Probabilistic Categorial Grammar

From/to Intensional Categories to/from Probabilities

Cem Bozşahin

bozsahin@metu.edu.tr

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Cognitive Science Department, The Informatics Institute, ODTÜ

The verb is the argument-taker par excellence.
Its form (root, stem, finite) appears to make a difference IN REFERENCE in all languages.

(1) a. Mary would *to run/*runs/run.

b. Mary wants *run/*runs/to run.

c. Mary *run/*to run/runs.

(a) is reference to construction of possible worlds, (b) to such constructed possible worlds, and (c) to actual or imaginarily realized worlds.

Category choice may reveal decision points for the INTENDED reference:

(2) a. She played the piano for an hour/*in an hour.

b. She played the sonata *for an hour/in an hour.

c. She played the sonata for a year.

d. She played the piano in a year.

They can be thought of arising from the following choices:

(3) a. played :: $(S\backslash NP)/NP$: $\lambda x \lambda y.play' xy$

b. played :: $(S\backslash NP)/Long/Piece$: $\lambda y \lambda x \lambda z.perform'(iter' x(play' yz))z$

c. played :: $(S\backslash NP)/Period/Instrmnt$: $\lambda y \lambda x \lambda z.practice'(iter' x(play' yz))z$

d. played :: $(S\backslash NP)/PP_{\mathrm{schdl}}/NP_{\mathrm{score}}$: $\lambda y \lambda x \lambda z.perform'(iter' x(play' yz))z$

e. played :: $(S\backslash NP)/PP_{\mathrm{duration}}/NP_{\mathrm{tool}}$: $\lambda y \lambda x \lambda z.practice'(iter' x(play' yz))z$

Compositionality in combinators may have something to say about these aspects.

- Thematic structure
- Argument structure
- Word order
- Tense
- Aspect
- Mood

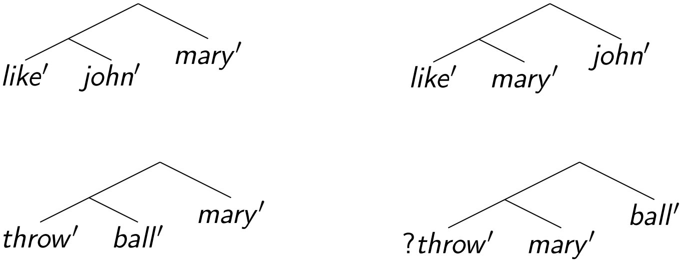
A brief history of Linguistics

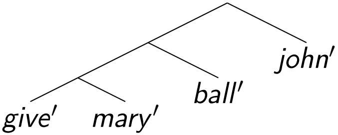
- Thematic structure from argument structure
- Argument structure from thematic structure
- syntax suffices
- semantics suffices
- Categorial grammarians: it is the correspondence, which seems necessary and sufficient
  - argument from necessity: syntactic identity of semantic differences (e.g. control verbs, ECM, raising)
  - argument from sufficiency: composition (surface constituency)
- How do we get syntactic forms, logical forms and phonological forms ON THE FLY?
- These "interfaces" must be quite trivial

Language of Thought

- There seems to be a universal conceptual space (things, actions, events)
- That space seems to be asymmetric
- All human languages are probably homomorphic in that space
- Since languages differ in surface structure, surface structure cannot be homomorphic to that space
- That brings us to WORD ORDER
- How do we capture BOTH aspects if parsing is a reflex? (Garrett)

Asymmetry and structure





$(((give' \; mary')ball')john')=$

$give' \; mary' \; ball' \; john'$

(4) a. The window broke.
$init'(broken'w')$

b. The stone broke the window.
$\lambda z.cause'(init'(broken'w'))st'\,z$

c. The man broke the window with a stone.
$cause'(init'(broken'w'))st'\,man'$

$init'\,state'$: an inchoative event culminating in state $state'$

What are these primes and LFs? Hypotheses about LOT.

Surface structure

(5)

a. persuades :: $(S\backslash NP_{\mathrm{3s}})/VP_{\mathrm{to\text{-}inf}}/NP$ — English

b. promises :: $(S\backslash NP_{\mathrm{3s}})/VP_{\mathrm{to\text{-}inf}}/NP$

c. expects :: $(S\backslash NP_{\mathrm{3s}})/VP_{\mathrm{to\text{-}inf}}/NP$

d. broke :: $(S\backslash NP)/PP/NP$

e. broke :: $(S\backslash NP)/NP$

f. broke :: $S\backslash NP$

g. gwelodd (*saw*.3s) :: $(S/NP)/NP_{\mathrm{3s}}$ — Welsh

h. iniutusan (*order*) :: $(S_{\mathrm{DV}}/VP)/NP_{\mathrm{ANG,AGR}}/NP_{\mathrm{NG}}$ — Tagalog

i. savundum (*defended*.1s) :: $S\backslash S'_{\mathrm{acc}}$ — Turkish

j. viu (*saw*.3s) :: $(S\backslash NP_{\mathrm{3s}})/NP$ — Portuguese

(6) a. The window broke.
broke :: $S\backslash NP : \lambda x.init'(broken' x)$

b. The stone broke the window.
broke :: $(S\backslash NP)/NP : \lambda x\lambda y\lambda z.cause'(init'(broken' x))y\ z$

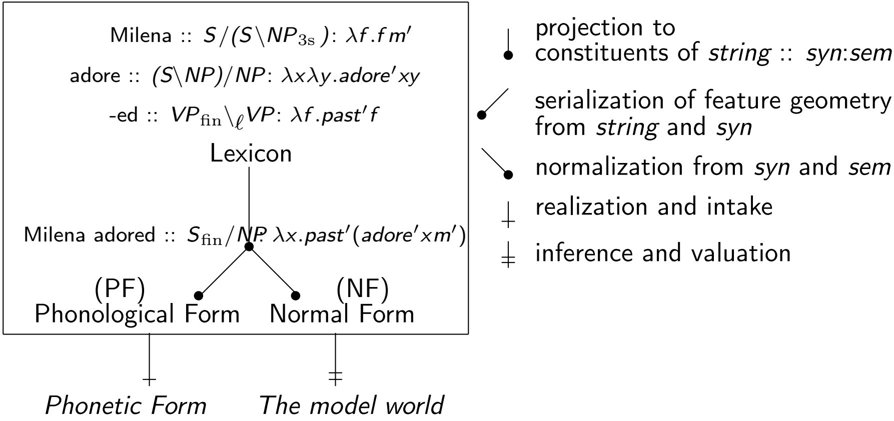
c. The man broke the window with a stone.
$(S\backslash NP)/PP/NP : \lambda x\lambda y\lambda z.cause'(init'(broken' x))y\ z$

We get thematic structure as an inference over predicate-argument structure

Question

If surface structure is not homomorphic to universal conceptual structure, how do children learn the word order of their language?

Linguistic architecture



Conjecture

- Syntax is a HIDDEN variable for the child (NB. necessity of correspondence).
- She has to infer a CATEGORY from form-meaning pairs only (NB. sufficiency of correspondence).
- These pairs are subject to universal combinatorics. (ANALYSIS)
- These inferences set up a MENTAL GRAMMAR.
- Such grammars are necessarily PROBABILISTIC.

- Change the nature of categories, and we might end up with PLANS and SCRIPTS.

(7) a. persuades ::
$(S\backslash NP_{3s})/VP_{\text{to-inf}}/NP$: $\lambda x\lambda p\lambda y.persuade'(px)xy$

b. promises ::
$(S\backslash NP_{3s})/VP_{\text{to-inf}}/NP$: $\lambda x\lambda p\lambda y.promise'(py)xy$

c. expects :: $(S\backslash NP_{3s})/VP_{\text{to-inf}}/NP$: $\lambda x\lambda p\lambda y.expect'(px)y$

d. broke :: $(S\backslash NP)/PP/NP$: $\lambda x\lambda y\lambda z.cause'(init'\,broken'\,x)yz$

e. broke :: $(S\backslash NP)/NP$: $\lambda x\lambda y\lambda z.cause'(init'\,broken'\,x)yz$

f. broke :: $S\backslash NP$: $\lambda x.init'(broken'\,x)$

g. gwelodd (*saw*.3s) :: $(S/NP)/NP_{3s}$: $\lambda x\lambda y.saw'\,yx$

h. iniutusan (*order*) ::
$(S_{\text{DV}}/VP)/NP_{\text{ANG,AGR}}/NP_{\text{NG}}$: $\lambda x\lambda y\lambda p.order'(py)yx$

i. savundum (*defended*.1s) ::
$S_{\text{pd}}\backslash S'_{\text{acc}}$: $\lambda p.defend'\,pi' \wedge topic'\,i'$

j. viu (*saw*.3s) :: $(S\backslash NP_{3s})/NP_{\text{rex}}$: $\lambda x\lambda y.saw'\,xy$

(8)
a. $(S\backslash NP)/NP$: $\lambda x\lambda y.verb'xy$ (SVO)
b. $(S/NP)\backslash NP$: $\lambda x\lambda y.verb'yx$ (SVO′)
c. $(S/NP)\backslash NP$: $\lambda x\lambda y.verb'xy$ (OVS)
d. $(S\backslash NP)/NP$: $\lambda x\lambda y.verb'yx$ (OVS′)
e. $(S\backslash NP)\backslash NP$: $\lambda x\lambda y.verb'xy$ (SOV)
f. $(S\backslash NP)\backslash NP$: $\lambda x\lambda y.verb'yx$ (OSV)
g. $(S/NP)/NP$: $\lambda x\lambda y.verb'xy$ (VOS)
h. $(S/NP)/NP$: $\lambda x\lambda y.verb'yx$ (VSO)

Categorial Word order: not a metrical concept

(9) a.	$(S\backslash NP)/NP$: $\lambda x \lambda y.verb' xy$	(SVO)	English
b.	$(S/NP)\backslash NP$: $\lambda x \lambda y.verb' yx$	(SVO′)	Huastec
c.	$(S/NP)\backslash NP$: $\lambda x \lambda y.verb' xy$	(OVS)	Hixkaryana
d.	$(S\backslash NP)/NP$: $\lambda x \lambda y.verb' yx$	(OVS′)	Päri
e.	$(S\backslash NP)\backslash NP$: $\lambda x \lambda y.verb' xy$	(SOV)	Turkish
f.	$(S\backslash NP)\backslash NP$: $\lambda x \lambda y.verb' yx$	(OSV)	Dyirbal
g.	$(S/NP)/NP$: $\lambda x \lambda y.verb' xy$	(VOS)	Tagalog
h.	$(S/NP)/NP$: $\lambda x \lambda y.verb' yx$	(VSO)	Welsh

A Micro Word-order Thought Experiment

- Syntax is a HIDDEN variable for the child.
- She has to infer a CATEGORY from form-meaning pairs only.
- These pairs are subject to universal combinatorics. (ANALYSIS)
- These inferences set up a MENTAL GRAMMAR.
- Such grammars are necessarily PROBABILISTIC.
- All word orders are available to the child IN THE BEGINNING.

My Lab in Cyberspace: TheBench

github.com/bozsahin/thebench

Probabilistic CG

L: Logical Form S: Sentence D: Derivation

- Hidden variable problem: θ are weights of lexical assumptions

$$\arg\max_{L} P(L \mid S; \bar{\theta}) = \arg\max_{L} \sum_{D} P(L, D \mid S; \bar{\theta}) \qquad (1)$$

- Ds are inferred, not observed.
- Relating probabilities and weights (hence categories):

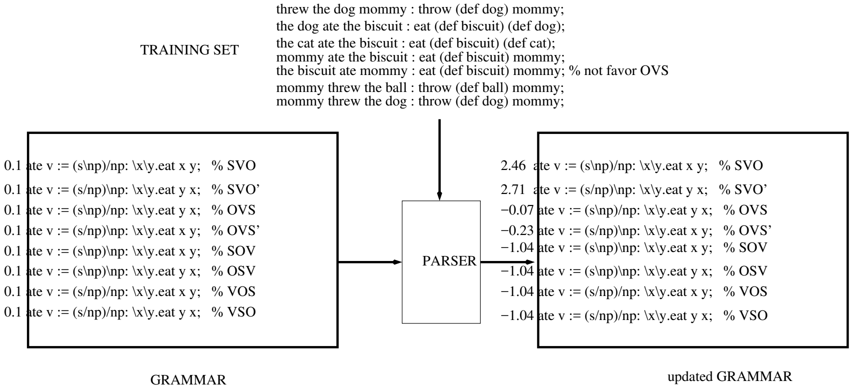
$$P(L, D \mid S; \bar{\theta}) = \frac{e^{\bar{f}(L,D,S)\cdot\bar{\theta}}}{\sum_{L}\sum_{D} e^{\bar{f}(L,D,S)\cdot\bar{\theta}}} \qquad (2)$$

- $f(L, D, S)$: some local measure function (use counts etc.)

Parameter estimation: weight update

- Assume a mental grammar.
- Assume some data to be true (training set)
- What is assumed is form-meaning correspondence
- Parse-to-learn to re-estimate the parameters

Learning workflow



Log-likelihood of training data S_i, L_i

Log-linear model of structure prediction

$$O(\bar{\theta}) = \sum_{i=1}^{n} log\, P(L_i \mid S_i; \bar{\theta}) = \sum_{i=1}^{n} log(\sum_{D} P(L_i, D \mid S_i; \bar{\theta})) \quad (3)$$

Derivative: How well each parameter serves training

$$\frac{\partial O}{\partial \theta_j} = E_{f_j(L_i,D,S_i)P(D|S_i,L_i;\bar{\theta})} - E_{f_j(L,D,S_i)P(L,D|S_i;\bar{\theta})} \tag{4}$$

Which is

$$\frac{\partial O}{\partial \theta_j} = \sum_{i=1}^{n}\sum_{D} f_j(L_i, D, S_i)P(D \mid S_i, L_i; \bar{\theta}) - \sum_{i=1}^{n}\sum_{L}\sum_{D} f_j(L, D, S_i)P(L, D \mid S_i; \bar{\theta}) \tag{5}$$

Roughly, the expected value of

item j's contribution to correct parses - contribution to all parses

NB. Both are expected values, not counts.

Too many items: we apply Stochastic Gradient to re-estimate

$$\text{Initialize } \bar{\theta} \text{ to some value.} \tag{6}$$

for $k = 0 \cdots N-1$

for $i = 1 \cdots n$

$$\bar{\theta} = \bar{\theta} + \frac{\alpha_0}{1 + c(i + kn)} \frac{\partial log\, P(L_i | S_i; \bar{\theta})}{\partial \bar{\theta}}$$

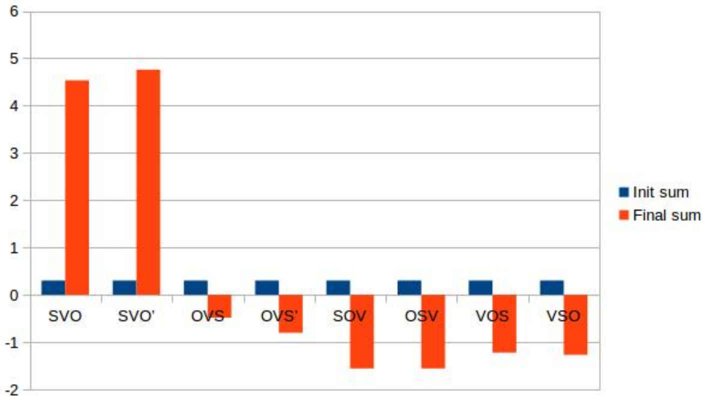
Micro-world experiment

- All possibilities for all verbs are entered in initial mental grammar.
- Give a set of utterances whose meanings are assumed to be known.
- Train the categories on probabilities coming from the parses.
- Some will increase, some decrease, some stay the same.
- How big is the difference from initial grammar?

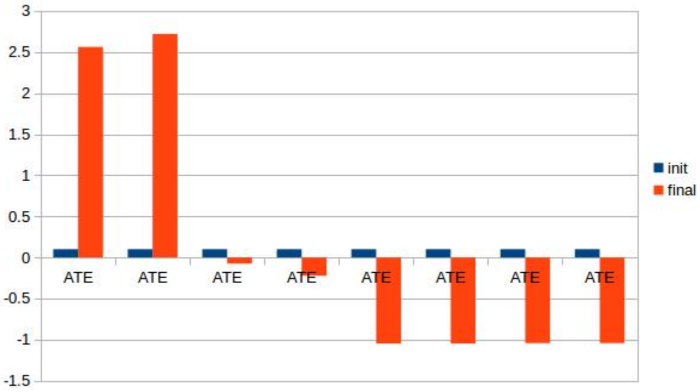
The training set

```
the dog ate the biscuit :  eat (def biscuit) (def dog);
the cat ate the biscuit :  eat (def biscuit) (def cat);
mommy ate the biscuit :  eat (def biscuit) mommy;
the biscuit ate mommy :  eat (def biscuit) mommy;
mommy threw the ball :  throw (def ball) mommy;
mommy threw the dog :  throw (def dog) mommy;
threw the dog mommy :  throw (def dog) mommy;
the dog saw mommy :  see mommy (def dog) ;
mommy saw the dog :  see (def dog) mommy;
the dog walked :  walk (def dog);
the cat slept :  sleep (def cat);
the cat walked :  walk (def cat);
the dog :  def dog;
the cat :  def cat;
mommy :  mommy;
```

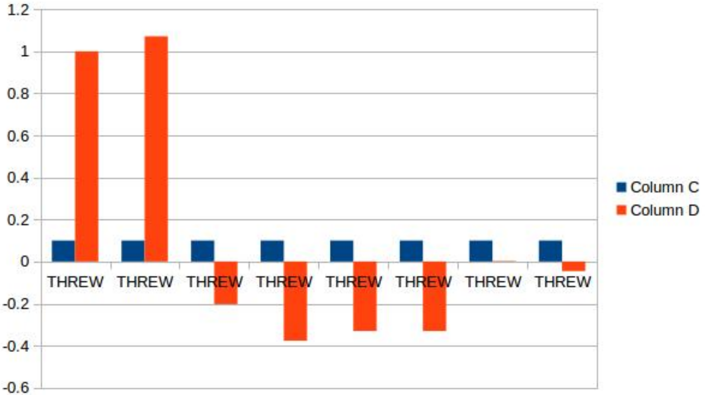
Verb categories update: 3 verbs total $\times$ 8 categories



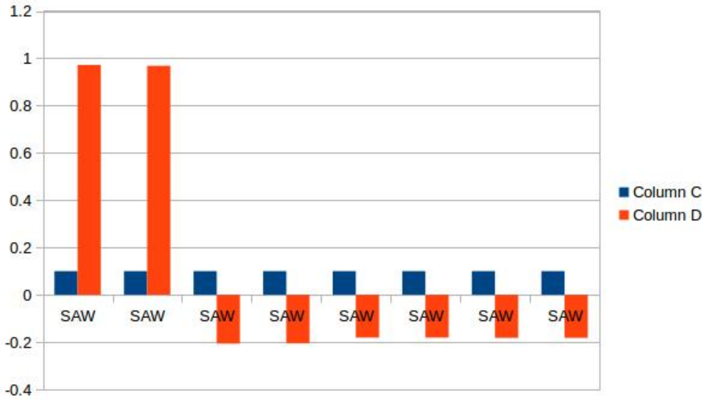
Ate parameters



Threw parameters



Saw parameters



Summary

- These conditions are quite realistic for the child.
- A computationally efficient grammatical theory can attack the hidden-variable problem in syntax
  - to fast convergence without brain switches,
  - to meet the timeframe of language acquisition and the size of grammars children learn.
- Having a correspondence is the prerequisite (necessity).
- Having a compositional correspondence may be sufficient.