A Very Short Introduction to CCG*

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Draft, November 1, 1996

This paper is intended to provide the shortest possible introduction to Combinatory Categorial Grammar.

1 Combinatory Grammars.

In Combinatory Categorial Grammar (CCG, Steedman 1987, 1996b), as in other varieties of Categorial Grammar reviewed by Wood 1993 and exemplified in the bibli0graphy below, elements like verbs are associated with a syntactic "category" which identifies them as *functions*, and specifies the type and directionality of their arguments and the type of their result. We here use the "result leftmost" notation in which a rightward-combining functor over a domain β into a range α are written α/β, while the corresponding leftward-combining functor is written $\alpha\backslash\beta$.[1] α and β may themselves be function categories. For example, a transitive verb is a function from (object) NPs into predicates—that is, into functions from (subject) NPs into S:

(1) likes := $(S\backslash NP)/NP$

(2) *Forward Application:* $(>)$
$X/Y \quad Y \quad \Rightarrow \quad X$

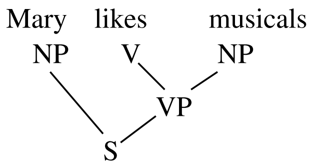
(3) *Backward Application:* $(<)$
$Y \quad X\backslash Y \quad \Rightarrow \quad X$

These rules have the form of very general binary PS rule schemata. In fact, pure categorial grammar is just context-free grammar written in the accepting, rather than the producing, direction, with a consequent transfer of the major burden of specifying particular grammars from the PS rules to the lexicon. While it is now convenient to write derivations as in a, below, they are equivalent to conventional phrase structure derivations b:

*The research was supported in part by NSF grant nos. IRI91-17110, IRI95-04372, ARPA grant no. N66001-94-C6043, and ARO grant no. DAAH04-94-G0426.

[1] There is an alternative "result on top" notation due to Lambek 1958, according to which the latter category is written $\beta\backslash\alpha$.

(4) a.
$$\begin{array}{ccc}
\text{Mary} & \text{likes} & \text{musicals} \\
\hline
NP & (S\backslash NP)/NP & NP \\
 & \multicolumn{2}{c}{\overline{\qquad\qquad\qquad}{>}} \\
 & \multicolumn{2}{c}{S\backslash NP} \\
\multicolumn{2}{c}{\overline{\qquad\qquad\qquad}{<}} & \\
\multicolumn{2}{c}{S} &
\end{array}$$

b. 

It is important to note that such tree-structures are simply a representation of the process of derivation. They are not structures that need to be built by a processor, nor do they provide the input to any rules of grammar.

Such categories can be regarded as encoding the semantic type of their translation, and this translation can be made explicit in the following expanded notation, which associates a translation with the entire syntactic category, via the colon operator, which is assumed to have lower precedence than the categorial slash operators. (Agreement features are also included in the syntactic category, represented as subscripts, much as in Bach 1983. The feature $3s$ is "underspecified" for gender and can combine with the more specified *3sm* by a standard unification mechanism that we will pass over here – cf. Shieber 1986.)[2]

(5) likes := $(S\backslash NP_{3s})/NP : like'$

We must also expand the rules of functional application in the same way:

(6) *Forward Application:* ($>$)
$X/Y : f \quad Y : a \quad \Rightarrow \quad X : fa$

(7) *Backward Application:* ($<$)
$Y : a \quad X\backslash Y : f \quad \Rightarrow \quad X : fa$

They yield derivations like the following:

(8)
$$\begin{array}{ccc}
\text{Mary} & \text{likes} & \text{musicals} \\
\hline
NP_{3sm} : mary' & (S\backslash NP_{3s})/NP : like' & NP : musicals' \\
 & \multicolumn{2}{c}{\overline{\qquad\qquad\qquad\qquad}{>}} \\
 & \multicolumn{2}{c}{S\backslash NP_{3s} : like' musicals'} \\
\multicolumn{3}{c}{\overline{\qquad\qquad\qquad\qquad\qquad\qquad}{<}} \\
\multicolumn{3}{c}{S : like' musicals' mary}
\end{array}$$

The derivation yields an S with a compositional interpretation, equivalent under a convention of left associativity to $(like' musicals') mary'$.

Coordination might be included in CG via the following rule, allowing constituents of like type to conjoin to yield a single constituent of the same type:[3]

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[2]This notation follows Steedman 1987. Another notation, used in Steedman 1990, associates a unifiable logical form with each primitive category, so that the same transitive verb appears as follows:

(i) likes := $(S : like' y\, x\backslash NP_{3s} : x)/NP : y$

The advantage is that the predicate-argument structure is built directly by the unification, and that the combination rules need no further modification. Otherwise the choice is largely a matter of notational convenience.

[3]The semantics of this rule, or rather rule schema, is somewhat complex, and is omitted here. The rule is also simplified syntactically in several respects for the present purpose.

(9) *Coordination:* $(<\&>)$

$$X \quad conj \quad X \quad \Rightarrow \quad X$$

(10)
$$\begin{array}{ccccc}
\text{I} & \text{loathe} & \text{and} & \text{detest} & \text{opera}\\
\overline{NP} & \overline{(S\backslash NP)/NP} & \overline{CONJ} & \overline{(S\backslash NP)/NP} & \overline{NP}\\
 & \multicolumn{3}{c}{\overline{\qquad\qquad\qquad\qquad\qquad}{}^{<\&>}} & \\
 & \multicolumn{3}{c}{(S\backslash NP)/NP} & \\
 & \multicolumn{4}{c}{\overline{\qquad\qquad\qquad\qquad\qquad\qquad\qquad}{}^{>}}\\
 & \multicolumn{4}{c}{S\backslash NP}\\
\multicolumn{5}{c}{\overline{\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad}{}^{<}}\\
\multicolumn{5}{c}{S}
\end{array}$$

In order to allow coordination of contiguous strings that do not constitute constituents, CCG allows certain further operations on functions related to Curry's combinators 1958. For example, functions may nondeterministically *compose*, as well as apply, under the following rule:

(11) *Forward Composition:* $(>B)$

$$X/Y \quad Y/Z \quad \Rightarrow \quad X/Z$$

The most important single property of combinatory rules like this is that their semantics is completely determined under the following principle:[4]

(12) *The Principle of Combinatory Transparency:* The semantic interpretation of the category resulting from a combinatory rule is uniquely determined by the interpretation of the slash in a category as a mapping between two sets.

In the above case, the category X/Y is a mapping of Y into X and the category Y/Z is that of a mapping from Z into Y. Since the two occurrences of Y identify the *same* set, the result category X/Z is that mapping from Z to X which constitutes the composition of the input functions. It follows that the only semantics that we are allowed to assign, when the rule is written in full, is as follows:

(13) *Forward Composition:* $(>B)$

$$X/Y : f \quad Y/Z : g \quad \Rightarrow \quad X/Z : \lambda x.f(gx)$$

No other interpretation is allowed. It is worth noticing that this principle would follow automatically if we were using the alternative unification-based notation discussed in note 2 and the composition rule as as it is given in 11.

The operation of this rule in derivations is indicated by an underline indexed $>B$ (because Curry called his composition combinator **B**). Its effect can be seen in the derivation of sentences like *I requested, and would prefer, musicals*, which crucially involves the composition of two verbs to yield a composite of the same category as a transitive verb (the rest of the derivation is given in the simpler notation). It is important to observe that composition also yields an appropriate interpretation for the composite verb *would prefer*, as $\lambda x.\lambda y.will'(prefer'\ x)\ y$, an object which if applied to an object *musicals* and a subject *I*

[4]This principle is stated differently in Steedman 1996b but is in fact identical.

yields the proposition $will'(prefer'\ musicals')\ me'$. The coordination will therefore yield an appropriate semantic interpretation.[5]

(14)

$$
\begin{array}{cccccc}
\text{I} & \text{requested} & \text{and} & \text{would} & \text{prefer} & \text{musicals} \\
\hline
NP & (S\backslash NP)/NP & CONJ & (S\backslash NP)/VP : will' & VP/NP : prefer' & NP \\
 & & & \multicolumn{2}{c}{\xrightarrow{\quad\quad\quad\quad\quad\quad\quad\quad} {>}B} & \\
 & & & \multicolumn{2}{c}{(S\backslash NP)/NP : \lambda x.\lambda y.will'(prefer'x)y} & \\
 & \multicolumn{4}{c}{\xrightarrow{\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad} {<}\&{>}} & \\
 & \multicolumn{4}{c}{(S\backslash NP)/NP} & \\
 & & & \multicolumn{3}{c}{\xrightarrow{\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad} {>}} \\
 & & & \multicolumn{3}{c}{S\backslash NP} \\
\multicolumn{6}{c}{\xrightarrow{\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad} {<}} \\
\multicolumn{6}{c}{S}
\end{array}
$$

Combinatory grammars also include type-raising rules, which turn arguments into functions over functions-over-such-arguments. These rules allow arguments to compose, and thereby take part in coordinations like *I dislike, and Mary likes, musicals*. For example, the following rule allows the conjuncts to form as below (again, the remainder of the derivation is given in the briefer notation):

(15) *Subject Type-raising:* ($>$T)

$$NP : a \ \Rightarrow\ \mathrm{T}/(\mathrm{T}\backslash NP) : \lambda f.f\ a$$

(16)

$$
\begin{array}{cccccc}
\text{I} & \text{dislike} & \text{and} & \text{Mary} & \text{likes} & \text{musicals} \\
\hline
NP & (S\backslash NP)/NP & CONJ & NP & (S\backslash NP)/NP & NP \\
 & & & : mary' & : \lambda x.\lambda y.like'xy & \\
\xrightarrow{\quad\quad} {>}T & & & \xrightarrow{\quad\quad} {>}T & & \\
S/(S\backslash NP) & & & S/(S\backslash NP) & & \\
 & & & : \lambda f.f\ mary' & & \\
\multicolumn{2}{c}{\xrightarrow{\quad\quad\quad\quad\quad\quad} {>}B} & & \multicolumn{2}{c}{\xrightarrow{\quad\quad\quad\quad\quad\quad} {>}B} & \\
\multicolumn{2}{c}{S/NP} & & \multicolumn{2}{c}{S/NP} & \\
 & & & \multicolumn{2}{c}{: \lambda x.like'x\ mary'} & \\
\multicolumn{5}{c}{\xrightarrow{\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad} {<}\&{>}} & \\
\multicolumn{5}{c}{S/NP} & \\
 & & \multicolumn{4}{c}{\xrightarrow{\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad} {>}} \\
 & & \multicolumn{4}{c}{S}
\end{array}
$$

Rule 15 has an "order-preserving" property. That is, it turns the NP into a *rightward* looking function over *leftward* function, and therefore preserves the linear order of subjects and predicates.

Like composition, type-raising rules are required by the Principle of Combinatory Transparency 12 to be transparent to semantics. This fact ensures that the raised subject NP has an appropriate interpretation, and can compose with the verb to produce a function that can either coordinate with a transitive verb or reduce with an object *musicals* to yield *like' musicals' mary'*.

Since complement-taking verbs like *think*, VP/S, can in turn compose with fragments like *Mary likes*, S/NP, we correctly predict the fact that right-node raising is unbounded, as

[5]The analysis begs some syntactic and semantic questions about the coordination rule and the interpretation of modals. See Steedman 1990, 1996b for more complete accounts of both.

in a, below, and also provide the basis for an analyis of the similarly unbounded character of leftward extraction, as in b (see the earlier papers and Steedman 1991a, 1996b for details, including ECP effects and other extraction asymmetries, and the involvement of similar fragments in intonational phrasing):

(17) a. [I dislike]$_{S/NP}$ and [you think Mary likes]$_{S/NP}$ musicals.
b. The musicals which [you think Mary likes]$_{S/NP}$.

This apparatus has been applied to a wide variety of coordination phenomena, including English "argument-cluster coordination", "backward gapping" and verb-raising constructions in Germanic languages, and English gapping. The first of these is relevant to the present discussion, and is illustrated by the following analysis, from Dowty 1988:[6]

(18)
$$\begin{array}{ccccc}
\text{introduce} & \text{Bill} & \text{to Sue} & \text{and} & \text{Harry to George}\\
\hline
(VP/PP)/NP & (VP/PP)\backslash((VP/PP)/NP)\ {}^{<T} & VP\backslash(VP/PP)\ {}^{<T} & CONJ & VP\backslash((VP/PP)/NP)\ {}^{<B}\\
\cline{2-3}
 & \multicolumn{2}{c}{VP\backslash((VP/PP)/NP)\ {}^{<B}} & & \\
\cline{2-5}
 & \multicolumn{4}{c}{VP\backslash((VP/PP)/NP)\ {}^{<\&>}} \\
\hline
\multicolumn{5}{c}{VP\ {}^{<}}
\end{array}$$

The important feature of this analysis is that it uses "backward" rules of type-raising $<$ **T** and composition $<$ **B** that are the exact mirror-image of the two "forward" versions introduced as examples 11 and 15, which similarly guarantee that the semantics of non standard constituents like *Bill to Sue* is such as to reduce appropriately with a ditransitive verb like *give*. It is in fact a prediction of the theory that such a construction can exist in English, and its inclusion in the grammar requires no additional mechanism whatsoever.

The earlier papers show that no *other* non-constituent coordinations of dative-accusative NP sequences are allowed in any language with the English verb categories, given the assumptions of CCG. Thus the following are ruled out in principle, rather than by stipulation:

(19) a. *Bill to Sue and introduce Harry to George
b. *Introduce to Sue Bill and to George Harry

A number of related well-known cross-linguistic generalisations concerning the dependency of so-called "gapping" upon lexical word-order are also captured (see Dowty 1988 and Steedman 1985, 1990). In English the phenomenon shows up in all constructions that can be assumed to involve multiple arguments of the same functor:

(20) a. I gave Deadeye Dick a sugar stick, and Mexican Pete a bun.
b. I saw Keats yesterday, and Chapman the day before.
c. I saw Gilbert arrive and George leave.
d. I persuaded Sid to take a bath and Nancy to have a wash.
e. I promised Mutt to go to the movies and Jeff to go to the play.
f. I told Shem I lived in London and Shaun I lived in Philadelphia.
g. I bet Sammy sixpence I would win and Rosie a dollar I would lose.

[6]In more recent work, Dowty has disowned this analysis, because it apparently entails an "intrinsic" use of logical form to account for binding phenomena. This issue is discussed in Steedman 1996b

Phenomena like the above immediately suggest that all complements of verbs bear type-raised categories. However, we do not want anything *else* to type-raise. In particular, we do not want raised categories to raise again, or we risk infinite regress in our rules. One way to deal with this problem is to explicitly restrict the two type-raising rules to the relevant arguments of verbs, as follows, a restriction that is a natural expression of the resemblance of type-raising to some generalized form of (nominative, accusative, etc) grammatical *case*—cf. Steedman 1985, 1990.

(21) *Forward Type-raising:* ($>$T)
$X : a \;\Rightarrow\; \mathrm{T}/(\mathrm{T}\backslash X) : \lambda f.fa$
where $X \in \{NP\}$

(22) *Backward Type-raising:* ($>$T)
$X : a \;\Rightarrow\; \mathrm{T}\backslash(\mathrm{T}/X) : \lambda f.fa$
where $X \in \{NP, PP, AP, VP, VP', S, S'\}$

The other solution is to simply expand the lexicon by incorporating of the raised categories that these rules define, so that categories like NP have raised categories, and all functions into such categories, like determiners, have the category of functions into raised categories.

These two tactics are essentially equivalent, because in some cases we need both raised and unraised categories for complements. (The argument is developed in Steedman 1996b, and depends upon the observation that any category that is not a barrier to extraction must bear an unraised category, and any argument that can take part in argument-cluster coordination must be raised). The correct solution from a linguistic point of view, inasfar as it captures the fact that some languages appear to lack certain unraised categories (notably PP and S'), is probably the lexical solution. However the restricted rule-based solution makes derivations easier to read and causes them to take up less space. We will therefore follow it here without further discussion.

Since categories like NP can be raised over a number of different functor categories, such as predicate, transitive verb, ditransitive verb etc, and since the resulting raised categories $S\backslash(S/NP)$, $(S\backslash NP)\backslash((S\backslash NP)/PP)$, etc. of NPs, PPs, etc are quite hard to read, it is sometimes convenient to abbreviate the raised categories as a schema written $NP^{\uparrow}$, $PP^{\uparrow}$, etc.[7]

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[7] In a computational implementation one would in fact want to schematise type-raised categories in this way—see Steedman 1991c for further discussion.

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