor category)*

Forward application

X/Y Y => X

Backward application

Y X\Y => X

Thus:

```
John  likes      Mary
 np   (s\np)/np  np
      ---------------- Forward
         s\np
 ------------- Backward
      s
```

a,the	np/n
old	**n/n**
in	(np\np)/np
man,ball,park	n
kicked	(s\np)/np

the	**old**	man	kicked	a	ball	in	the	park
np/n	**n/n**	n	(s\np)/np	np/n	n	(np\np)/np	np/n	n
	------							
	n							

a,the **np/n**
old n/n
in (np\np)/np
man,ball,park n
kicked (s\np)/np

```
the   old man kicked      a     ball in           the   park
np/n  n/n n   (s\np)/np   np/n  n    (np\np)/np   np/n  n
      ------              -------                 -------
        n                   np                      np
----------
   np
```

a,the	np/n
old	n/n
in	**(np\np)/np**
man,ball,park	n
kicked	(s\np)/np

```
the   old man kicked      a      ball in             the   park
np/n n/n n     (s\np)/np np/n n     (np\np)/np np/n n
      ------                -------                  -------
         n                     np                       np
 ----------                              -----------------
    np                                          np\np
                            -----------------------
                                      np
```

a,the	np/n
old	n/n
in	(np\np)/np
man,ball,park	n
kicked	**(s\np)/np**

```
the   old man kicked     a      ball in              the   park
np/n n/n n      (s\np)/np np/n n      (np\np)/np np/n n
        ------                     -------                     -------
          n                          np                          np
 ----------                                  ------------------
    np                                              np\np
                                   -------------------------
                                                np
                       --------------------------
                                   s\np
  --------------------------------
                      s
```

Handling Coordination

- Constituent Coordination
  - John and Mary like books

    (NP and NP) VP
  - John likes fishing and dislikes baseball.

    NP (VP and VP)
- Non-constituent coordination
  - John likes and Mary dislikes sports.

    ???

Coordination

X CONJ X’ => X”

John **likes** **Mary** and **dislikes** **Bob**

np **(s\np)/np np** conj **(s\np)/np np**

---------------FA **----------------FA**

s\np **s\np**

Coordination

X CONJ X’ => X”

John likes Mary **and** dislikes Bob

np (s\np)/np np **conj** (s\np)/np np

--------------FA --------------FA

s\np s\np

---------------------------------------CONJ

s\np

---BA

s

Type Raising

TR: X => Y/(Y\X)

COMP: A/B + B/C => A/C

John	likes	and	**Mary**	dislikes	Bob
np	(s\np)/np	conj	**np**	(s\np)/np	np
------TR			**-------TR**		
s/(s\np)			**s/(s\np)**		

Type Raising

TR: X => Y/(Y\X)

COMP: A/B + B/C => A/C

John likes and **Mary dislikes** Bob

np (s\np)/np conj np (s\np)/np np

------TR -------TR

s/(s\np) s/(s\np)

----------------COMP ----------------COMP

s/np **s/np**

Type Raising

TR: X => Y/(Y\X)

COMP: A/B + B/C => A/C

```
John likes         and      Mary dislikes      Bob
np     (s\np)/np   conj     np      (s\np)/np  np
------TR                    -------TR
s/(s\np)                    s/(s\np)
-----------------COMP       -----------------COMP
        s/np                         s/np
--------------------------------------------- CONJ
                    s/np
```

Type Raising

TR: X => Y/(Y\X)

COMP: A/B + B/C => A/C

```
John likes        and      Mary dislikes      Bob
np    (s\np)/np conj      np    (s\np)/np    np
------TR                  -------TR
s/(s\np)                  s/(s\np)
-----------------COMP -----------------COMP
        s/np                      s/np
------------------------------------------ CONJ
                    s/np
-----------------------------------------------
                      s
```

Type Raising

- Computationally unbounded:
  - could happen for any category
  - makes parsing intractable
- Controlled type raising
  - needs to be guarded
  - only (some) lexical items

CCG Semantics

- Remember goals:
  - More tightly couple with semantics, particularly lambda calculus
  - One-to-one relationship between syntactic and semantic constituents
- Add semantics to CCG rules
  - Lambda calculus (again)
- "Montague semantics"

A/B:S + B:T = A:S.T

B:T + A\B:S = A:S.T

John np:j

walks s\np: λX.walks(X)

John walks

np:j s\np: λX.walks(X)

----

s : walks(j)

B:T + A\B:S = A:S . T

np:j + s\np: λX.walks(X)

s : λX.walks(X) . j

s : walks(j)

$A/B{:}S + B{:}T = A{:}S.T$

$B{:}T + A\backslash B{:}S = A{:}S.T$

John np:j

walks s\np: λX.walks(X)

John walks

np:j s\np: λX.walks(X)

----

s : walks(j)

$B{:}T + A\backslash B{:}S = A{:}S\ .\ T$

np:j + s\np: λX.walks(X)

s : λX.walks(X) . j

s : walks(j)

A/B:S + B:T = A:S.T

B:T + A\B:S = A:S.T

John   np:j

walks   s\np: λX.walks(X)

John **walks**

np:j   **s\np: λX.walks(X)**

----

s : walks(j)

B:T + A\B:S = A:S . T

np:j + s\np: λX.walks(X)

s : λX.walks(X) . j

s : walks(j)

A/B:S + B:T = A:S.T

B:T + A\B:S = A:S.T

John np:j

walks s\np: λX.walks(X)

John walks

np:j s\np: λX.walks(X)

----

s : walks(j)

B:T + A\B:S = A:S . T

np:j + s\np: λX.walks(X)

s : λX.walks(X) . j

s : walks(j)

John np:j

Mary np:m

likes (s\np)/np: λY.λX.likes(X,Y)

```
John        likes                                 Mary
np:j        (s\np)/np:λY.λX.likes(X,Y)            m
             ------------------------------------------
                    s\np: λX.likes(X,m)
---------------------------------------------
                s likes(j,m)
```

λY.λX.likes(X,Y) . m

λX.likes(X,m)

λX.likes(X,m) . j

likes(j,m)

John np:j

Mary np:m

likes (s\np)/np: λY.λX.likes(X,Y)

John	**likes**	Mary
np:j	**(s\np)/np:λY.λX.likes(X,Y)**	m

---

s\np: λX.likes(X,m)

----

s likes(j,m)

λY.λX.likes(X,Y) . m

λX.likes(X,m)

λX.likes(X,m) . j

likes(j,m)

John np:j

Mary np:m

likes (s\np)/np: $\lambda Y.\lambda X.likes(X,Y)$

John	**likes**	Mary
np:j	(s\np)/np:$\lambda Y.\lambda X.likes(X,Y)$	m

----

s\np: $\lambda X.likes(X,m)$

---

s likes(j,m)

$\lambda Y.\lambda X.likes(X,Y)\ .\ m$

$\lambda X.likes(X,m)$

$\lambda X.likes(X,m)\ .\ j$

$likes(j,m)$

Coordination:

X:A **CONJ** X':A' = X'': **λS.(**A . **S &** A'. **S)**

Composition:

X/Y:A Y/Z:B => X/Z: λQ.(A . (B . Q))

Type raising:

NP:a -> T/(T\NP): λR.(R . a)

```
John  likes       and   Mary dislikes    Bob
np      (s\np)/np  conj  np      (s\np)/np  np
------TR                 ------TR
s/(s\np)                 s/(s\np)
----------------COMP ----------------COMP
        s/np                     s/np
       ----------------------------- CONJ
                  s/np
       -----------------------------
                   s
```

Coordination:

X:A CONJ X’:A’ = X”: λS.(A . S & A’. S)

Composition:

X/Y:A Y/Z:B => X/Z: **λQ.**(A . (B . **Q**))

Type raising:

NP:a -> T/(T\NP): λR.(R . a)

```
John  likes      and   Mary dislikes    Bob
np    (s\np)/np  conj  np    (s\np)/np  np
------TR               ------TR
s/(s\np)               s/(s\np)
---------------COMP ----------------COMP
      s/np                   s/np
     ----------------------------- CONJ
               s/np
     -----------------------------
                s
```

Coordination:

X:A CONJ X’:A’ = X”: λS.(A . S & A’. S)

Composition:

X/Y:A Y/Z:B => X/Z: λQ.(A . (B . Q))

Type raising:

NP:a -> T/(T\NP): **λR.(R** . a)

```
John  likes        and   Mary dislikes    Bob
np      (s\np)/np  conj  np      (s\np)/np  np
------TR                 ------TR
s/(s\np)                 s/(s\np)
----------------COMP ----------------COMP
        s/np                   s/np
     ------------------------------- CONJ
                 s/np
     -------------------------------
                  s
```

Coordination:

X:A CONJ X':A' = X'': λS.(A . S & A'. S)

Composition:

X/Y:A Y/Z:B => X/Z: **λQ.(A . (B . Q))**

Type raising:

NP:a -> T/(T\NP): **λR.(R . a)**

John likes ...

np:**j** (s\np)/np: **λY.λX.likes(X,Y)**

---**TR**

s/(s\np): **λR.(R . j)**

-------------------------**COMP**

s/np:

λQ.(A . (B . Q))

λQ.((λR.(R . j)) . (**λY.λX.likes(X,Y)** . Q))

λQ.((**λR.(R . j)**) . (λX.likes(X,Q)))

λQ.(λX.likes(X,Q) . j)

λQ.(likes(j,Q))

Coordination:

X:A CONJ X':A' = X'': λS.(A . S & A'. S)

Composition:

X/Y:A Y/Z:B => X/Z: λQ.(A . (B . Q))

Type raising:

NP:a -> T/(T\NP): λR.(R . a)

... Mary dislikes ...

np:m (s\np)/np:λY.λX.dislikes(X,Y)

---TR

s/(s\np): λR.(R . m)

---------------------------COMP

s/np:

λQ.(A . (B . Q))

λQ.((λR.(R . m)) . (**λY.λX.dislikes(X,Y)** . Q))

λQ.((**λR.(R . m)**) . (λX.dislikes(X,Q)))

λQ.(λX.dislikes(X,Q) . m)

λQ.(dislikes(m,Q))

Coordination:

X:A CONJ X':A' = X'': $\underline{\boldsymbol{\lambda} \mathbf{S.(A\ .\ S\ \&\ A'.\ S)}}$

Composition:

X/Y:A Y/Z:B => X/Z: λQ.(A . (B . Q))

Type raising:

NP:a -> T/(T\NP): λR.(R . a)

John likes and Mary dislikes Bob

.... CONJ .... np:b

--------COMP --------COMP

s/np: **λQ.(likes(j,Q))**

s/np: **λQ.(dislikes(m,Q))**

--------------------------- CONJ

s/np: λS.(**λQ.(likes(j,Q))** . S &

λQ.(dislikes(m,Q)) . S)

s/np: λS.(likes(j,S) &

dislikes(m,S))

----------------------COMP

s: $\underline{\boldsymbol{\lambda} \mathbf{S.(\ likes(j,S)\ \&\ dislikes(m,S)\ )}}$. b

s: likes(j,b) & dislikes(m,b)

Compositionality and Incrementality

- Compositionality:
  - all constituents have a denotation
- Incrementality:
  - all initial substrings have a denotation
  - all substrings have a denotation (stronger)

Categorical Unification Grammar

- Extending the formalism to allow features:
  - agreement, grammatical relations
- Embedding CCG techniques in other formalisms
  - SUBCAT, predicate/arguments

```
the   np/n
boy   n
boys  n
walk  s\np
walks s\np
```

Forward application

X/Y Y => X

Backward application

Y X\Y => X

Thus

```
the  boy  walks
np/n n    s\np
----- FA
  np
  ----------- BA
       s
```

the [cat: np]/[cat: n]
boy [cat: n]
boys [cat: n]
walk [cat: s]\[cat: np]
walks [cat: s]\[cat: np]

Forward application
X/Y Y => X
Backward application
Y X\Y => X

Thus

```
the                    boy       walks
[cat: np]/[cat: n]  [cat: n]  [cat: s]\[cat: np]
    ------------------ FA
        [cat: np]
            ----------------- BA
                [cat: s]
```

the [cat: np **num: !X**]/
[cat: n **num: !X**]

boy [cat: n **num: sg**]

boys [cat: n **num: pl**]

walk [cat: s]\
[cat: np **num: pl**]

walks [cat: s]\
[cat: np **num: sg**]

```
the             boys            walk
[cat: np        [cat: n         [cat: s]\
  num: !X]/       num: pl]        [cat: np
    [cat: n                         num: pl]
      num: !X]
  -------------------- FA
      [cat: np
        num: pl]
          ------------------------ BA
              [cat: s]
```

```
the   [cat: np num: !X]/
          [cat: n num: !X]
boy   [cat: n num: sg]
boys  [cat: n num: pl]
walk  [cat: s]\
          [cat: np num: pl]
walks [cat: s]\
          [cat: np num: sg]

the            boy            walks
[cat: np       [cat: n        [cat: s]\
 num: !X]/      num: sg]          [cat: np
    [cat: n                         num: sg]
     num: !X]
  ------------------- FA
       [cat: np
        num: sg]
           ------------------------ BA
                 [cat: s]
```

the [cat: np num: !X]/
[cat: n num: !X]
boy [cat: n num: sg]
boys [cat: n num: pl]
walk [cat: s]\
[cat: np num: pl]
walks [cat: s]\
[cat: np num: sg]

```
the            boys          walks
[cat: np       [cat: n       [cat: s]\
  num: !X]/     num: pl]       [cat: np
    [cat: n                      num: sg]
      num: !X]
  ------------------ FA
      [cat: np
        num: pl]
          ---------------- *****
```

SUBCAT Feature

- In GPSG and HPSG
  - SUBCAT feature identifies features of arguments:

    [SUBCAT [NP]]   *like +np feature in previous lecture*
- This is actually CCG-like
  - S\NP is verb looking for one argument
  - (S\NP)/NP is verb looking for two arguments
- Can be extended to full SUBCAT feature
  - required PPs, VCOMP, etc.

Some properties

- Mildly context sensitive
- Weakly equivalent to LTAG (Lexicalized TAG)
- Derived/gapped categories prevent non-projective parses
- Complexity:
  - unrestricted type raising: unbounded
  - restricted type raising: $O(n^3)$
    - *(also without general Coordination)*

Some other points of interest

- Free word order languages: “|”
- Relationship to intonation (Steedman 1991)
- Extension to Lambek calculus to allow changes in argument order and real incr. processing
- CCGBank: Julia Hockenmaier and Steedman
  - CCG version of Penn Treebank
- PCCG: Luke Zettlemoyer and Collins
  - Learn to produce logical form statistically

Sentence 2

```
{S[dcl] {S[dcl] {NP {N {N/N  Mr.}
                       {N  Vinken}}}
              {S[dcl]\NP {(S[dcl]\NP)/NP  is}
                         {NP {NP {N  chairman}}
                             {NP\NP {(NP\NP)/NP  of}
                                    {NP {NP {N {N/N  Elsevier}
                                               {N  N.V.}}}
                                        {NP[conj] {,  ,}
                                                  {NP {NP[nb]/N  the}
                                                      {N {N/N  Dutch}
                                                         {N {N/N  publishing}
                                                            {N  group}}}}}}}}}}
   {.  .}}
```

Mr.	**(N/N)**	Vinken	
is	**((S[dcl]\NP)/NP)**	Vinken	chairman
of	**((NP\NP)/NP)**	chairman	N.V., group
Elsevier	**(N/N)**	N.V.	
the	**(NP[nb]/N)**	group	
Dutch	**(N/N)**	group	
publishing	**(N/N)**	group	

Learning a PCCG

- See slides and videos courtesy of Yoav Artzi, Nicholas FitzGerald and Luke Zettlemoyer
- http://yoavartzi.com/tutorial/