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Plans and the (Predicate Argument) Structure of Behavior

Mark Steedman

19th April 2015



Outline

- Introduction
- I: Planning
- II: From Planning to Semantics
- III: The Problem of Content
- IV: Hanging Language onto (Human) Planning
- Conclusions

Introduction

- There is a long tradition associating language and other serial cognitive behavior with an underlying motor planning mechanism (Piaget 1936, Lashley 1951, Miller *et al.* 1960).
- The evidence is evolutionary, neurophysiological, and developmental.
- It raises the possibility that language is much more closely related to embodied cognition than current linguistic theories of grammar suggest.

Introduction

- I'm going to argue that practically every aspect of language reflects this connection transparently, and that both **cognitive and linguistic theories should be adjusted accordingly**.
- The talk discusses this connection in terms of planning as it is viewed in Robotics and AI, with some attention to applicable machine learning techniques (Steedman 2002a,b).
- Work In Progress under ERC Advanced Fellowship 249520 GRAMPLUS and EU grant Xperience

Introduction

- The paper will sketch a path between representations at the level of the grounded sensory manifold and perceptron learning to the mid-level of plans and explanation-based learning, and on up to the level of language grammar and parsing model learning.
- At the levels of planning and linguistic representation, two simple but very general combinatory rule types, **Composition** (the operator **B**) and **Type-Raising** (the operator **T**) will appear repeatedly.

$$\mathbf{B}fg \equiv \lambda x.f(gx)$$

$$\mathbf{T}a \equiv \lambda f.fa$$

- Human planning requires an additional element, in the form of **plan variables**, which also provides the basis for distinctively human language..

I: Plans and the Structure of Behavior

- Apes really can solve the “monkeys and bananas” problem, using tools like old crates to gain altitude in order to reach objects out of reach.



Figure 1: Köhler 1925



Figure 2: Köhler 1925

What does it Take to Plan?

- Such planning involves
 - Retrieving **appropriate actions** from memory (such as piling boxes on top of one another, and climbing on them),
 - **Sequencing them** in a way that has a reasonable chance of bringing about a desired state or goal (such as having the bananas).

◊ It is qualitatively different from Skinnerian shaping of purely reactive behavior in animals like pigeons—cf.

<http://www.youtube.com/watch?v=mDntbGRPeEU>

What does it Take to Plan?

- Köhler showed that, in apes at least, such search seems to be
 - *object-oriented*—that is, reactive to the presence of the tool, and
 - *forward-chaining*, working forward *breadth-first* from the tool to the goal, rather than backward-chaining (working from goal to tool).
- The first observation implies that actions are accessed via perception of the objects that mediate them—in other words that actions are represented in memory *associatively*, as properties of objects—in Gibson’s 1966 terms, as *affordances of objects*.
- The second observation suggests that in a cruel and nondeterministic world it is better to *identify reasonably highly valued states that you have a reasonable chance of getting to* than to optimize complete plans.

What does it Take to Plan?

- The problem of planning can therefore be viewed as the problem of **Search** for a sequence of actions or affordances in a “Kripke model”:
- A Kripke model is a tree or more accurately a **lattice**, in which **nodes are states**, and **arcs are actions**.
- A plan is then a sequence of actions that culminates in a state that satisfies the goal of the plan.
- ◊ Search for plans is **intrinsically recursive**, and requires a Push-Down Automaton (PDA) to keep track of alternative paths to some limited depth.
- It is interesting that **a PDA is also necessary to process recursive languages**.
- But a PDA clearly **isn't enough for human language**, which animals lack.

Representing Actions

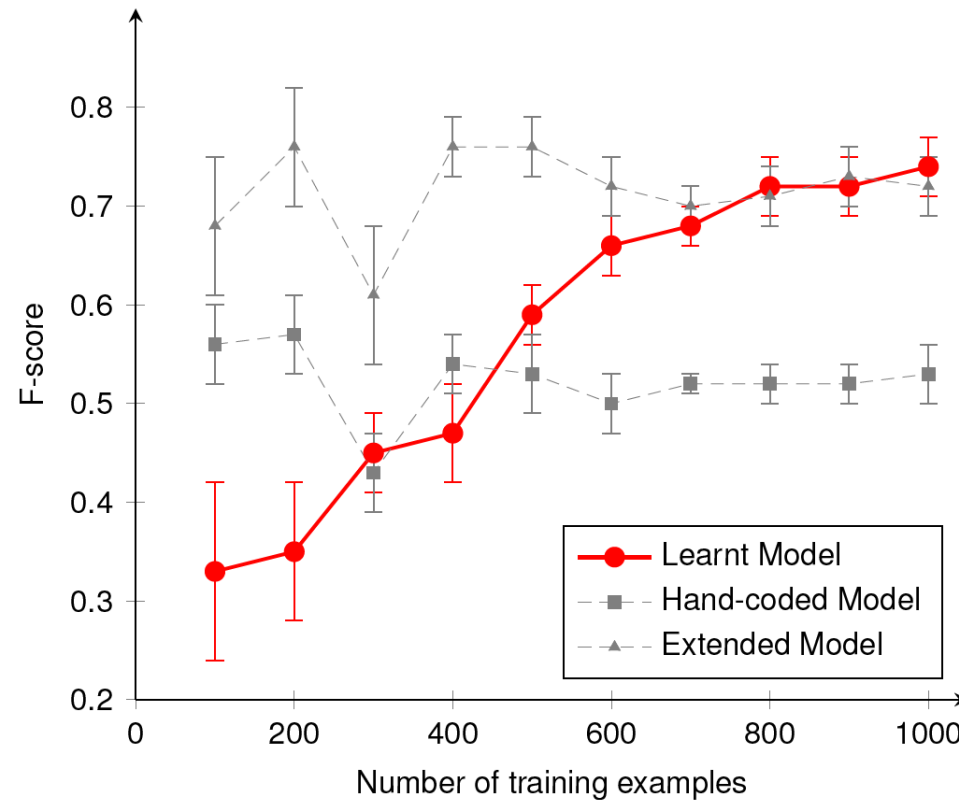
- We can think of actions as STRIPS operators or as finite-state transducers (FSTs) over (sparse) state-space vectors
 - FSTs are **closed under composition**, and can be represented as simple neural computational devices such as Perceptrons, or the Associative Network or Willshaw Net (Willshaw 1981 cf. Marr 1969).
- ◊ We still need a **stack memory** to run **the search for plans**.

Reducing Complexity

- We need the Kernel Generalization of Perceptrons to learn STRIPS rules (and their more modern descendants) as FSTs (Mourão *et al.* 2009, 2010).
- This calls for a **highly structured state representation** (Hume, 1738; Kant, 1781, *passim*), of a kind that can only be developed by more than 500M years of chordate evolution, using resources on a scale that is **completely beyond machine learning**.
- Like everyone else, we have to **define a state-description language by hand**.
- Complexity is $O(n^2)$, so we still need to **keep the state vector small**.
- We do this via a via a “deictic” or **location-based attention mechanism** cf. Agre and Chapman (1987) and Pasula *et al.* (2007)

Mourão 2012: Predicting STRIPS Update

10-fold cross-validation results



II: From Planning to Semantics

- How do we get from seriation and affordance (which we share with other animals) to language (which is uniquely human)?
- *Seriation* of actions to form a plan is **Composition** of FSTs or functions of type *state* \rightarrow *state*
- The *Affordance* of a state is a function from all those actions that are possible in that state into their respective result states.
- States are defined by the objects they include, so this is like exchanging objects for **Type-Raised** functions that map states into other states resulting from actions on those objects.

Actions as Functions

- Thus, the affordance of a (state including a) box to an ape is a function from actions like *the box falling, their climbing-on the box and their putting the box on another box* into resulting states whose utility the ape can evaluate.
- The functions are of the following (Curried) types, where e is the type of a state satisfying preconditions including the presence of an entity, and t is a consequent state:
 - $fall_{e \rightarrow t}$,
 - $climb-on_{e \rightarrow (e \rightarrow t)}$
 - $put-on_{e \rightarrow (e \rightarrow (e \rightarrow t))}$

Objects as Affordances

- Thus the ape's concept of a box is an **object-oriented** set of Type-Raised functions of type
 - $box1_{(e \rightarrow t) \rightarrow t}$
 - $box2_{(e \rightarrow (e \rightarrow t)) \rightarrow (e \rightarrow t)}$
 - $box3_{(e \rightarrow (e \rightarrow (e \rightarrow t))) \rightarrow (e \rightarrow (e \rightarrow t))}$
- —that is, functions from the current situation to the results of the actions it affords.
- Planning is then object-oriented **seriation of affordances**
- So the only place for human planning to differ from animal planning in a way that supports language is in the **event representation** itself.

“Grounding” Actions and Affordances

- The fact that actions and objects have (fairly) simple types doesn't mean that the actions themselves are simple.
- A box *falling* is not a volitional action, and has perceptual preconditions like a *looming* flow-field. The event is a complex conjunction of **entailments** of a box falling, such as a *hurting* event, and the consequent state concerns issues other than the mere lowering of the box's position.
- The ramified nature of this **dynamic event knowledge** is the reason that **languages can vary** in the way they **carve the conceptual representation at the joints** to define their (much terser) **lexical semantics**.
- E.g. English *run across the road* vs. French *traverser la rue à la course*.
- To understand the connection between planning and semantics, we need to **better understand the grounded event representation**.

III: The Problem of Content

- Linguists and the Artificial Intelligencia have notably **failed** to devise **a semantics that captures this cross-linguistic variety**.

- (1) Thomason, 1974: $\forall x[bug'x \Rightarrow \exists y[plants(y) \wedge kill'y x]]$
 McCawley, 1968: $[_sCAUSE\ BUGS[_sBECOME[_sNOT[_sALIVE\ PLANTS]]]]$
 Dowty, 1979: $[CAUSE[DO\ BUGS\ \emptyset][BECOME\ \neg[ALIVE\ PLANTS]]]$
 Talmy, 2000: *Bugs ARE-the-AUTHOR''-OF[plants RESULT-TO-die]*
 Van Valin, 2005: $[do'(bugs', \emptyset)]CAUSE[BECOME[dead'(plants)]]$
 Goddard, 2010: *BUGS* do something to *PLANTS*; because of this, something happens to *PLANTS* at the same time; because of this, something happens to *PLANTS'* body; because of this, after this *PLANTS* are not living anymore.

- Can we identify the primitive concepts **automatically**, as **hidden variables**?

Two Approaches

- Clustering **by Collocation** (Landauer and Dumais, 1997; Baroni and Zamparelli, 2010; Grefenstette and Sadrzadeh, 2011; Padó and Lapata, 2007; Mitchell and Lapata, 2008; Mikolov *et al.*, 2013).
 - Composition via **Linear Algebraic Operations**
 - Good for **underspecification** and **disambiguation**
- Clustering **by Denotation** (Lin and Pantel, 2001; Hovy *et al.*, 2001), using sentences involving identifiable **Named Entities** (Lewis and Steedman, 2013a; Reddy *et al.*, 2014)
 - Composition via **traditional Logical Operators**
 - Good for **inference**.

Clustered Entailment Semantics

- ◊ We must distinguish **paraphrase** from **entailment**.
 - X_{person} *elected to* Y_{office} **entails** X_{person} *ran for* Y_{office} **but not vice versa**.
- ◊ The paraphrase relation depends on **global properties** of the named entity relation graph.
 - Lewis (2015); Lewis and Steedman (2014b) apply the entailment graphs of Berant *et al.* (2012) to generate **more articulated entailment structures**.

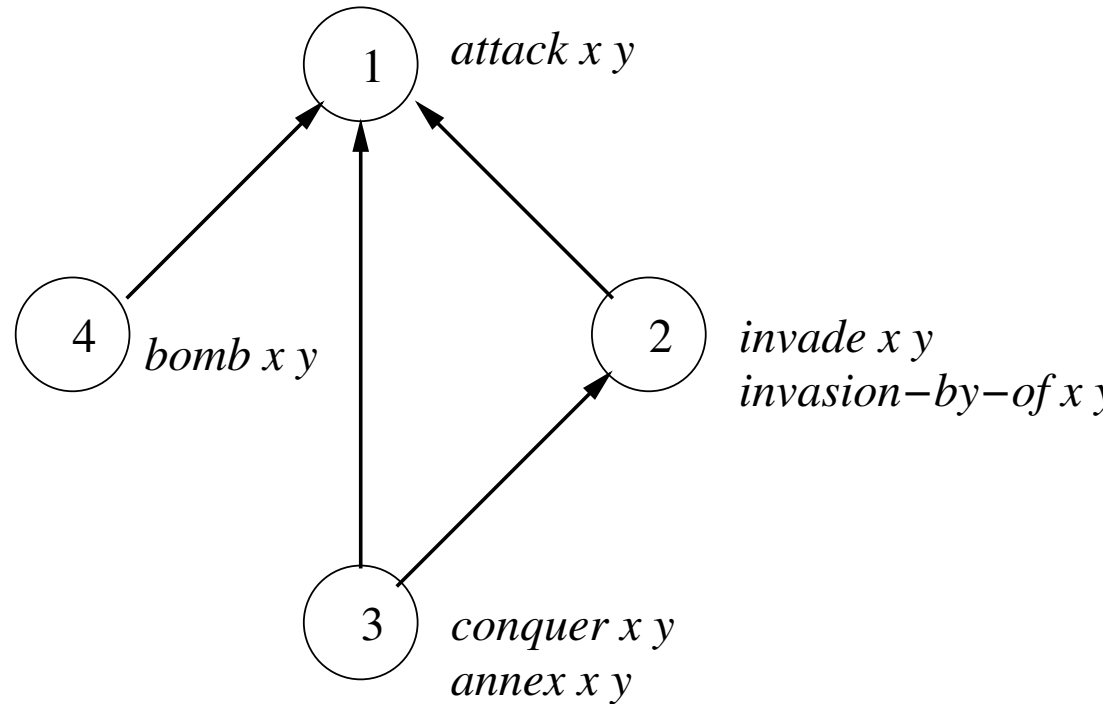
Local Entailment Probabilities

- The typed named-entity technique is applied to (errorfully) estimate **local probabilities of entailments**:
 - a. $p(\text{conquer } xy \Rightarrow \text{invade } xy) = 0.9$
 - b. $p(\text{invade } xy \Rightarrow \text{attack } xy) = 0.8$
 - c. $p(\text{conquer } xy \Rightarrow \text{attack } xy) = 0.4$
 - d. $p(\text{bomb } xy \Rightarrow \text{attack } xy) = 0.7$(etc.)

Global Entailments

- The local entailment probabilities are used to construct an entailment graph using integer linear programming with \pm weights around $p = 0.5$ with the global constraint that the graph must be closed under transitivity.
- Thus, (c) will be included despite low observed frequency, while other low frequency spurious local entailments will be excluded..
- Cliques within the entailment graphs are collapsed to a single paraphrase cluster relation identifier.

Entailment graph



- A simple entailment graph for **relations between countries**.

Lexicon

- The lexicon obtained from the entailment graph

attack := $(S \setminus NP) / NP : \lambda x \lambda y \lambda e. rel_1 x y e$

bomb := $(S \setminus NP) / NP : \lambda x \lambda y \lambda e. rel_1 x y e \wedge rel_4 x y e$

invade := $(S \setminus NP) / NP : \lambda x \lambda y \lambda e. rel_1 x y e \wedge rel_2 x y e$

conquer := $(S \setminus NP) / NP : \lambda x \lambda y \lambda e. rel_1 x y e \wedge rel_2 x y e \wedge rel_3 x y e$

annex := $(S \setminus NP) / NP : \lambda x \lambda y \lambda e. rel_1 x y e \wedge rel_2 x y e \wedge rel_3 x y e$

- These logical forms support correct inference under negation, such as that *conquered* entails *attacked* and *didn't invade* entails *didn't conquer*
 - To answer a question “Did X invade Y” we look for sentences which subsume the conjunctive logical form $rel_2 \wedge rel_1$, or satisfy its negation $\neg rel_2 \vee \neg rel_1$.
- ⚡ Note that if we know that *invasion-of* is a paraphrase of $invade = rel_2$, we also know *invasion-of* entails $attack = rel_1$.

Lexicon

- Primitives like *rel₃* correspond to “hidden” semantic primitives that distinguish these concepts.
- If we do the machine-reading cross-linguistically (Lewis and Steedman, 2013b), we will see that some of them correspond to universal elements masked in English (see earlier remarks about *run across the road*).
- Others will be more arcane.

Results (Lewis and Steedman, 2014b)

| System | Accuracy (all) | AUC (all) |
|----------------------------------------------------|----------------|-------------|
| Majority Class | 56.8% | 0.46 |
| Non Compositional | 57.4% | 0.48 |
| CCG Baseline | 57.8% | 0.46 |
| CCG ChineseWhispers | 58.0% | 0.50 |
| VectorMultiplicative | 61.3% | 0.51 |
| VectorAdditive | 63.5% | 0.57 |
| CCG Entailment Graphs | 64.0% | 0.58 |
| CCG Entailment Graphs+ Implicative Verb Lexicon | 65.0% | 0.59 |

Philosophical Reflections

- Our hidden relations resemble “meaning postulates”, such as the one that says that in every model where X is a *bachelor*, X is also *unmarried* and *male*
- Carnap (1952) introduced meaning postulates in support of **Inductive Logic**, including a model of **Probability**, basically to **keep the model small and consistent**.
- This suggests that our semantic representation expresses an a **pragmatic empiricist** view of “analytic meaning”, of the kind advocated by Quine (1951).
- It can also be viewed as a statistical and text-based approach to treating “**meaning as use**” (Wittgenstein, 1953).

IV: Hanging Language onto Planning

- We saw that (partially) searching the plan graph is an intrinsically **recursive** process.
- So we need *at least* a push-down automaton (PDA) to keep track of it.
- ◊ Is a PDA expressive **enough**?
 - It depends on the class of plans
 - If the set of plan- **types** is unbounded, than a **a PDA is not enough**.
 - (For the same reason that a PDA is not enough for a **PS grammar with unboundedly many non-terminals**.)

Language and Cooperative Planning

- Collaborative Plans are **functions over arbitrary numbers of other agents**:
 - (2) a. Find someone to help to mind the baby
 - b. Find someone to promise to help to mind the baby
 - c. Find someone to ask to promise to help to mind the baby. *(etc.)*
- ◊ Searching a graph with unboundedly many node-types needs an **Embedded PDA (EPDA)**, in which the stack of the PDA can include stack-valued elements.
- Collaborative planning with other minds provides not only the only known **motivation** for language (Tomasello, 1999), but also the **characteristic automaton that supports its use**.
- So we should **look at the grammar of sentences such as (2)**.

Combinatory Categorical Grammar

- CCG (Steedman, 2000; Bozşahin, 2012) eschews language-specific syntactic rules like (3) for English.

$$\begin{array}{l}
 (3) \ S \rightarrow NP \ VP \\
 \quad VP \rightarrow TV \ NP \\
 \quad TV \rightarrow \{proved, found, met, \dots\}
 \end{array}$$

- Instead, all language-specific syntactic information is *lexicalized*, via lexical entries like (4) for the English transitive verb, where *met'* is an abbreviation for *some conjunction of clustered entailments* of the kind discussed earlier.:

$$(4) \text{ met} := (S \setminus NP) / NP : \text{met}'$$

- In CCG, syntactic projection from the lexicon is mediated by **type-raising T** and **composition B**.

The Lexicon

- The syntactic “category” identifies the transitive verb as a function, and specifies the type and directionality of its arguments and the type of its result. For Turkish:

(5) $rastladı := (S \setminus NP) \setminus NP : met'$

- ◇ This is a good **example of the different ways languages carve meaning at the joints**. *rastladı* means something like “came across”, and is distinct from reciprocal “meet” *tanıştı* which is the same word in English.
- A **cross-linguistic clustered entailment semantics, obtained from multilingual machine-reading**, would split these meanings into **two distinct clusters**, rather than one *met'*

Type Raising as Case

- We will assume that type-raising in the form of case is a universal primitive of grammar, as it is for planning in the form of affordance.
- ◊ All noun-phrases (NP) like “Harry” are (polymorphically) type-raised.
- In Japanese and Latin this is the job of case morphemes like nominative *-ga* and *-us*. (Same for Turkish, except nominative is null.)
- In English NPs are ambiguous as to case, and must be **disambiguated by the parsing model** (a.k.a. “structural case”).

Syntactic Derivation

- (6)
$$\frac{\overline{S/(S\backslash NP)}^{>T} \quad \overline{(S\backslash NP)/NP} \quad \overline{(S\backslash NP)\backslash((S\backslash NP)/NP)}^{<T}}{S\backslash NP} <$$

$$\frac{}{S} >$$

- (7)
$$\overline{S/(S\backslash NP)}^{>T} \quad \overline{(S\backslash NP)/NP} \quad \overline{(S\backslash NP)\backslash((S\backslash NP)/NP)}^{<T}$$

$$\frac{}{S/NP} >B$$

$$\frac{}{S} >$$

“Surface Compositional” Semantics

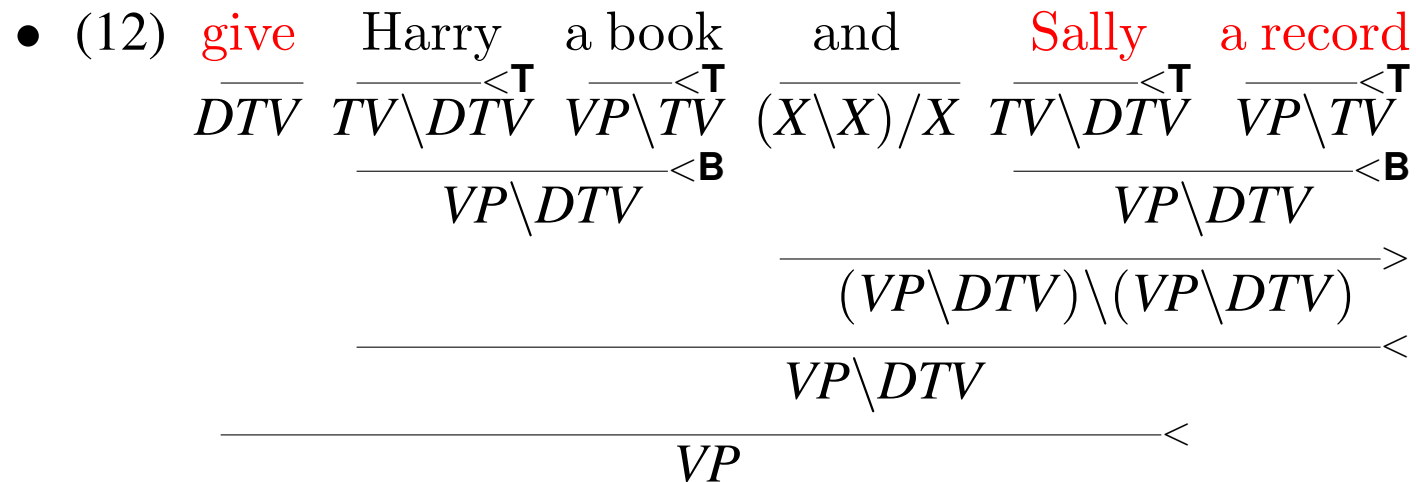
• (8)

$$\begin{array}{c}
 \text{Harry} \qquad \text{met} \qquad \text{Sally} \\
 \frac{\text{Harry}}{S/(S\backslash NP)^{>T}} \quad \frac{\text{met}}{(S\backslash NP)/NP} \quad \frac{\text{Sally}}{(S\backslash NP)\backslash((S\backslash NP)/NP)^{<T}} \\
 : \lambda p.p \text{ harry}' \quad : \text{met}' \quad : \lambda p.p \text{ sally}' \\
 \hline
 \qquad \qquad \qquad S\backslash NP : \text{met}' \text{ sally}' \qquad \qquad \qquad < \\
 \hline
 S : \text{met}' \text{ sally}' \text{ harry}' \qquad \qquad \qquad >
 \end{array}$$

• (9)

$$\begin{array}{c}
 \text{Harry} \qquad \text{met} \qquad \text{Sally} \\
 \frac{\text{Harry}}{S/(S\backslash NP)^{>T}} \quad \frac{\text{met}}{(S\backslash NP)/NP} \quad \frac{\text{Sally}}{(S\backslash NP)\backslash((S\backslash NP)/NP)^{<T}} \\
 : \lambda p.p \text{ harry}' \quad : \text{met}' \quad : \lambda p.p \text{ sally}' \\
 \hline
 \qquad \qquad \qquad S\backslash NP : \lambda x.\text{met}' x \text{ harry}' \qquad \qquad \qquad >^B \\
 \hline
 S : \text{met}' \text{ sally}' \text{ harry}' \qquad \qquad \qquad >
 \end{array}$$

Coordination



◊ CCG reduces the linguists' MOVE and COPY/DELETE to adjacent MERGE

CCG is “Near Context-Free”

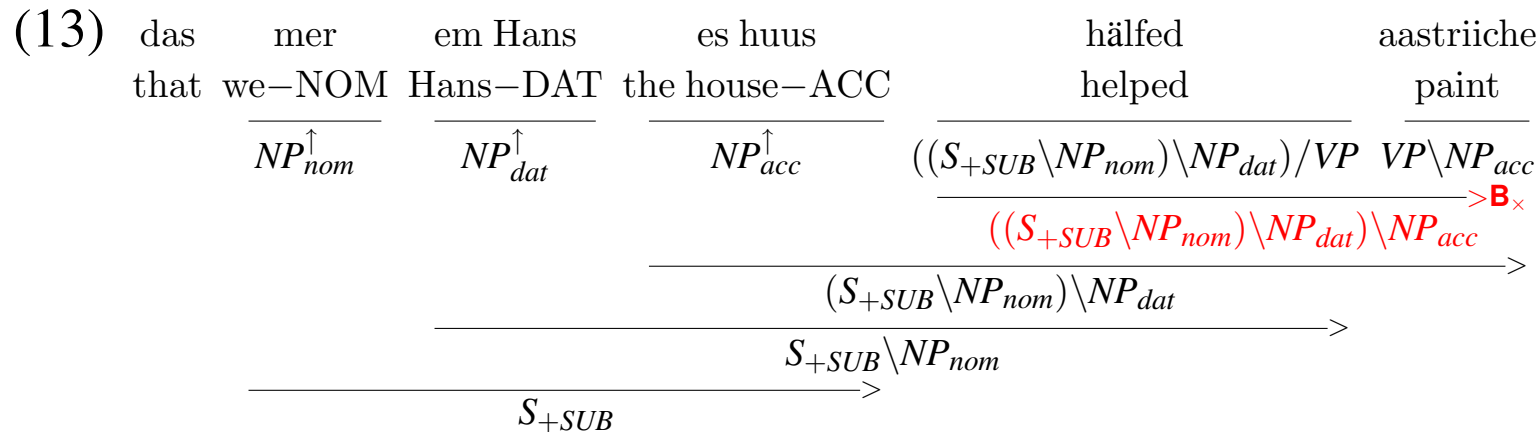
- The composition rules in CCG are generalized to \mathbf{B}^2 , and “crossed composition” \mathbf{B}_\times
- The combination of type-raising and generalized composition yields a permuting and rebracketing calculus closely tuned to the needs of natural grammar.
- CCG and TAG are provably weakly equivalent to Linear Indexed Grammar (LIG) Vijay-Shanker and Weir (1994).
- Hence they are not merely “Mildly Context Sensitive” (Joshi 1988), but rather “Near Context Free,” or “Type 1.9” in the Extended Chomsky Hierarchy.

The Extended Chomsky Hierarchy

| Language Type | Automaton | Rule-types | Exemplar |
|---------------|------------------------------|-----------------------------------------------------------------------------|----------------------------|
| Type 0: RE | Universal Turing Machine | $\alpha \rightarrow \beta$ | |
| Type 1: CS | Linear Bound Automaton (LBA) | $\phi A \psi \rightarrow \phi \alpha \psi$ | |
| I | Nested Stack Automaton(NSA) | $A_{[(i),\dots]} \rightarrow \phi B_{[(i),\dots]} \psi C_{[(i),\dots]} \xi$ | a^{2^n} |
| LCFRS/MCF | <i>i</i> th-order EPDA | $A_{[[i),\dots],\dots]} \rightarrow \phi B_{[[i),\dots],\dots]} \psi$ | $\mathcal{P}(a^n b^n c^n)$ |
| LI | Embedded PDA (EPDA) | $A_{[(i),\dots]} \rightarrow \phi B_{[(i),\dots]} \psi$ | $a^n b^n c^n$ |
| Type 2: CF | Push-Down Automaton (PDA) | $A \rightarrow \alpha$ | $a^n b^n$ |
| Type 3: FS | Finite-state Automaton (FSA) | $A \rightarrow \begin{cases} a & B \\ a \end{cases}$ | a^n |

⊳ All higher language classes properly contain all lower **except** LCFRS and I, which properly intersect.

Zürich German is Strongly Near Context-Free

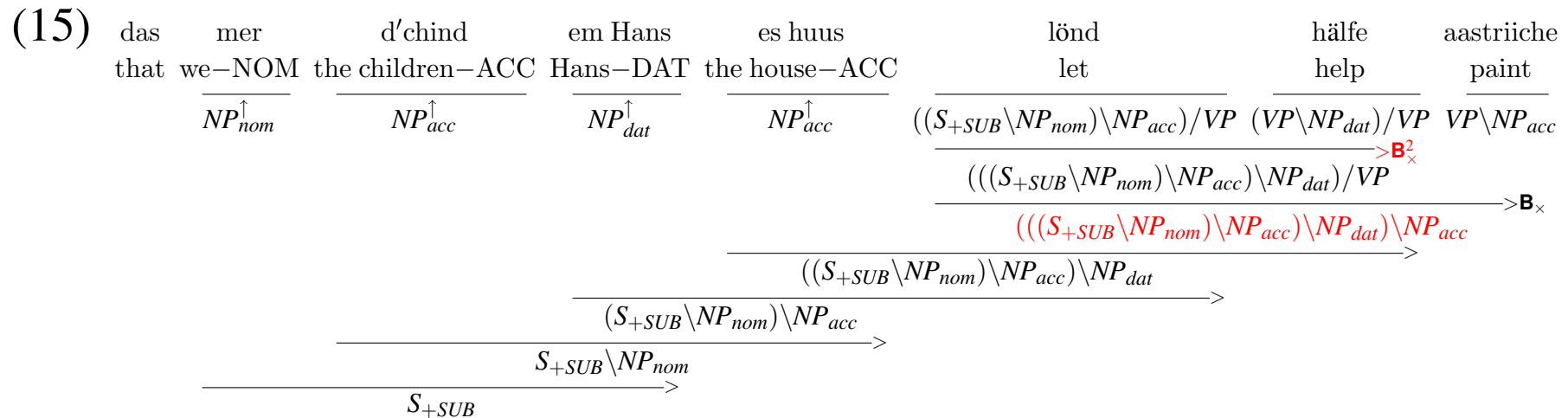


“that we helped Hans paint the house”

- The following is correctly also allowed (Shieber, 1985):

(14) Das mer em Hans hälfed es huus aastriiche.

Zürich German is Strongly Near Context-Free



“that we let the children help Hans paint the house”

- Again, other word orders are correctly allowed.

⚡ Constituents like “es huus lönd hälfe aastriiche” are **homologous to collaborative plans** like earlier “Find someone to let someone help someone mind the baby”.

Conclusion (I)

- The lexicon is the **only** locus of language specific information in the grammar.
- The universal projective syntactic component of natural language grammar is based on the **combinators B, T**.
- In evolutionary terms, these combinators were provided **ready-made**, by a sensory motor planning mechanism most of which we share with a number of animals.
- The problem of parsing is automata-theoretically equivalent to the problem of **planning for cooperation with other minds**.
- **Both of the latter abilities seem unique to humans.**

Conclusion (II)

- The following progression over the last 200M years of vertebrate evolution may have resulted in an essentially instantaneous recent emergence of language:
 1. Pure **reactive planning** with non-recursive KR (finite-state);
 2. (Forward-chaining, breadth-first) **deliberative planning** with non-recursive KR requiring composition, type-raising, and a (simulated) PDA for search;
- A PDA also supports **recursive concepts** in KR. But a PDA alone **isn't enough** to support human planning and human language, which other animals lack.

Conclusion (III)

- We must postulate the following further developments:
 3. Human planning is characterized by the use of **plan variables** corresponding to unknown provided by external agencies such as phone-books, Google search, or **other human beings**.
 - Planning with the particular recursive concepts that are necessary human collaboration for purposes like neotenic child-reading generates plans with **unboundedly many plan variables** (agents) (Hrды, 2009; Steedman, 2014).
 4. Such planning requires a (simulated) **embedded PDA**
 5. The EPDA immediately **supports near-context-free Natural Language Grammar**, as attested by English, Turkish, and Zürich German
 - **This can happen without any further evolutionary work** other than a little specialization of the vocal tract.

Appendix: Practical Applications of CCG

- It was widely expected in the '80s that the degree of derivational ambiguity CCG allows would make it completely impractical for parsing.
- However, **any grammar that covers these data has the same problem.**
- The universal recognition in the '90s of the need for statistical modeling in NLP was a great leveler.
- With such models, CCG can be parsed as fast and as accurately as anything else—
- —with the advantage of a surface compositional semantics including discontinuity and “non-projectivity”.

Practical Applications of CCG

- Many applications exploit the “surface compositional” semantics of CCG—for example:
 - Hockenmaier (2003); Clark and Curran (2004); Çakıcı and Steedman (2009); Lewis and Steedman (2014a) provide **publicly available efficient parsers** trained on WSJ.
 - Birch *et al.* (2007); Hassan *et al.* (2009); Mehay and Brew (2012) use CCG for **statistical machine translation**
 - Prevost (1995); White (2006) apply it to **sentence realization**
 - Briscoe (2000); Kwiatkowski *et al.* (2012); Krishnamurthy and Mitchell (2012) apply it to **semantic parsing and language acquisition**
 - Bos and Markert (2005); Lewis and Steedman (2013a,b, 2014b) apply it to **open-domain question answering and entailment**

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