

## 1 CCGlab coverage

CCGlab is a tool for experimenting with Combinatory Categorical Grammar (CCG; Steedman 1996, 2000, 2012, Clark and Curran 2003, Zettlemoyer and Collins 2005, Steedman and Baldridge 2011, Bozsahin 2012). You write CCGlab grammars almost in paper-style and look at the results in almost paper format.

It is written in COMMON LISP. It implements all the established combinators of CCG, namely application, composition and substitution, including their finite powers (quadratic for **S**; cubic for **B**), in all their directional variants. [Every rule has a switch for experimentation](#). CCGlab also implements subcomposition and its directional variants up to cubic power for further experimentation (variously called **D** and **O** by Hoyt and Baldridge 2008, Bozsahin 2012 respectively). Hereafter we assume intermediate familiarity with CCG.

CCGlab is designed with linguists, cognitive scientists and computational linguists in mind. Raw input to the system is lexical specifications and lexical rules, much like in Steedman papers. Unlike unification-inspired systems, the logical form (LF) is associated with the overall syntactic category, and the underlying lambda-calculus is visible at all times. Wide-coverage parsing with CCGlab models is a long-term goal.

The examples below show raw input to CCGlab.<sup>1</sup> The first three are lexical items, and the last one is a lexical rule. Order of specifications and whitespacing are not important.

```
John   n := np[agr=3s] : !john ;
likes  v := (s\np[agr=3s])/\np : \x\y. !like x y ;
and     x := (@X\*@X)/*@X : \p\q\q. !and (p x)(q x) ;
(L1) np[agr=?x] : lf --> s/(s\np[agr=?x]) : \p. p lf ;
```

Unification plays no role in CCGlab. Features are checked for atomic category consistency only, and no feature is passed non-locally. All features are simple, feature variables are for values only, they are local to a category, and they are atomic-valued. For example, if we have the sequent (a) below, we get the result (b) by composition, not (c). We could in principle compile all finite feature values for any basic category in a grammar and get rid of its features (but nobody does that).

```
(a) s[f1=?x1, f2=v2]/s[f1=?x1]   s[f1=v1, f2=?x2]/np[f2=?x2]
(b) s[f1=v1, f2=v2]/np[f2=?x2]
(c) s[f1=v1, f2=v2]/np[f2=v2]
```

Because type-raising is unary, it is left to lexical rules, or to lexical generalizations. Lexical rules are implemented. Slash modalities are implemented too (see Baldridge 2002, Steedman and Baldridge 2011).

Meta-categories such as  $(X \backslash X)/X$  are allowed with application only, which maintains a very important property of CCG: it is procedurally neutral (Pareschi and Steedman, 1987). Given two substantive categories and CCG's understanding of universal rules, there is only one way to combine them, so that the parser can eschew other rules for that sequent if it succeeds in one rule. For this reason, 'X\$' categories have not been incorporated. They require structured unification and jeopardize procedural neutralism.

Below is the output for the Latin phrase for *Balbus is building the wall*. The first column is the rule index. The rest is about the current step: a lexical assumption, result of a lexical rule, or one step of a derivation.

```
Derivation 1
-----
LEX  MUR := N : WALL
LEX  UM := (S/(S\NP))\N : (LAM X (LAM P (P X)))
<    (MUR)(UM) := S/(S\NP) : ((LAM X (LAM P (P X))) WALL)
LEX  BALB := N : BALB
LEX  US := (S/(S\NP))\N : (LAM X (LAM P (P X)))
<    (BALB)(US) := S/(S\NP) : ((LAM X (LAM P (P X))) BALB)
LEX  AEDIFICAT := (S\NP)\NP : (LAM X (LAM Y ((BUILD X) Y)))
>Bx  (BALB US)(AEDIFICAT) := S\NP : (LAM X
      ((LAM X (LAM P (P X))) BALB)
      ((LAM X (LAM Y ((BUILD X) Y))) X)))
>    (MUR UM)(BALB US AEDIFICAT) := S : (((LAM X (LAM P (P X))) WALL)
      (LAM X
        ((LAM X (LAM P (P X))) BALB)
        ((LAM X (LAM Y ((BUILD X) Y))) X))))
```

Final LF, normal-order evaluated: ((BUILD WALL) BALB)

<sup>1</sup>The slash modality correspondences from CCGlab to papers are:  $\cdot \rightarrow \cdot$   $\hat{\cdot} \rightarrow \diamond$   $\ast \rightarrow \star$   $+\rightarrow \times$

The inductive component prints associated parameter-weighted local counts of features and the final count, for verification. Every lexical entry, word or lexical rule, is assigned a parameter. In the example below, all parameters were set to unity so that weighted counting to be described in (2) below can be seen easily. The only feature is the number of times lexical items are used in a derivation. 18 is the total here.

```

LEX      1.0 MUR := N : WALL
LEX      1.0 UM := (S/(S\NP))\N : (LAM X (LAM P (P X)))
<        2.0 (MUR)(UM) := S/(S\NP) : ((LAM X (LAM P (P X))) WALL)
LEX      1.0 BALB := N : BALB
LEX      1.0 US := (S/(S\NP))\N : (LAM X (LAM P (P X)))
<        2.0 (BALB)(US) := S/(S\NP) : ((LAM X (LAM P (P X))) BALB)
>0       4.0 (MUR UM)(BALB US) := S/((S\NP)\NP) : (LAM H
                                                    ((LAM X (LAM P (P X)))
                                                    WALL)
                                                    (LAM X
                                                    ((LAM X (LAM P (P X)))
                                                    BALB)
                                                    (H X))))))
LEX      1.0 AEDIFICAT := (S\NP)\NP : (LAM X (LAM Y ((BUILD X) Y)))
>        18.0 (MUR UM BALB US)(AEDIFICAT) := S : ((LAM H
                                                    ((LAM X (LAM P (P X)))
                                                    WALL)
                                                    (LAM X
                                                    ((LAM X (LAM P (P X)))
                                                    BALB)
                                                    (H X))))))
                                                    (LAM X
                                                    (LAM Y ((BUILD X) Y))))
Normalized LF: ((BUILD WALL) BALB)

```

The deductive component computes all the constituents and their LFs that are consequences of lexical assumptions. The inductive component computes (i) the most likely LF for a given string, (ii) the most probable derivation for that LF, and (iii) the highest-weighted derivation for any LF. We assume that the inductive component is supplied with lexical parameters after parameter estimation. (The deductive component starts with the assumption that they are unity.) Some preliminary models are included in the package.

The algorithm for the basic inductive component is more or less standard in Probabilistic CCG (PCCG). The one we use is summarized from Zettlemoyer and Collins (2005) throughout the manual:

$$\arg \max_L P(L \mid S; \bar{\theta}) = \arg \max_L \sum_D P(L, D \mid S; \bar{\theta}) \quad (1)$$

where  $S$  is the sequence of words to be parsed,  $L$  is a logical form for it,  $D$  is a sequence of CCG derivations for the  $(L, S)$  pair, and  $\bar{\theta}$  is the  $n$ -dimensional parameter vector for a grammar of size  $n$  (the total number of lexical items and rules). The term on the right-hand side is induced from the following relation of probabilities and parameters in PCCG (*ibid.*);<sup>2</sup> where  $\bar{f}$  is a vector of 3-argument functions  $\langle f_1(L, D, S), \dots, f_n(L, D, S) \rangle$ :

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

The functions of  $\bar{f}$  count local substructure in  $D$ . Namely,  $f_i$  is the number of times the lexical element  $i$  (item or rule) is used in  $D$ , sometimes called the *feature*  $i$ . If you want to count other substructures in  $D$  or  $L$ , as in Clark and Curran (2003), you need to write some code. A plug-in is provided. That was one motivation for giving detailed specs. There is a growing body of literature on the topic, starting with Clark and Curran.

You can think of CCGlab as Lisp code in three layers, Paul Graham 1994-style: (i) the representational layer, which is based on (name value) pairs and lists of such pairs, so on; (ii) the parsing layer, which is based on hash tables and the representation layer; and (iii) the post-parsing layer, which is based on  $\lambda$ -calculus and the parsing layer, which is used for checking LF equivalence. Combinators are Lisp macros on the last layer. Because our lambda layer has nothing to do with Lisp's lambdas (the internals of LFs are always visible), you can use the top layer as a debugging tool for your LF assumptions. It has two LF evaluators: normal-order and applicative-order. If they do not return the same LF on the same parse result, then there is something strange about your LF.<sup>3</sup>

<sup>2</sup>You may be alarmed by the exponentiation in formula (2) potentially causing floating-point overflow, and may worry about what your value range should be for  $\theta_i$  to avoid that. We recommend starting with  $0 < \theta_i \leq 1$ . Keep also in mind that  $\theta_i$  are not probabilities but weights. They can be negative. Formula (2) takes care of any weight.

<sup>3</sup>It doesn't follow that your LF is correct if both evaluations return the same result. If it did, we wouldn't need empirical sciences like linguistics and cognitive science. Your categories, and derivations with them, can tell you more.

## 2 CCGlab projects

We suggest that you create a separate directory for each project to keep things clean. CCGlab will need around six files in the working directory to set up a CCG grammar and a model.

By a grammar we mean a set of CCG assumptions like the one above which you want to subject to CCG's universal combinatorics. By a model we mean a version of the grammar which you've subjected to empirical training and parameter estimation, results of which you want to subject to CCG's universal combinatorics. They have the same representation in CCGlab.

A project with name *P* consists of the following files (we explain their format in §4):

- *P.ccg* : The CCG grammar as text file, much like in papers. You write this one.
- *P.lisptokens* : The version of the text file suited for the Lisp reader, and wrapped in `(. .)`. The `sed` script called `tokens` does this by taking into account Lisp's hypersensitivity to special symbols such as `'('`, `')'`, `'\'` etc., and CCGlab's stubbornness that e.g. `':'=` is one token, not two. They are wrapped in vertical bars, e.g. `|:|=|`. Keep in mind that Lisp has its own tokenizer and whitespace preprocessor, so this step is crucial to turn your grammar into Lisp code in the way you intended, rather than Lisp. Your grammar becomes a Lisp object at one fell swoop because of this wrapping.
- *P.ded* : Lisp translation of the input grammar *P.lisptokens*, as input to deduction. The deducer just closes universal syntax-semantics of CCG on your lexical assumptions.
- *P.ind* : The model-trained version of the grammar, as input to induction and parse ranking. It has the same format as *P.ded*. This is possible because the deducer already knows how to compute the parameter-weighted sums of features in a derivation. We assume that model training and parameter estimation set the parameters right.
- *P.sup* : The supervision file. This is the training data for PCCG parameter estimation. It consists of sentence-LF pairs. Syntax and derivations are hidden variables in PCCG, and training is done solely on sentence-LF pairs.
- *P.lisp* : Optional. Project-specific code developed by you. For example, your plug-in for feature counts can go in here if you have one. In fact you can call this file anything you like as long as you know what to load into Lisp. A standard name is recommended for others to keep track of your work.
- *P.testsuite.lisp* : Optional. I put my test sentences and their output display code in such files to keep things tidy.

The last two optional files are recommended so that one can make easier sense of sample files in a release.

## 3 Workflows

There are basically two workflows. Model development cannot be fully automated, so it's harder.<sup>4</sup> In the cases below, the Lisp parts must be done after `ccglab` command. The README file explains how.

### 3.1 Grammar development and testing

If you start with a linguistically-motivated grammar, you'd probably take the following steps, assuming your project's name is `example`:

1. In your working directory, write your grammar and save it as plain text e.g. `example.ccg`
2. In CCGlab do e.g. `(load-grammar "example" :maker 'sbcl)`.  
This means Lisp tokens will be generated by `sed` from within Lisp, called in this case by SBCL Lisp. This step prepares the `example.ded` file and loads it onto Lisp.  
If you omit the `":"maker 'sbcl"` part, it will be assumed that `.lisptokens` file is already fresh, and `sed` is not called.
3. Do: `(ccg-deduce '(a sequence of words))` to run the CKY parser.
4. Do: `(cky-show-deduction)` to see all the results.

You can also do `(cky-pprint)` to see the CKY table. It prints all the detail.

If there were errors in your grammar file, step 2 would fail to load the grammar, and you'd need to go back to editing to fix it. Partially-generated `example.ded` will tell you where the *first error* was found. If you change the `example.ccg` file, go back to step 2. Other functionalities of CCGlab are explained in §5.

<sup>4</sup>Grammar development cannot be fully automated either, but that's another story. Beware of claims to the contrary, sometimes emanating from CL/NLP/logic circles. This is good for business, for us grammarians.

### 3.2 Model testing

At some point, you may turn to modeling. It usually means taking the `example.ded` file and saving it as `example.ind` first, then adjusting its parameters (because they were set to default in `.ded`) by parameter estimation, and playing with its categories.

Model training is not easy to reduce to a standard workflow because it depends on what your model is intended to do (whereas we all know what a grammar is supposed to do—get to semantics). This process is up to you. CCGlab helps with the basics (lexical parameters) to compute (1–2) and other formulae like (3–6) below. A plug-in called `(count-more-substructure <resultcell>)` is provided, where CKY result cells and their derivation sequences are at your disposal.

In the end, you can create an `example.ind` file in the same format that you started. This means that every lexical entry (lexical item or lexical rule) is associated with a parameter. This is the minimum. If you have more parameters, you must write some code above the minimal machinery provided by CCGlab to change induction. The model testing workflow is:

1. In CCGlab, do: `(load-model "example")`.  
This will load the grammar in `example.ind` with its parameter set.
2. Do: `(ccg-induce '(a sequence of words))` to CKY-parse and rank the parses.
3. Do: `(cky-show-induction)` to see three results for the sentence: (i) most likely LF for it, (ii) its most likely derivation, and (iii) most likely derivation for any LF for the sentence. You can also do `(cky-pprint)` to see the CKY table. It prints all the detail. If you like, do `(cky-show-deduction)` to see all the results. It does not recompute anything.

### 3.3 Model development: parameter estimation

Parameters of an `.ind` file can be re-estimated from training data of  $(L_i, S_i)$  pairs where  $L_i$  is the logical form associated with sentence  $S_i$ . The log-likelihood of the training data of size  $n$  is:

$$O(\bar{\theta}) = \sum_{i=1}^n \log P(L_i | S_i; \bar{\theta}) = \sum_{i=1}^n \log \left( \sum_T P(L_i, T | S_i; \bar{\theta}) \right) \quad (3)$$

Notice that syntax is marginalized by summing over all derivations  $T$  of  $(L_i, S_i)$ .

For individual parameters we look at the partial derivative of (3) with respect to parameter  $\theta_j$ . The local gradient of  $\theta_j$  with feature  $f_j$  for the training pair  $(L_i, S_i)$  is the difference of two expected values:

$$\frac{\partial O_i}{\partial \theta_j} = E_{f_j(L_i, T, S_i)} - E_{f_j(L, T, S_i)} \quad (4)$$

The gradient will be negative if feature  $f_j$  contributes more to any parse than it does for the correct parses of  $(L_i, S_i)$ . It will be zero if all parses are correct. Expected values of  $f_j$  are therefore calculated under the distributions  $P(T | S_i, L_i; \bar{\theta})$  and  $P(L, T | S_i; \bar{\theta})$ . For the overall training set, using sums, the partial derivative is:

$$\frac{\partial O}{\partial \theta_j} = \sum_{i=1}^n \sum_T f_j(L_i, T, S_i) P(T | S_i, L_i; \bar{\theta}) - \sum_{i=1}^n \sum_L \sum_T f_j(L, T, S_i) P(L, T | S_i; \bar{\theta}) \quad (5)$$

Once we have the derivative, we use stochastic gradient ascent to re-estimate the parameters:

Initialize  $\bar{\theta}$  to some value. (6)

for  $k = 0 \dots N - 1$

  for  $i = 1 \dots n$

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

where  $N$  is the number of passes over the training set,  $n$  is the training set size, and  $\alpha_0$  and  $c$  are learning-rate parameters. The function `update-model` computes (6) by taking these as arguments.

This is gradient *ascent*, so initialize  $\bar{\theta}$  accordingly. [You can standardize them as z-scores, if you like.](#) The partial derivative in (6) is  $\frac{\partial O_i}{\partial \bar{\theta}}$ , for the training pair  $i$ , i.e. without the outermost sums in (5). It is what `update-model` computes first, then (6).

An example workflow is provided for the ‘corner’ project in the package. The steps were:

1. Write `corner.ccg` and create `corner.ded`.
2. Copy `corner.ded` to `corner.ind`.
3. Initialize the parameters in `corner.ind`.
4. Design the training set `corner.sup`.
5. (`update-model "corner" 10 1.0 1.0 :load t :verbose t :debug t`). Notice that the training set size is not an argument to the function since it can be found from `corner.sup`.
6. (`show-training`)
7. (`save-training "corner.ind.re-estimated"`). The trained model is now in the output file. You can go back to workflow in §3.2 to parse and rank the parses with the trained model if you rename the output `corner.ind`.

## 4 CCGlab representations

### 4.1 .ccg

This file defines lexical items and lexical rules in Steedman style, with the following amendments (stylistic ones are marked with ‘–’, and the grammatical ones with ‘★’):

- ‘;’ is the terminator of a lexical specification. It is required. Each spec must start on a new line.
- ‘-->’ is the lexical rule marker.
- ★ A part-of-speech tag comes before ‘:=’. Its value is up to you. (This is the only way CCG can tell whether e.g.  $(S \backslash NP) / (S \backslash NP)$  can be a verb—say ‘want’—rather than an adjunct, which is crucial for type-raising.)
- ★ Special categories are pseudo-atomic. They start with @, e.g. @X. They must be lexically headed, and they must be across the board in a category. For example,  $and := (@X * @X) / * @X : \dots$  is fine but  $so := (@X * @Y) / * (@X * @Y) : \dots$  is not. And  $and := (S \backslash NP) / * @X : \dots$  is bad too. We therefore eliminate the need for structured unification.
- ★ If you use an @X category in a lexical rule, it will be treated as an ordinary category.
- Non-variables in LF must be prefixally exclaimed to avoid substitution/application by Lisp. Write *hit* as *!hit*. It will be converted to the Lisp string constant "hit" by a Lisp reader macro.
- ★ Avoid names for LF variables that start with the special symbol ‘&’. Combinators use it. The only exception is the identity combinator, &i, which you may need in an LF when a functor subcategorizes for a type-raised argument rather than the argument itself.<sup>5</sup> The ‘tokens’ script converts your &i to  $(\lambda m \ x \ x)$ ; see §4.4.
- Phonological strings that span more than one word must be double-quoted. You must use them as such in your parse string as well. The contents of a string are not capitalized by the Lisp reader whereas everything else is made case-insensitive, which must be kept in mind. We assume that there are no special symbols in the string. One or two punctuations (comma, period, exclamation or question mark) are allowed.
- Features need names. The basic categories in  $S_{fin} / (S_{fin} \backslash NP_{3s})$  could be  $s[type=fin]$  and  $np[agr=3s]$ . Order of features is not important if you have more than one. They must be comma-separated.
- Capitalization is not important for names, unless they are in a string constant. This is also true of atomic categories, feature names, and values. NP is same as np. Lisp does it, not CCGlab.
- Comments start with ‘%’. The rest of the line is ignored.

The rules for lexical specifications are given in Table 1. They are used by the LALR parser, which converts the .lisptokens version of your textual grammar to .ded. Notice that lambdas can be grouped together, or written separately. Both  $\lambda x \lambda y. hit'xy$  and  $\lambda x. \lambda y. hit'xy$  are fine, and mean the same thing. As standard, CCG slashes and sequencing in the body of an LF are left-associative, and lambda binding is right-associative.

All LF bodies will be curried internally. For example, you can write ‘ $\backslash x \backslash y \backslash z. !give \ x \ y \ z$ ’ in the .ccg file for convenience. It will be converted to ‘ $\backslash x \backslash y \backslash z. ((!give \ x) \ y)z$ ’. Beta normalizer wants that.

<sup>5</sup>An example of this formal need can be given as follows. Suppose that we want to subcategorize for a type-raised NP, e.g.  $f := S / (S / (S \backslash NP)) : \lambda p. f'(p(\lambda x. x))$ . Type-raised arguments are universally  $\lambda p. p d'$ , so an argument could be e.g.  $a := S / (S \backslash NP) : \lambda p. p d'$ . Application of  $f$  to  $a$  would be odd if we didn’t have  $\lambda x. x$  inside the LF of  $f$ , because  $f$  seems to be claiming—by its syntactic category—that its predicate-argument structure is  $f' d'$ , not  $f'(\lambda p. p d')$ . Neutralization of type-raising by a head is a forced move in theories like CCG because some languages seem to subcategorize for type-raised arguments syntactically, eg. Dyirbal, Turkish, and

## 4.2 .ded and .ind

These files are lists of (name value) pair lists bound to the global variable called `*cgg-grammar*`. We chose such pairs because Lisp’s usual choice for such simple mappings, association lists, are difficult to read.<sup>6</sup> Table 2 describes the format. For CCGlab, the order is not important in these lists—it does matter to Lisp—because the values are unique.

## 4.3 .sup and .supervision files

These are the supervision files for training. `.sup` is the native format, as before, which is difficult to type because LFs must be curried. You can get it from the `.supervision` file which does that for you, which has the syntax **words : lf**; where each lf has the same format as in `.cgg` file. Native input to the trainer is a list of lists, where each member has first a list of words for a sentence, and second, a list which is the expected LF for the sentence, in the format described next.

## 4.4 The logical form’s form

All LFs are curried. Lambda is not Lisp’s ‘lambda’, to avoid confusion. Formally, the mapping from  $\lambda$ -calculus to CCGlab’s LFs is:<sup>7</sup>

$$\begin{aligned} x \text{ or } c &\rightarrow \text{Lisp symbol or constant} \\ (e \ e) &\rightarrow (\text{e } e) \\ \lambda x.e &\rightarrow (\text{lam } x \ e) \end{aligned}$$

You can see from Table 1’s non-terminal called ‘lf’ that lambdas of CCGlab LFs are grouped to the left, the only exception being `&i` (see footnote 5). So CCGlab’s LFs are a subset of lambda terms defined above. They correspond to *supercombinators*, which epitomize argument-taking; see Bozşahin (2012).

## 4.5 Parser’s representations

All parser objects are represented as hash tables. COMMON LISP’s hash tables are expressive devices. They do not support hash collision or chaining (we like them this way), and the keys can be anything, even a function or another hash table. We harness this property. Unlike association lists, access to a key’s value does not involve search, e.g. formula (1) is computed without CKY search because beta-normalized LF is the key for that formula’s table. When you have Catalan number of logical forms to check, you’ll appreciate this property. (We employ alpha-equivalence of lambda-calculus in counting different LFs.) So we opted for efficiency by reducing LF search, rather than employing beam-search for the same task which cannot guarantee that the correct LF has a non-zero probability of making it to the result table.

The structure of the CKY table is the following: the first index is the length of the derivation, the second index is the starting position of the derivation in the input, and the last index is the analysis number.

There are five kinds of hash tables in CCGlab. Table 3 shows example snapshots during parsing. Their keys and structure are explained in Table 4.

# 5 Top-level functions

The basic parsing functions were explained in §3. Others are quite useful for grammar development and testing. A more complete list is provided in Table 5. The code includes commentary to make use of them and others. All CCGlab functions are callable if you know what you’re doing.

# 6 CCGlab in the large

---

Inuit, where there is no determiner to value-raise an argument NP modified by a relative clause. Dyirbal’s absolutive relative marker bears the category  $-nu := ((S/(S \setminus NP_{abs})) \setminus (S/(S \setminus NP_{abs}))) \setminus (S \setminus NP_{abs})$ , rather than  $-nu := (N \setminus N) \setminus (S \setminus NP_{abs})$ .

<sup>6</sup>In Lisp terminology, an association list would be (name . value), rather than (name value). It is easy to feel annoyed when there are too many of these ‘.’ to look at. Since we do sequential search only during pre-parsing, efficiency is not the concern here. Legibility is. Rest returns the value of an association pair, whereas second returns the value of a name-value pair.

<sup>7</sup>If you really think COMMON LISP has  $\lambda$ -calculus built-in and this is redundant, think again. Try `((lambda (x) (lambda (y) (list x y))) 'a) 'b)`. You will get an error message! We don’t live in John McCarthy world anymore.

Now try `(beta-normalize-outer '(((lam x (lam y (x y))) 'a) 'b))`.

There are many good implementations of ANSI Common Lisp. I briefly comment on publicly available ones for their suitability for large-scale development.

My personal experience has been that CCL is best suited for large model development. It has a dynamically growing heap, which won't fail you after waiting for days in a training. SBCL is good too. I did most of the code development in it. Recompile it with the option `-dynamic-size` to work with larger models in a larger heap. CLISP is good for mini projects only (it's not fully ANSI either). Non-ANSI Common Lisps are not compatible with CCGlab. In case you want to make them compatible with CCGlab, try fixing macro characters and dispatch macros in Lisp reader of CCGlab, and much more critically, reimplement the hash-table system.

You can work with many Lisps for CCGlab at the same time by setting the shell variable `CCGLAB_LISP` to different Lisp binaries. The default is set by you during install.

The hash tables for the CKY parser can grow very big. To work with very long sentences without rehashing all the time, change the variable `*hash-data-size*` to a bigger value in `ccg.lisp` source. Tables of these sizes (two tables: one for CKY parses, one for different LFs in argmax calculation) are created once, during the first load, and cleared before every parse. The default size is the 11th Catalan number.

CKY hash tables are doubled in size when full. The logic is, if the sentence is long enough to overflow a big hash table, chances are that the table is going to grow just as fast, and we don't want to keep rehashing in long training sessions.

## Acknowledgments

Translations from `.ccg` to `.ded` and from `.supervision` to `.sup` are made possible by Mark Johnson's LALR parser. Translation of the LFs of paper-style representations in `.ccg` to a self-contained lambda-calculus processor is based on Alessandro Cimatti's abstract data structure implementation. Thanks to both gentlemen, and to Luke Zettlemoyer for help with the PCCG paper. (Without the lambda translation, you'd be at the mercy of a particular Lisp implementation of lambdas and closures to get the formula (1) right, or to verify derived LFs. Lisp implementations can represent closures differently, if you can believe that.)

I am grateful to my university at Ankara, ODTÜ; to Cognitive Science Department of the Informatics Institute, for allowing me to work on this project; to Turkish TÜBİTAK for a sabbatical grant (number 1059B191500737), which provided the financial support for a research of which this work is a part; and to the ANAGRAMA group of the CLUL lab of University of Lisbon, in particular to Amália Mendes, for hosting me in a friendly and relaxed academic environment, all of which made CCGlab possible.

## References

- Baldrige, Jason. 2002. *Lexically Specified Derivational Control in Combinatory Categorical Grammar*. Doctoral Dissertation, University of Edinburgh.
- Bozşahin, Cem. 2012. *Combinatory Linguistics*. Berlin: De Gruyter Mouton.
- Clark, Stephen, and James R. Curran. 2003. Log-linear models for wide-coverage CCG parsing. In *Proceedings of the Conference on Empirical Methods in Natural Language Processing*, 97–104. Sapporo, Japan.
- Graham, Paul. 1994. *On Lisp*. Englewood Cliffs, NJ: Prentice Hall.
- Hoyt, Frederick M., and Jason Baldrige. 2008. A logical basis for the **D** combinator and normal form in CCG. In *Proc. of the Annual Meeting of the ACL*. Columbus, OH.
- Pareschi, Remo, and Mark Steedman. 1987. A lazy way to chart-parse with categorial grammars. In *Proceedings of the 25th Annual Meeting of the ACL*, 81–88.
- Steedman, Mark. 1996. *Surface Structure and Interpretation*. Cambridge, MA: MIT Press.
- Steedman, Mark. 2000. *The Syntactic Process*. Cambridge, MA: MIT Press.
- Steedman, Mark. 2012. *Taking Scope*. Cambridge, MA: MIT Press.
- Steedman, Mark, and Jason Baldrige. 2011. Combinatory Categorical Grammar. In *Non-transformational syntax*. eds. R. Borsley and Kersti Börjars, 181–224. Oxford: Blackwell.
- Zettlemoyer, Luke, and Michael Collins. 2005. Learning to map sentences to logical form: Structured classification with probabilistic categorial grammars. In *Proc. of the 21st Conf. on Uncertainty in Artificial Intelligence*. Edinburgh.

Table 1: .ccg format specification.

special cases:	$T$ : Any token		$@A$ : special category	$?A$ : value variable
	$!A$ : LF constant		Default modality: $\cdot$	$\%$ : start of comment
$start$	$\rightarrow$	$start\ lex ; \mid lex ;$	$eqns$	$\rightarrow eqns, eqn \mid eqn$
$lex$	$\rightarrow$	$T\ mtag := cat \mid lrule$	$eqn$	$\rightarrow T = T$
$lrule$	$\rightarrow$	$(T)\ cat \ --> \ cat$	$dir$	$\rightarrow \backslash \mid /$
$mtag$	$\rightarrow$	$T$	$mod$	$\rightarrow \cdot \mid \wedge \mid * \mid +$
$cat$	$\rightarrow$	$sync : lf$	$lf$	$\rightarrow body s \mid lterm$
			$lterm$	$\rightarrow \backslash T \cdot lbody$
$sync$	$\rightarrow$	$basic \mid parentd \mid sync\ slash\ syn$	$lbody$	$\rightarrow lterm \mid body s$
$syn$	$\rightarrow$	$basic \mid parentd$	$body s$	$\rightarrow body s\ body \mid body$
$basic$	$\rightarrow$	$T\ feats$	$body$	$\rightarrow (body s)$
$parentd$	$\rightarrow$	$(sync)$	$body$	$\rightarrow T$
$slash$	$\rightarrow$	$dir\ mod \mid dir$		
$feats$	$\rightarrow$	$[eqns] \mid \epsilon$		

Table 2: `.ded` and `.ind` feature names in name-value pairs lists.

BCAT: basic category		FEATS: basic category features as name-value pairs list	
DIR: directionality of a complex category		MODAL: slash modality (ALL CROSS HARMONIC STAR)	
lex item features		lex rule features	
PHON	phonological form	INSYN	input category
MORPH	pos tag	INSEM	input lf
SYN	syntactic type	OUTSYN	output category
SEM	logical form	OUTSEM	output lf
PARAM	parameter value	PARAM	parameter value

Table 3: (a): CKY representation for: ‘hits v := (s\+ np[agr=3s])/np : \x\y. !hit x y;’ during (ccg-deduce ’(hits)). A ‘#’ means the value is a hash table. It is not part of the name. (b): ARGMAX representation for: ‘hits v := (s\+ np[agr=3s])/np : \x\y. !hit x y;’ after (ccg-deduce ’(hits)). Shown LF is the key. It is beta-normalized, given this input to the parser.

(a)	(1 1 1)	LEFT	(1 1 1)						
		RIGHT	(1 1 1)						
		SOLUTION#	PHON	HITS					
			MORPH	V					
			SYN#	RESULT#		RESULT#	BCAT	S	
						ARG#	BCAT	NP	
							AGR	3S	
						DIR	BS		
						MODAL	CROSS		
				ARG#		BCAT	NP		
				DIR		FS			
				MODAL		ALL			
		SEM	(LAM X (LAM Y (("HIT" X)Y)))						
		INDEX	LEX						
		PARAM	1.0						
(b)	(LAM X (LAM Y (("HIT" X)Y))) (1.0 ((1 1 1)))								



Table 4: Keys and value types for CCGlab hash tables, and the global variables.

Table type	Key	Value	Description
CKY	(I J K)	(LEFT RIGHT SOLUTION)	LEFT/RIGHT's value: component cells of the solution in (I J K). I: length of derivation. J: starting position. K: analysis number. SOLUTION's value: LEX or CKY-ENTRY table.
CKY-ENTRY	SYN	table of type BCAT or CCAT	Syntactic category hash table
	SEM	Logical form	See §4.4 and Table 1
	INDEX	Rule index	LEX for lex entries, rule name for lex rules, >Bx for >B <sub>x</sub> , etc.
	PARAM	real number	Cumulative for partial results, lexical for entries/rules
BCAT	BCAT	symbol or constant	Name of the basic category: either constant or '@' variable
	<name>	symbol or constant	atomic value of the feature <name>: either constant or '?' variable
CCAT	RESULT	table of type BCAT or CCAT	Result of a complex category
	ARG	table of type BCAT or CCAT	Argument of a complex category
	DIR	one of FS BS	Directionality, corresponding to '/' and '\' respectively
	MODAL	name	Slash modality. name: one of ALL CROSS HARMONIC STAR
LEX	SYN	table of type BCAT or CCAT	Syntactic category hash table
	SEM	Logical form	See §4.4 and Table 1
	INDEX	Rule index	LEX
	PARAM	real number	Parameter's value for that lex entry (set to unity in .ded)
	PHON	symbol or string	Phonological string for the lex entry
	MORPH	symbol	Morphological category (part of speech) of the lex entry
LRULE	INSYN	table of type BCAT or CCAT	Input syntactic category
	INSEM	Logical form	Input LF as one object. It is the only input to OUTSEM.
	OUTSYN	table of type BCAT or CCAT	Output syntactic category
	OUTSEM	Logical form	Output LF as a function of INSEM. See §4.4 and Table 1
	INDEX	Rule index	Rule name (given by you)
	PARAM	real number	parameter value for the rule (set to unity in .ded)
ARGMAX	<lf>	(number cells)	key: beta-normalized LF of the result. number: weight-sum, cells: list of cells for the sum

  

Global variable	Type or value (see above)
*cgg-grammar*	List of list of name-value pairs, where current grammar is internally represented
*loaded-grammar*	The name of the currently loaded project file (.ded or .ind)
*cky-hashtable*	CKY table
*cky-lf-hashtable*	ARGMAX table for computing formula (1)
*cky-lf*	the maximum of the numerator of formula (2) without exponentiation, and its LF
*cky-lf-hashtable-sum*	the value of the denominator of formula (2) without exponentiation
*cky-argmax-lf-max*	CKY index of the argmax result's highest weight-summed derivation
*cky-argmax-lf*	List of CKY indices which have the same LF as argmax result
*cky-max*	CKY index of the highest weight-summed derivation for any LF
*lex-rules-table*	List of LRULE tables
*training-hashtable*	Keeps progress of parameter updates. Key is the item's key. Value is the list of original and current value.
*supervision-pairs-list*	List of sentence-LF pairs, in this order.
grammar	LALR's preset grammar to convert your textual specs to Lisp
lexicon	LALR parser's token values (i.e. <i>its</i> lexicon, not yours)
lexforms	LALR parser's token types (ID is any name, others are special symbols)
*endmarker*	LALR parser's end-of-input designator, currently set to \$ in two places (by the LALR parser)

Table 5: Some useful functions of CCGlab.

<code>tokens &lt;pname&gt;</code>	From <code>&lt;pname&gt;.ccg</code> file generates <code>&lt;pname&gt;.lisptokens</code> at command line. Also called from within CCGlab. Self-contained bash script.
<code>suptokens &lt;pname&gt;</code>	From <code>&lt;pname&gt;.supervision</code> file generates <code>&lt;pname&gt;.sup</code> at command line. Also called from within CCGlab. Self-contained bash script.
<code>(load-grammar &lt;pname&gt; :maker &lt;m&gt;)</code>	Loads the <code>&lt;pname&gt;.ded</code> file if <code>&lt;m&gt;</code> is nil or if <code>:maker</code> key argument is not supplied. Generates it from the <code>.lisptokens</code> file by the Lisp <code>&lt;m&gt;</code> if not nil. Recognized values for <code>&lt;m&gt;</code> are 'SBCL', 'CCL' and 'CLISP'. There is no default maker.
<code>(load-model &lt;pname&gt;)</code>	Loads the <code>&lt;pname&gt;.ind</code> file.
<code>(cky-pprint)</code>	Pretty-prints the CKY table with row, column, solution indices so that you can see the values of syntactic features, LFs, partial results, etc. Strings print unquoted. Parses the input words in <code>&lt;list&gt;</code> . Returns true/false.
<code>(ccg-deduce &lt;list&gt;)</code>	First parses then ranks the derivations for the input words in <code>&lt;list&gt;</code> . Returns true/false.
<code>(ccg-induce &lt;list&gt;)</code>	Shows all derivations in paper style. Final LF is displayed normal-evaluated.
<code>(cky-show-deduction)</code>	Shows 3 derivations mentioned in §3.2, in paper style.
<code>(cky-show-induction)</code>	Applies normal-order and applicative-order evaluation to the results, and reports the differences. For this reason, the LFs of intermediate derivations are not beta-normalized during parsing. We know that they look ugly, but you can in fact cut/paste them and simplify; see <code>cky-show-normal-forms</code> .
<code>(cky-show-lf-eqv)</code>	Shows normal forms of all results in CKY table entry row <code>&lt;r&gt;</code> column <code>&lt;c&gt;</code> .
<code>(cky-show-normal-forms &lt;r&gt; &lt;c&gt;)</code>	Returns the LF in CKY table entry row <code>&lt;r&gt;</code> column <code>&lt;c&gt;</code> result <code>&lt;z&gt;</code> . An argument of type <code>&lt;cell&gt;</code> is the list <code>(&lt;r&gt; &lt;c&gt; &lt;z&gt;)</code> . Use <code>cky-pprint</code> beforehand for help.
<code>(cky-sem &lt;cell&gt;)</code>	Prints the deduction sequence ending in CKY table cell <code>&lt;cell&gt;</code> ; see <code>cky-sem</code> for <code>&lt;cell&gt;</code> . Final LF is normalized for mortals; the table is kept intact.
<code>(cky-reveal-cell &lt;cell&gt;)</code>	Prints the induction sequence ending in CKY <code>&lt;cell&gt;</code> . See <code>cky-sem</code> for <code>&lt;cell&gt;</code> argument.
<code>(cky-pprint-probs &lt;cell&gt;)</code>	Returns true iff two input LFs are structurally equivalent, i.e. if they have the same structure modulo bound-variable names.
<code>(alpha-equivalent &lt;e1&gt; &lt;e2&gt;)</code>	Returns a summary of the current state (loaded grammar, its size, CKY info etc.)
<code>(status)</code>	Resets the current state of CCGlab grammar to almost tabula rasa.
<code>(reset-globals)</code>	Computes the final weight-sum $\bar{f} \cdot \bar{\theta}$ at the result cell <code>&lt;cell&gt;</code> , from its constituent cells; cf. formula (2). If you change the formula, <code>argmax</code> (1) will be computed correctly if you save the result in result <code>&lt;cell&gt;</code> .
<code>(count-local-structure &lt;cell&gt;)</code>	A plug-in to give you access to all derivational history to extract more features from result cell <code>&lt;cell&gt;</code> . NB where it is called. Does nothing by default.
<code>(plugin-count-more-substructure &lt;cell&gt;)</code>	Updates a model's parameters after loading the supervision set <code>&lt;pname&gt;.sup</code> . See §3.3 for meanings of arguments. If <code>&lt;l&gt;</code> is not nil, the model <code>&lt;pname&gt;.ind</code> is first loaded. If <code>&lt;v&gt;</code> is not nil, it displays progress of stochastic gradient ascent through iterations, for every lexical item. If <code>&lt;d&gt;</code> is not nil, it displays stepwise update of the derivative in algorithm (6).
<code>(update-model &lt;pname&gt; &lt;N&gt; &lt;alpha0&gt; &lt;c&gt; :load &lt;l&gt; :verbose &lt;v&gt; :debug &lt;d&gt;)</code>	Shows parameter values for every lexical item before and after training.
<code>(show-training)</code>	Saves the currently trained model with the new parameter values to file.
<code>(save-training &lt;file&gt;)</code>	Makes a lisp-ready <code>pname.sup</code> file from <code>pname.supervision</code> and <code>pname.suptokens</code> . See §4.3. For makers see <code>load-grammar</code> above.
<code>(make-supervision &lt;pname&gt; :maker &lt;m&gt;)</code>	Saves the currently loaded grammar to file.
<code>(save-grammar &lt;file&gt;)</code>	Prints the current values of rule switches. Follow the instructions there to (re)set them.
<code>(switches)</code>	Z-scores the parameter values of the currently loaded grammar.
<code>(z-score-grammar)</code>	All LFs will be shown in display of a derivation. The last one is simplified for readability.
<code>(show-lf)</code>	Only the final LF of a derivation is shown.
<code>(hide-lf)</code>	Take a look at the bottom of <code>ccg.lisp</code> code for shorter names for top functions.
Shortcuts	