Combinatory Categorial Grammar (CCG)

11-711 Algorithms for NLP

22 October 2019

(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

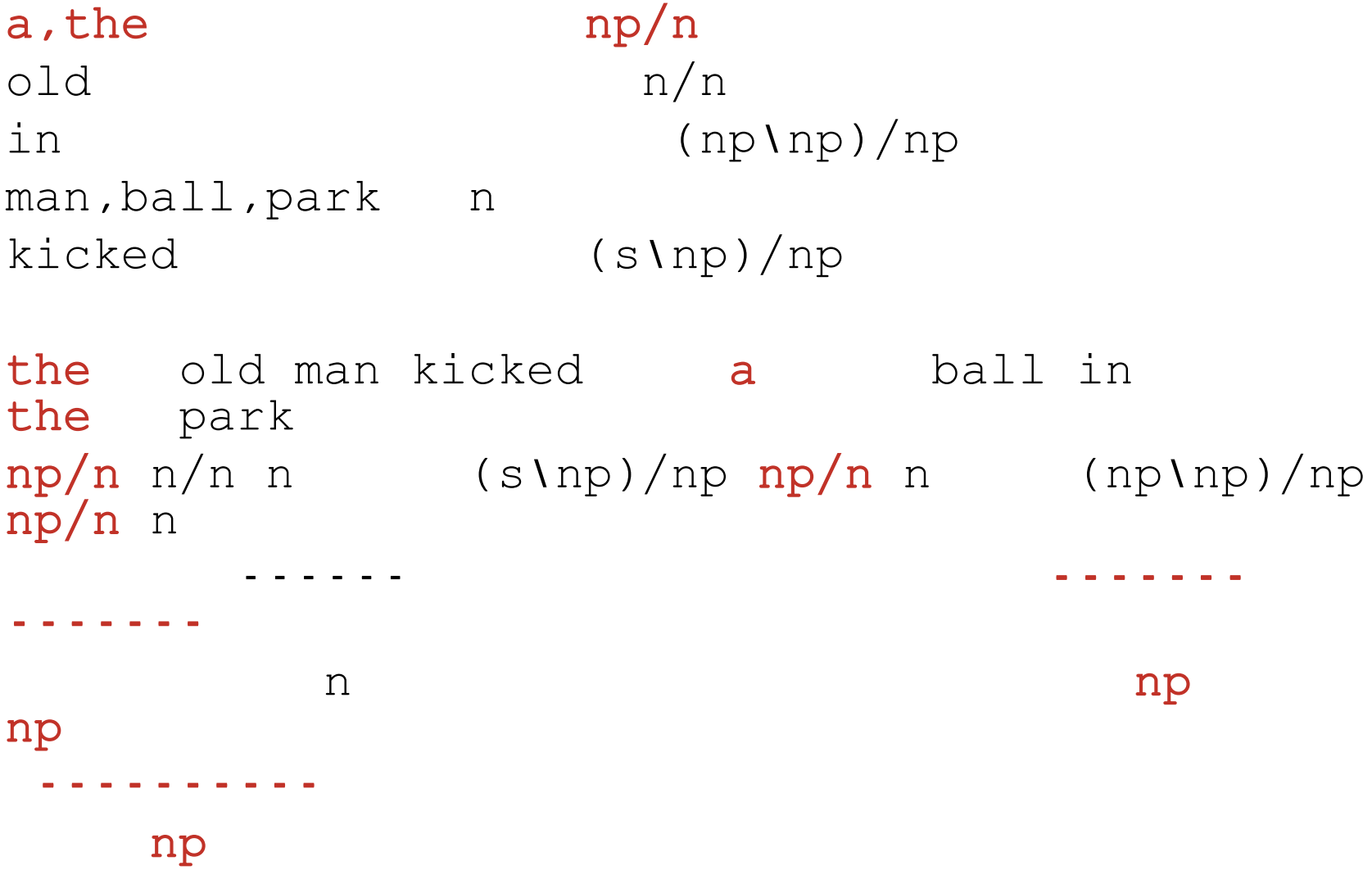
kicked (s\np)/np

the old man kicked a ball in the park

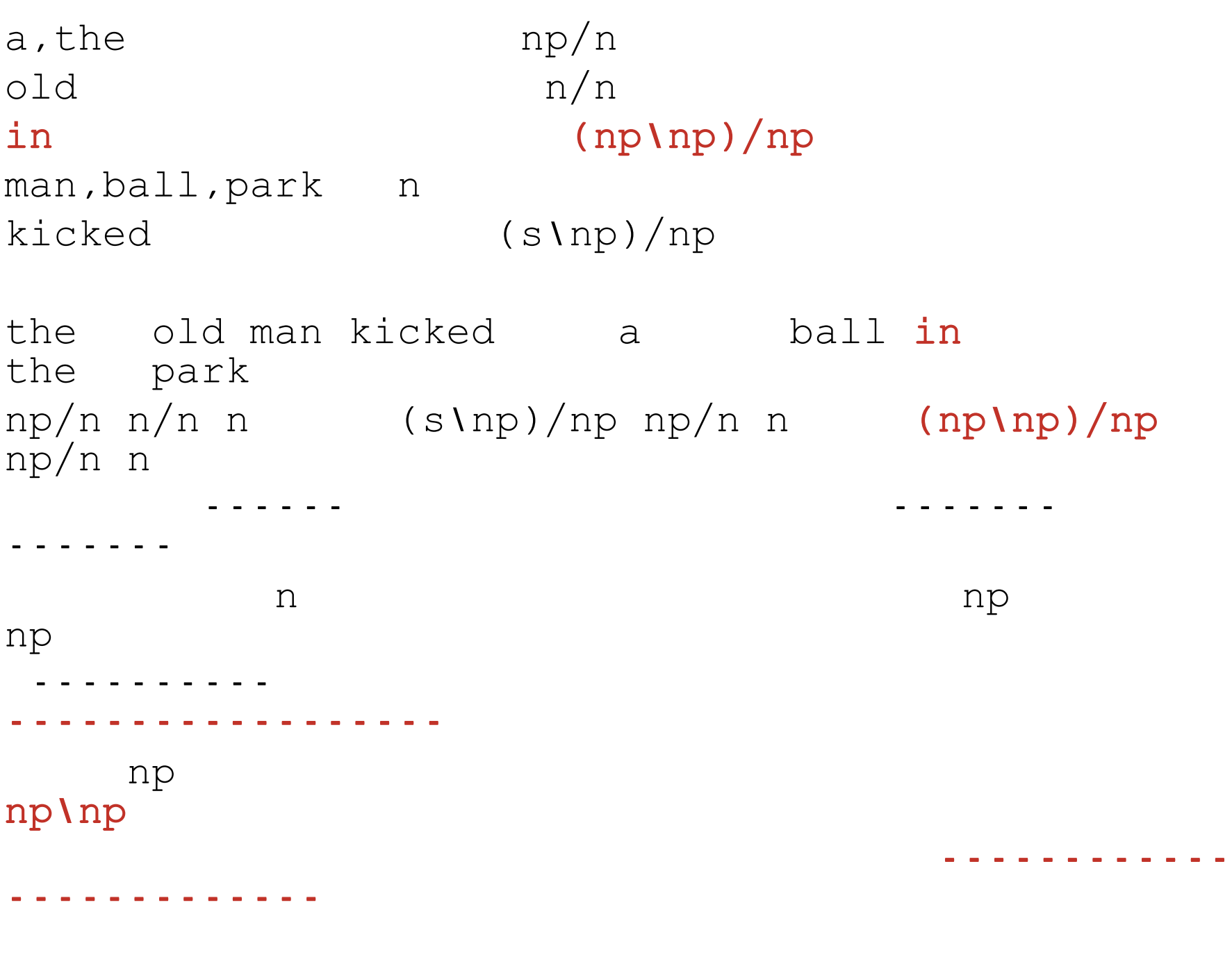
np/n n/n n (s\np)/np np/n n (np\np)/np np/n n

------

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
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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

```
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
                                        ------------
-------------
```

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.

    ???

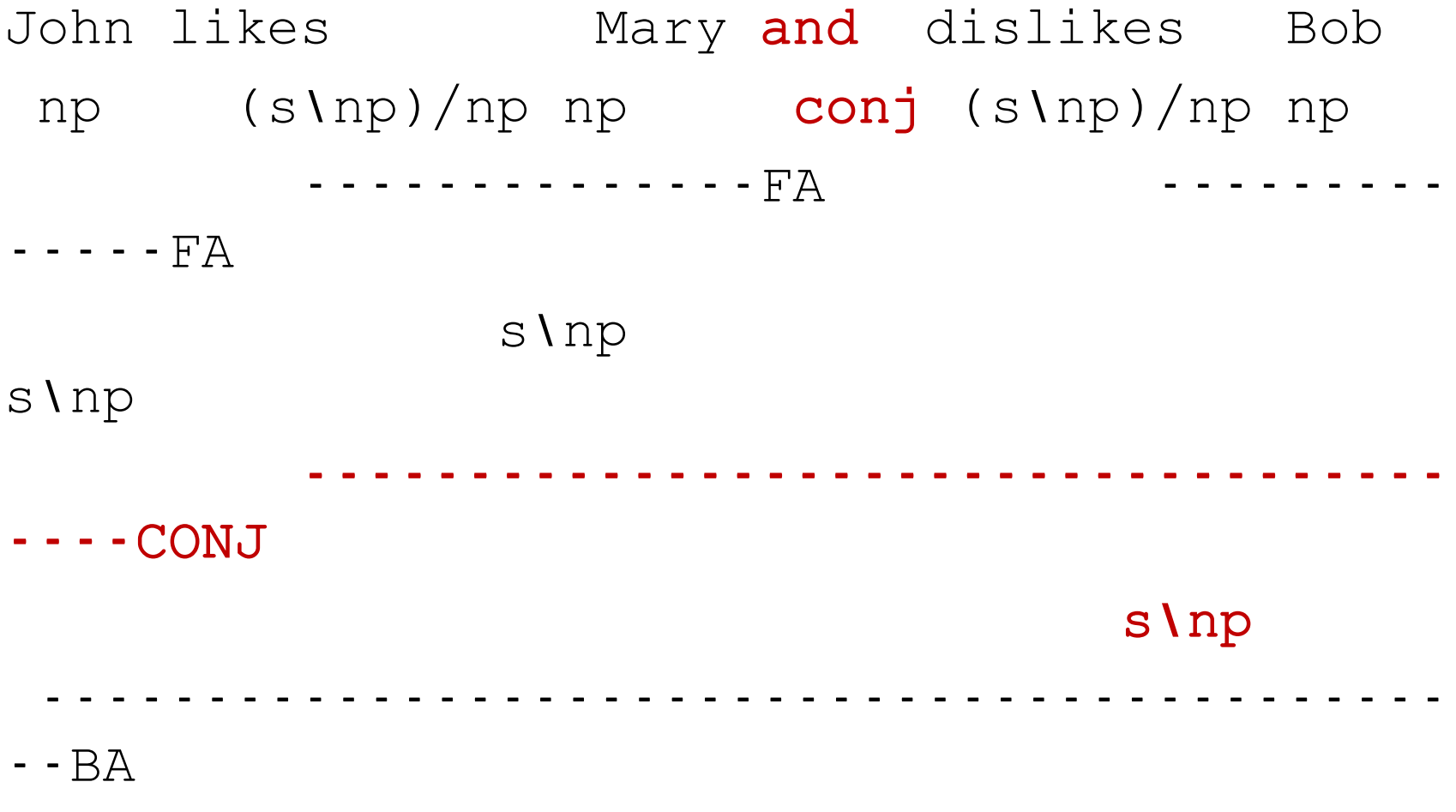
Coordination

```
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′′



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

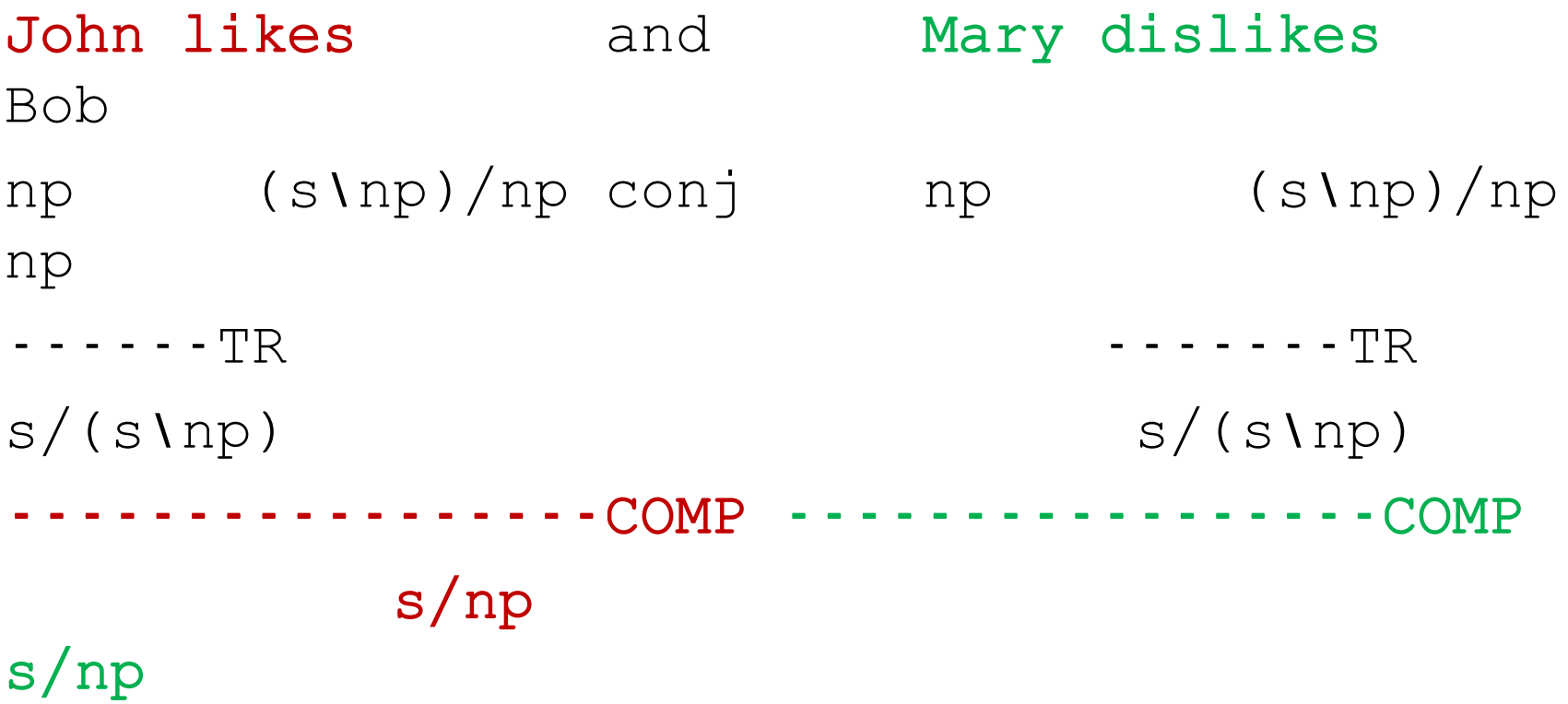
------TR -------TR

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

Type Raising

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

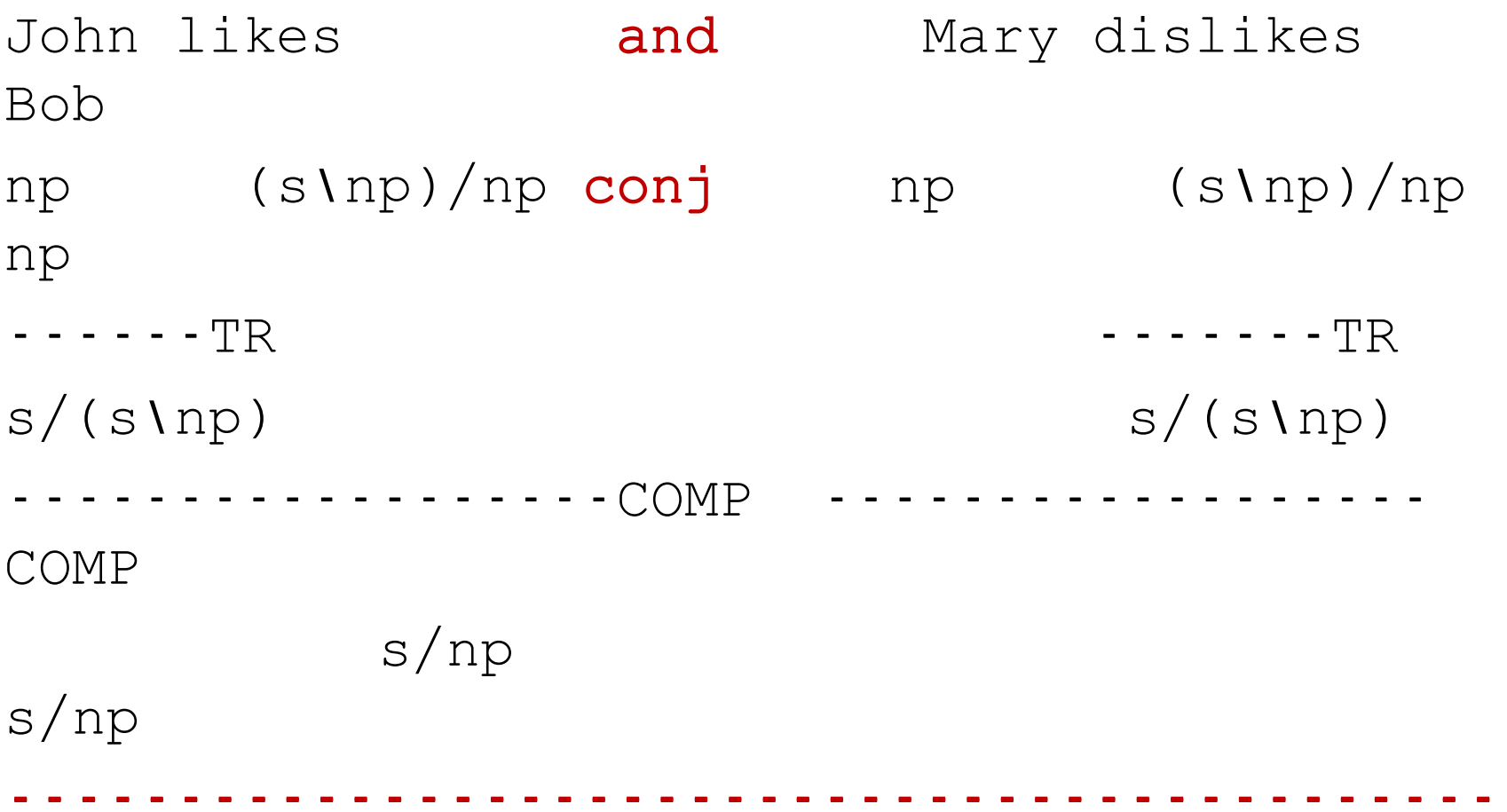
COMP: A/B + B/C => A/C



Type Raising

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

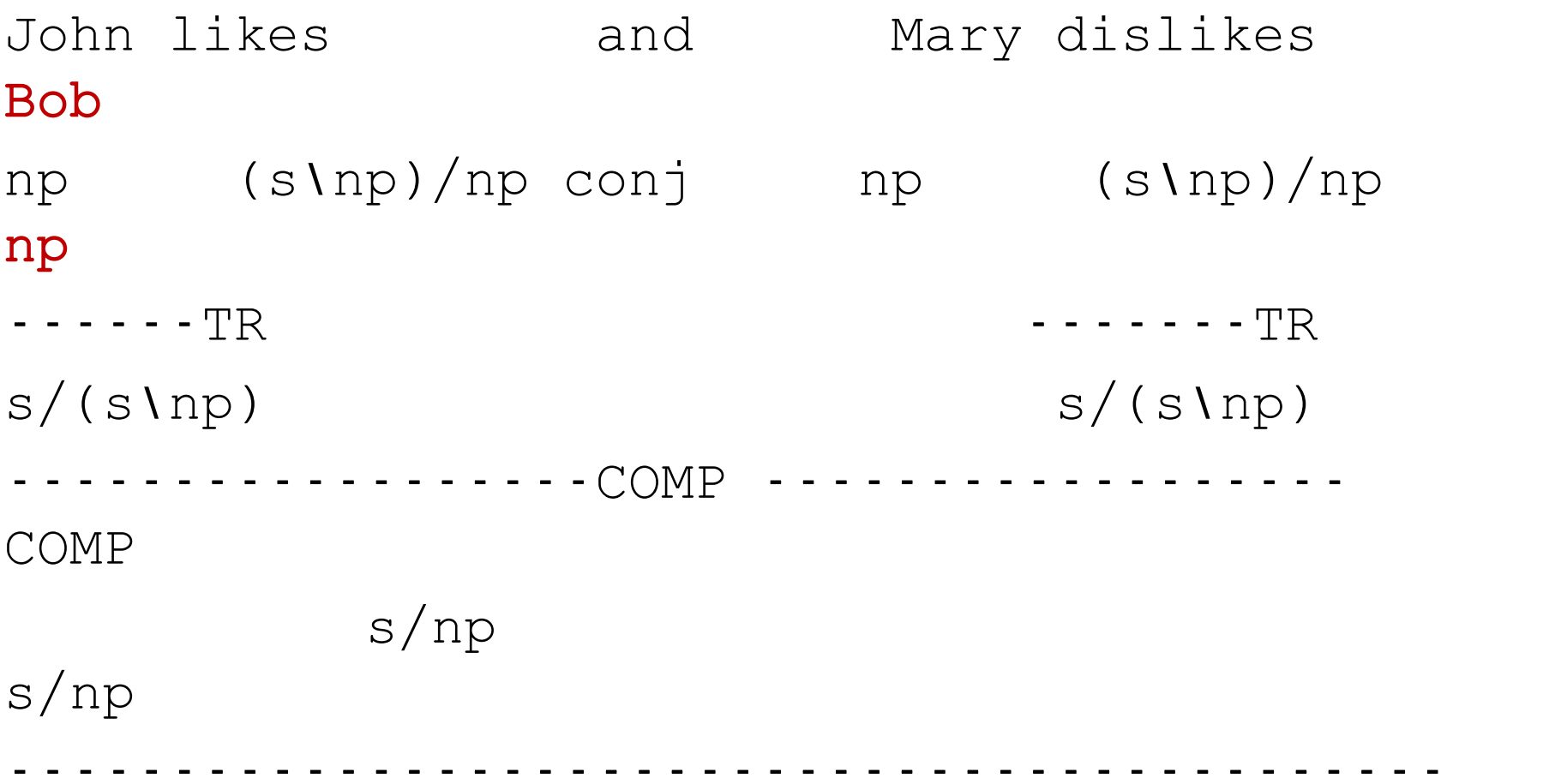
COMP: A/B + B/C => A/C



Type Raising

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

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



Type Raising

- Computationally unbounded:
  - could happen for any category
  - makes parsing intractable
- Controlled type raising
  - needs to be *guarded*
  - only allowed for 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\B:S = A:S.T

John np:j

walks s\np: λX.walks(X)

John walks

np:j s\np: λX.walks(X)

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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)

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

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

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

Coordination:

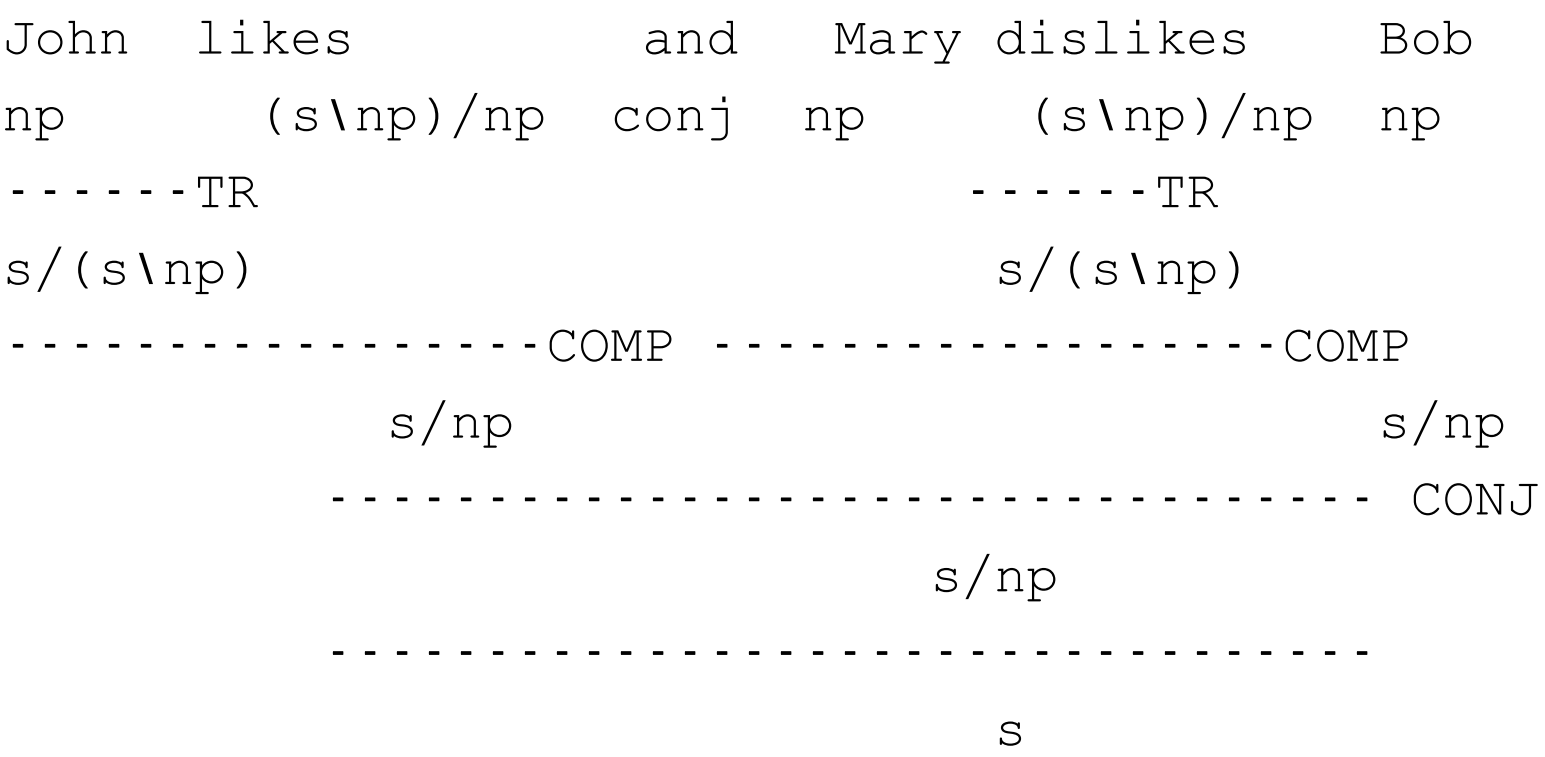
X:A CONJ X′:A′ = X′′:λS.(A . S & A′. S)

Composition:

X/Y:A Y/Z:B => X/Z: λQ.(A . (B . Q))

Type raising:

NP:a -> T/(T\NP): λR.(R . a)



Coordination:

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

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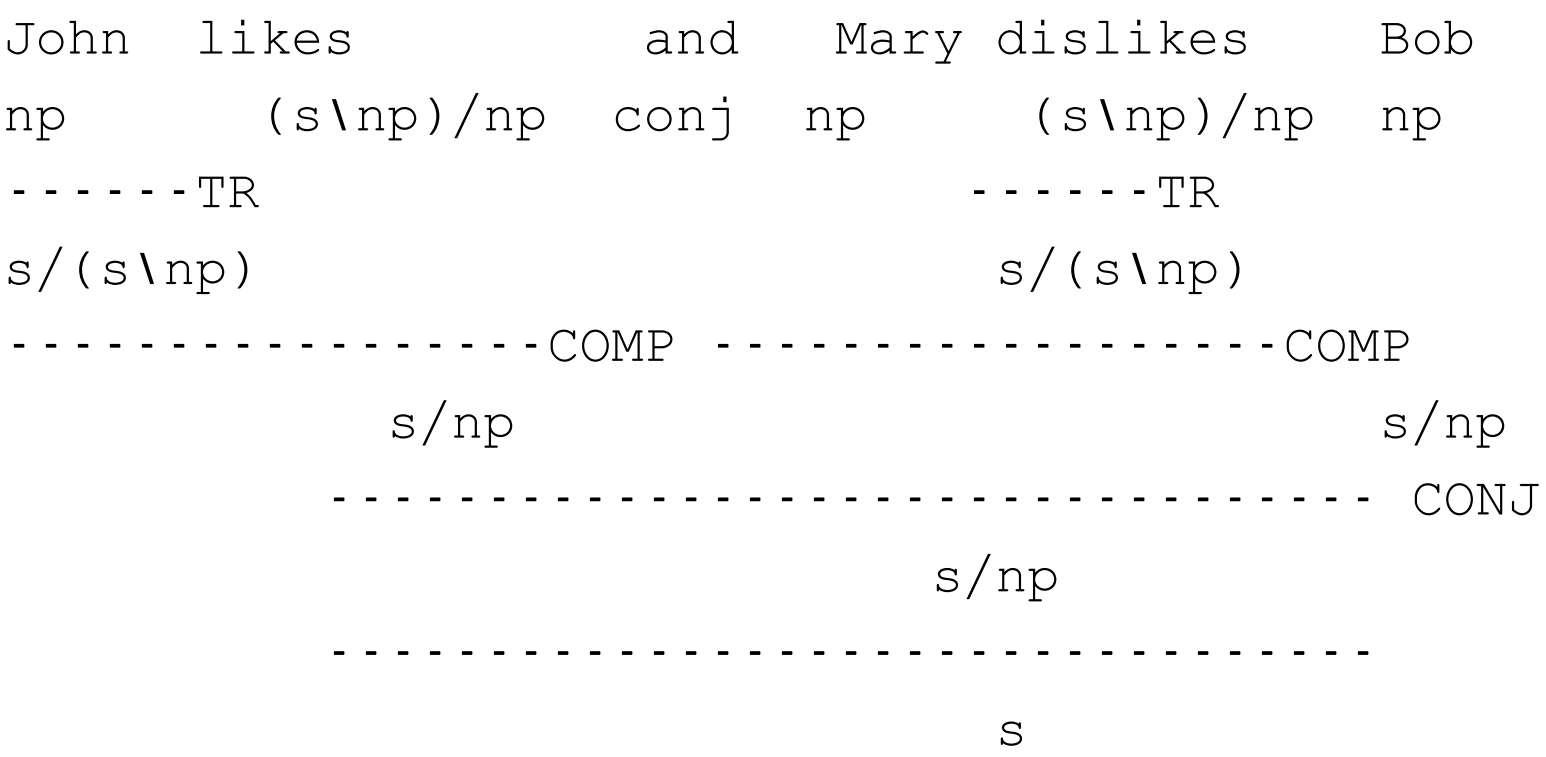

Coordination:

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′′:**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

```
   ....     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: λS.( 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/