The (new) LKB system

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system development by

Ann Copestake, John Carroll, Rob Malouf, Stephan Oepen
and others

documentation (mainly) written by

Ann Copestake
`aac@csli.stanford.edu`

This document describes the new version of the LKB system: a grammar and lexicon development environment for use with constraint-based linguistic formalisms.

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Chapter 1

Introduction

1.1 A brief introduction to the LKB system

The LKB (Linguistic Knowledge Building) system is a grammar and lexicon development environment for use with constraint-based formalisms.[1] It is specifically designed for the use of typed feature structures. It is intended to be used for Natural Language Processing research involving unification-based linguistic formalisms for parsing and/or generation, and also for teaching. It has been most extensively tested with grammars based on HPSG (Pollard and Sag, 1987, 1994), but it is intended to be framework independent. In this philosophy, and in much else, we have tried to follow PATR (Shieber, 1986). The LKB system is implemented in Common Lisp and the basic system is intended to run on any Common Lisp implementation, although the graphical environment is currently limited to Macintosh Common Lisp (MCL) or Allegro Common Lisp with the Common Lisp Interface Manager (CLIM).[2] Sites without a Lisp license that have suitable hardware can also use the LKB system: for details of hardware requirements and installation, see Chapter 2.

The best way to think about the LKB system, and other comparable systems such as ALE and PAGE, is as a development environment for a very high-level specialized programming language. Typed feature structure languages are essentially based on one data structure — the typed feature structure, and one operation — unification. This combination is powerful enough to allow the grammar developer to write grammars and lexicons that can be used to parse and generate natural languages. In effect, the grammar developer is a programmer, and the grammars and lexicons comprise code to be run by the system.[3] But because the typed feature structure language is so high level, working in it requires relatively little knowledge of computers. Typed feature structure languages were designed (by linguists) as a formal way of specifying linguistic behaviour rather than as programming languages, and they are used in this way by people who have no involvement in computational linguistics. So, at least potentially, these languages have several advantages: they

[1]Development of the LKB system was originally supported by ACQUILEX projects BRA-3030 and 7315 under the Esprit program. More recent research has been supported by the National Science Foundation under grant number IRI-9612682. Detailed acknowledgments are in §1.4.

[2]**MCL** and **Macintosh Common Lisp** are trademarks of Digitool, Inc. **Macintosh** is a trademark of Apple Computer. **Allegro CL** is a trademark of Franz Inc. All other trademarks used in this document are the property of their owners.

[3]From now on, we'll use grammar to mean all the linguistic code: that is grammar rules, lexicon, lexical rules and so on.

make computational linguistics and natural language processing accessible to linguists with a very limited background in computers, they enable computational linguists to adopt techniques from theoretical linguistics with minimal reinterpretation, and they allow formal theories to be tested on a range of data in a way that allows the interaction between treatments to be checked.

The LKB system is therefore a software package for writing linguistic programs, i.e., grammars, and it's important not to confuse the system and the grammars which run on it. By itself the LKB system is of no use in an application, since there has to be some associated grammar. Although we distribute some grammars with the LKB, they are primarily there to act as examples, just as programming language packages include example code. The LKB system can be used to develop many different grammars. What's more, a grammar developed on the LKB system could in principle be run on another platform that used the same typed feature structure language, just as a C++ program can be run by a variety of compilers.[4] The performance of the LKB system in tasks such as parsing depends critically on the grammar: it makes little sense to talk about performance except with respect to a particular grammar. We have, however, tried to make it reasonably efficient with fairly large grammars.

The LKB system must therefore be distinguished from the LinGO English resource grammar (ERG) which is also being developed at CSLI. The LinGO ERG runs on several systems beside the LKB, including PAGE. The ERG is being distributed in parallel with the LKB system, but is not discussed in this documentation. However some examples of the ERG are used here in order to illustrate some of the facilities the system has for dealing with large and complex grammars.

1.2 This manual

The purpose of this manual is to teach users how to use the LKB system to program their own grammars or to adapt existing ones. We have tried not to make too many assumptions about what the user knows how to do, but there are some things we have to assume if the documentation is ever going to be finished. With respect to the content of the system, we've tried to write the documentation so that a user can start building grammars even if they have never used a grammar development environment before, and we have provided a chapter which is a non-technical introduction to typed feature structure formalisms, but we do not try and cover any linguistic theory. Some of the grammars distributed with the LKB are linked to a textbook which introduces formal syntax using a typed feature structure formalism: Sag and Wasow (1999). There are some places where to fully understand the documentation a knowledge of some NLP concepts, such as chart parsing, will be helpful, but this should not be essential to use the system. On the interaction side, we assume the user knows how to open, close, resize windows etc and how to select menu items. We also assume that the user knows how to use emacs, at least at a fairly elementary level, if running the ACL/CLIM version of the LKB, or the MCL editor, if using a Mac. There are a couple

[4]In practise, however, there is no agreed standard for typed-feature structure systems. The current situation is roughly similar to the different Lisp implementations which existed before Common Lisp was initially developed, which is to say that some grammars can be converted relatively easily between platforms, while others are extremely difficult to convert because they use facilities which are not shared by all typed feature structure based systems. For example, the LKB system uses a version of default unification which is not available on other typed feature structure systems, and so grammars which use defaults are less portable than ones which don't. It's unlikely that there will ever be an ANSI-standard typed feature structure language, though developers of the different systems are trying to make portability easier, so the situation should improve in the near future.

of places where it's useful to have a very basic understanding of Common Lisp, in particular when installing the system, but we've tried to avoid this being essential.

The rest of this chapter contains a few more brief details of the LKB system and how it has been developed. The following chapter describes installation of the LKB. The third chapter is intended for first time users: it gives a fairly detailed tour through some of the LKB's functionality. The fourth chapter is a basic and informal introduction to typed feature structures. Chapter 5 contains a formal description of typed feature structures as used in the LKB. The subsequent chapters are the reference manual proper — they are not intended to be read straight through, but to act as a source of information about error messages, user interface commands which have less than obvious behaviour and so on. The first of these chapters covers the file organization, loading, error messages and so on. The next describes the user interface. The last chapter covers 'advanced' features: generally speaking, this can be ignored by people who are adapting an existing grammar. The appendices cover details of the available parameters and other details which most readers probably do not wish to know about.

1.3 Some history

Initially the LKB system was developed on the EU-funded ACQUILEX project primarily as a tool to allow the construction of typed feature structure based lexicons (both monolingual and bilingual).[5] Although it incorporated a parser, this was of secondary importance, since it was mostly intended as a way of verifying lexical entries. The most extensive documentation of that version of the system is Copestake (1993): published papers include Copestake (1992) and several papers in Briscoe et al (1993). The current version of the LKB has been extensively updated. Some of the main changes compared to the older version are:

1. Extensive efficiency improvements, so the system is capable of parsing reasonable length sentences with a large grammar.
2. Default unification is based on YADU, defined in Lascarides and Copestake (1999).
3. Automatic computation of greatest lower bounds in the type hierarchy.
4. Integration with the [incr tsdb()][6] test suite machinery (Oepen and Flickinger, 1998).
5. Integration with MRS semantics (Copestake et al, 1999).
6. Tactical generation from MRS input (relatively experimental).
7. Many new user interface features.

Some of the earlier functionality has not made it into the new version: either because the developers consider it obsolete or simply because of shortage of time.

[5]At this point, LKB stood for Lexical Knowledge Base — the LKB system was a tool for building LKBs.

[6]This is really what the system is called, but this is not the responsibility of the current author. Please direct any comments about [incr tsdb()] to `oe@coli.uni-sb.de`.

1.4 Acknowledgments

The main developers of the LKB system are Ann Copestake, John Carroll, Rob Malouf and Stephan Oepen. The distributed system also incorporates code written by Bernie Jones, Dan Flickinger and John Bowler. Ted Briscoe and Antonio Sanfilippo had a great deal of influence on the design of the original system, Dan Flickinger played a similar role for the new version. Uli Callmeier has done extensive testing and uncovered numerous bugs and infelicities. Invaluable input has also been provided by users too numerous to thank individually, including researchers on the ACQUILEX and LinGO projects, at the Copenhagen Business School and Edinburgh University, students at the University of Cambridge Computer Laboratory and Stanford University and students on a course taught by Copestake, Flickinger and Oepen at ESSLLI-98. Special thanks go to Matt Kodama, Ryan Ginstrom, Christopher Callison-Burch, Scott Guffey for their detailed comments on design and extensive testing.

Chapter 2

Installing and running the system

This chapter gives details of downloading, installing and starting up the LKB system. CSLI users can skip to §2.2.3 (most users) or §2.2.4 (users who are editing Lisp code). Other users will need to look at the next section to decide in what form to download the system, then go through the steps in the other sections, depending on their choice.

2.1 Hardware and software requirements

The LKB system is freely available for teaching, research or commercial use, though we retain copyright: the conditions placed on redistribution are described on the LKB Web Site. We encourage users to make enhancements and upgrades to the system, and will be happy to make any improvements available from the Web site.

The full LKB system is available in a variety of configurations:

1. Solaris image (using Allegro Common Lisp)
2. Linux image (using Allegro Common Lisp)
3. Source files for Allegro Common Lisp and CLIM
4. Source files for Macintosh Common Lisp (MCL)

Both images are made using Allegro Common Lisp and can be run without a license, though since they do not contain a Lisp compiler, anyone who wants to make any substantial modifications to the system will need a license from the Lisp vendor so that they can work with the source files.

To use any version of the LKB, you need a machine with adequate amounts of memory. We would suggest 32 Meg of RAM as a minimum on MCL, and 64 Meg for ACL with CLIM. To run larger grammars you will need larger amount of memory. The Solaris image should run on recent versions of SunOS. The Linux image was made for Red Hat 6.0 with Metrolink Motif 1.2 (glibc version). It should run on some other versions of Linux, but is known not to be compatible with most other versions of Motif: please see the Franz Website.

If you have Allegro Common Lisp with CLIM or Macintosh Common Lisp, you can download the source files and compile them. This will be necessary if you want to substantially modify the LKB source code, and is likely to be advantageous in any case, since we make minor bug fixes available as source, rather than providing new images. We have tested the curent version of the LKB system on Allegro Common Lisp 5.0 on SunOS 5.6 (with all patches installed) and on Red Hat Linux 6.0 with Metrolink Motif 1.2 and (less extensively) on Macintosh Common Lisp 4.0. It should work on other versions of these Lisps, but we are not in a position to offer much advice in case of problems for Lisp/OS versions we don't use.

If you do not have access to a machine for which we provide an image, and do not have either Allegro Common Lisp with CLIM or Macintosh Common Lisp, the LKB can still be run in 'tty' mode from other Common Lisps. tty mode is also useful if you are accessing a machine over a modem or a slow network where the graphical display is impossible or would take too long. In this mode, commands are entered by typing rather than menu selection, and display commands result in ASCII output (or in some cases are not available). tty mode is described in detail in Appendix A.

Some source code is available for the Windows version of Allegro Common Lisp (Common Graphics) but the port is incomplete and this will only be useful for someone who is prepared to do substantial programming: please contact Ann Copestake for details.

For up-to-date information on what is available, check the LKB Web Site and/or subscribe to the LKB mailing list (see the website for instructions). If you want to consider acquiring ACL/CLIM or MCL in order to run the source, please see the links to the companies on the LKB web page.[1]

2.2 Downloading the LKB

2.2.1 Downloading an image

The image files for Linux and Sun Solaris are available from the LKB Web Site as gzipped Unix tar files. Download the appropriate file, making sure you are using binary mode. Then:

```
gunzip climimage5-2.tar.gz
```

or

```
gunzip linuximage5-2.tar.gz
```

this should give you a file called `climimage5-2.tar` or `linuximage5-2.tar` Put this in a directory where you want the LKB system to reside and extract the LKB image directory by:

```
tar xf climimage5-2.tar
```

or

```
tar xf linuximage5-2.tar
```

This will create the new directory called `lkb` containing several files.

Also download the data files, and unzip etc in the same way:

[1]We would be grateful if you let the vendor know if you intend to use the system primarily for the LKB and also let us know of any such purchase, since it allows us to be more persuasive when it comes to requesting the vendors to fix bugs etc . . .

```
gunzip data5-2.tar.gz
tar xf data5-2.tar
```

This will create a new directory tree called `data` containing various sample grammars.

Now follow the instructions in §2.5.1 or §2.5.2 to start the LKB.

2.2.2 Downloading source files

The source files are distributed as a gzipped Unix tar file which is available from the LKB Web Site. A single file is used for all systems, since most of the code is shared. Download the file, making sure you are using binary mode. Then:

```
gunzip lkbsrc5-2.tar.gz
```

this should give you a file called `lkbsrc5-2.tar`. Make sure this in a directory where you want the LKB system to reside and extract the LKB by:

```
tar xf lkbsrc5-2.tar
```

This will create the new directory and various subdirectories. It may take a few minutes to do this. At this point, you have your own local copy of the LKB system source. Note that you may need to change the directory locations in `general/loadup` and `main/userfns` to be appropriate for your system (especially if you wish to run the system using MCL).

Also download the data files, and unzip etc in the same way:

```
gunzip data5-2.tar.gz
tar xf data5-2.tar
```

This will create a new directory tree called `data` containing various sample grammars.

Now follow the instructions in §2.3.1 or §2.3.2 to compile the files.

2.2.3 Running the LKB at CSLI

To run the LKB on eo or the linear machines follow the instructions in §2.4.1 (`fi:common-lisp` is already installed) but give the file `/usr/acl/lkb` in response to the prompt for **Executable image name:**

2.2.4 Getting a local copy of the LKB source at CSLI

In order to get a local copy of the LKB source at CSLI, you need to checkout the latest version from the cvs system. To do this, you must have access to eo or one of the linear machines. You will also need filespace on these machines.

In the directory which you wish to act as the root for the LKB source (your home directory is fine), execute the following:

```
cvs checkout newlkb
```

This will create the new directory and various subdirectories. It may take a few minutes to do this. At this point, you have your own local copy of the LKB system. Instructions on using cvs are on the CVS website.

Now follow the instructions in §2.3.1 to compile the files, and in §2.4.1 to start the LKB system from within emacs.

2.3 Compiling the source files

2.3.1 Allegro Common Lisp and CLIM (ACL/CLIM)

To compile the LKB system files in ACL/CLIM, do the following:

1. cd to `newlkb/src`.
2. Start ACL/CLIM. The command needed will vary with your local installation. For instance, at CSLI, the command to start ACL with CLIM is `/usr/acl/base`. [2]
3. At the Lisp prompt enter:

   ```
   (load "general/loadup")
   ```

4. Once the loadup files have been loaded, enter the following:

   ```
   (compile-system "lkb" :force t)
   ```

   This compiles and loads all the LKB files that are appropriate for your system.[3] If you intend to use any of the MRS code, including the generator, you should replace `"lkb"` with `"mrs"`: i.e.,

   ```
   (compile-system "mrs" :force t)
   ```

   In either case, you should now see the LKB interaction window, as shown in Figure 2.1.

5. At this point, you may simply exit Lisp: you can restart the system from the compiled files as described in §2.4.1.

[2]Note that since the objective is just to compile the system, we describe the procedure for starting the system from the command line. For actually running the LKB, it is preferable to start Lisp from within emacs, as described in §2.4.1. If you prefer, you can follow the steps described there, replacing the `load-system` command with `compile-system`, as below.

[3]There may be some warning messages — these can usually be ignored, but if you subsequently have problems using the LKB, you should redo this process and examine the warning messages.

2.3.2 Macintosh Common Lisp (MCL)

To compile the LKB system files do the following:

1. Double-click on the MCL icon to start MCL

2. If the LKB files are somewhere other than `Macintosh HD:newlkb` (e.g., because your hard disk is not called `Macintosh HD`), open the `src:general:loadup.lisp` file (Open is in the File menu in MCL) and edit the definition of `%sys-home%` to be appropriate for your machine. For instance, if your hard disk is called `carrot`, and you want to use the folder name `lkb5.2` rather than `newlkb`, the definition would look like:

   ```
   (defparameter %sys-home%
     #-:mcl (rest (butlast
                   (pathname-directory *load-truename*) 2))
     #+:mcl '("carrot" "lkb5.2"))
   ```

   Save the file. You may also need to edit the file `src:main:user-fns.lsp` to change the function definition of `lkb-tmp-dir` which refers to `Macintosh HD`. These are the only places where you should need to change file names.

3. Use the Load menu option to load `newlkb:src:general:loadup`

4. Once the loadup files have been loaded, enter the following into the Listener window:

   ```
   (compile-system "lkb" :force t)
   ```

   If you intend to use any of the MRS code, including the generator, you should replace `"lkb"` with `"mrs"`: i.e.,

   ```
   (compile-system "mrs" :force t)
   ```

   This compiles and loads all the LKB files that are appropriate for your system.[4] You should now see LKB on the menu-bar.

5. At this point, you may simply exit Lisp: you can restart the system from the compiled files as described in §2.4.3.

2.4 Running the LKB from compiled files

2.4.1 ACL/CLIM with emacs

To use the LKB commands for interacting with source files in ACL/CLIM, you must use the emacs text editor and run a command that allows the linkage. We suggest the use of `fi:common-lisp` which is available from ftp: //ftp.franz.com/pub/emacs/eli/eli-2.0.21.16.2/. The following

[4]There may be some warning messages — these can probably be ignored, but if you subsequently have problems using the LKB, you should examine the warning messages.

instructions assume that this is installed on your system. You can run the LKB from emacs in a shell using the standard emacs commands, or you can start lisp with the emacs function `run-lisp`, but the commands to show the grammar files will not work.

1. The first time you use the system, add the following lines to the bottom of your `.emacs` file, with the pathnames modified as appropriate for your installation.

   ```
   (if (not (member "/usr/acl/fi" load-path))
       (setq load-path (cons "/usr/acl/fi" load-path)))
   (if (not (member "~/newlkb/src" load-path))
       (setq load-path (cons "~/newlkb/src" load-path)))

   (load "fi-site-init")
   (load "tdl-mode")
   (load "lkb")
   ```

2. The first time you run the system, create a temporary directory (see §2.5.4). By default, this is a directory called `tmp` in your home directory.

3. Start emacs. We will assume you do this in the `newlkb/src` directory.

4. Start ACL/CLIM from within emacs using the command `fi:common-lisp` which takes a number of arguments. The default values should be accepted with the exception of the image name (the Lisp image appropriate for your system should be specified), as follows:

   `M-x fi:common-lisp`
   Buffer: `<RET>`
   Host: `<RET>`
   Process directory: `<RET>`
   Executable image name: `/usr/acl/base`
   Lisp image: `<RET>`
   Image arguments: `<RET>`

   You should then get a new buffer called `*common-lisp*` with a running Lisp process.

5. At the Lisp prompt enter:

   ```
   (load "general/loadup")
   ```

6. Once the loadup files have been loaded, enter the following:

   ```
   (load-system "lkb")
   ```

   If you intend to use any of the MRS code, including the generator, you should replace `"lkb"` with `"mrs"`: i.e.,

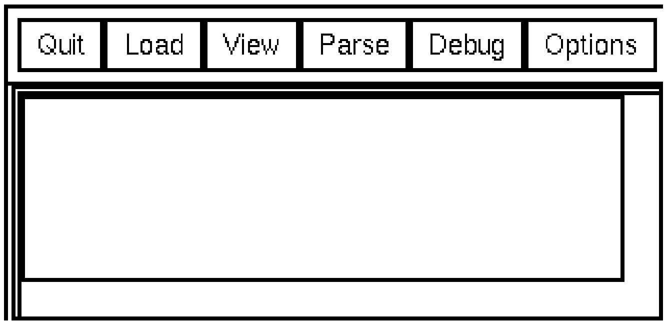

Figure 2.1: The LKB interaction window in ACL/CLIM

```
(load-system "mrs")
```

(If you haven't been following the instruction exactly, you may be asked whether you want to compile some or all of these files. Respond `y` to this question.)

You should now see the LKB interaction window, as shown in Figure 2.1. To continue, see Chapter 3.

2.4.2 ACL/CLIM without emacs

If for some reason you cannot or do not wish to use the LKB from emacs, you can start the LKB from compiled files as follows:

1. The first time you run the system, create a temporary directory (see §2.5.4). By default, this is a directory called `tmp` in your home directory.
2. cd to `newlkb/src`.
3. Start ACL/CLIM as in §2.3.1
4. At the Lisp prompt enter:

   ```
   (load "general/loadup")
   ```

5. Once the loadup files have been loaded, enter the following:

   ```
   (load-system "lkb")
   ```

   If you intend to use any of the MRS code, including the generator, you should replace `"lkb"` with `"mrs"`: i.e.,

   ```
   (load-system "mrs")
   ```

You should now see the LKB interaction window, as shown in Figure 2.1. To continue, see Chapter 3.

2.4.3 MCL

To start the LKB from MCL with compiled files, proceed as follows:

1. Create a temporary directory (see §2.5.4).
2. Start MCL (double-click on the MCL icon)
3. At the Lisp prompt enter:

   ```
   (load "general/loadup")
   ```

4. Once the loadup files have been loaded, enter the following:

   ```
   (load-system "lkb")
   ```

   if you intend to use any of the MRS code, including the generator, you should replace `"lkb"` with `"mrs"`: i.e.,

   ```
   (load-system "mrs")
   ```

You should now see the LKB interaction menu on the menu-bar. To continue, see Chapter 3.

2.5 Running the LKB from an image

2.5.1 ACL/CLIM from emacs

To use the LKB commands for interacting with source files in ACL/CLIM, you must use the emacs text editor with a command that allows the linkage. We suggest the use of `fi:common-lisp` which is available from ftp: //ftp.franz.com/pub/emacs/eli/eli-2.0.21.16.2/. The following instructions assume that this is installed on your system. You can run the LKB from emacs in a shell using the standard emacs commands, but the commands to show the grammar files will not work.

1. The first time you use the system, add the following lines to the bottom of your `.emacs` file, with the pathnames modified as appropriate for your installation.

   ```
   (if (not (member "/usr/acl/fi" load-path))
       (setq load-path (cons "/usr/acl/fi" load-path)))
   (if (not (member "~/newlkb/src" load-path))
       (setq load-path (cons "~/newlkb/src" load-path)))

   (load "fi-site-init")
   (load "tdl-mode")
   (load "lkb")
   ```

2. The first time you run the system, create a temporary directory (see §2.5.4). By default, this is a directory called `tmp` in your home directory.

3. Start emacs

4. Start the LKB from within emacs using the command `fi:common-lisp` which takes a number of arguments. If you have downloaded the image from our website and stored it in the directory `lkb`, accept all emacs's default suggestions, with the exception of the **Executable image name:** as follows:

   `M-x fi:common-lisp`
   Buffer: `<RET>`
   Host: `<RET>`
   Process directory: `<RET>`
   Executable image name: `/lkb/lkb`
   Lisp image: `<RET>`
   Image arguments: `<RET>`

   You should then get a new buffer called `*common-lisp*` with a running Lisp process (without a compiler, if you are using our image).[5]

You should now also see the LKB interaction window, as shown in Figure 2.1. To continue, see Chapter 3.

2.5.2 ACL/CLIM without emacs

If you cannot use emacs, or do not wish to for some reason, simply start the saved image by running the executable `lkb` within the lkb directory (or whatever other name you chose for it in the earlier stages). You should now see the LKB interaction window, as shown in Figure 2.1.[6] The first time you run the system, you should create a temporary directory (see §2.5.4). By default, this is a directory called `tmp` in your home directory. To continue, see Chapter 3.

2.5.3 Macintosh

If you are starting the LKB from a Mac image, you simply double-click on the icon for the image. You should now see the LKB interaction menu on the menu-bar. The first time you run the system, you will need to create a temporary directory (see §2.5.4). To continue, see Chapter 3.

2.5.4 Temporary file locations

The LKB requires some temporary files be created for lexicon handling. Unfortunately, there is no way of ensuring that these will be created in a sensible place for every user on every Lisp system. For Unix, the default location for the files is in a directory `tmp` in the user's home directory. For MCL, the default location is `Macintosh HD:tmp`. If it is possible to use these locations, then

[5]If you get an error message concerning a missing library, see §2.7.

[6]If you get an error message concerning a missing library, see §2.7.

simply create the requisite directory before loading the grammar. If it is not convenient to have these directories, if you are using source files, you can edit the file `main/user-fns.lsp` so that the function `lkb-tmp-dir` identifies a more suitable directory. If you are using a supplied image file, you need to add a `lkb-tmp-dir` function to the `user-fns` file to be loaded by every grammar you use. For instance, if your Mac has a disc called `Applications`, add the following to the `user-fns` file (or replace `lkb-tmp-dir` if it exists already):

```
(defun lkb-tmp-dir nil
  (let ((pathname
          #-mcl (user-homedir-pathname)
          #+mcl (make-pathname :directory "Applications"))
        (tmp-dir '("tmp")))
    (make-pathname
     :host (pathname-host pathname)
     :device (pathname-device pathname)
     :directory (append (pathname-directory pathname) tmp-dir)
     :name (pathname-name pathname)
     :type (pathname-type pathname)
     :version (pathname-version pathname))))
```

2.6 Building an image

If you wish to make a development image, for instance because you want to make the LKB available for several users at your site, this section gives brief instructions.

2.6.1 Allegro Common Lisp

To build an image, see the file `ACL_specific/image.lsp`. This should be loaded into a fresh Lisp image, after loading `general/loadup`. Notice that the distributed version has CSLI-specific filenames, which you will have to alter as appropriate for your site.

2.6.2 Macintosh Common Lisp

The function `dump-lkb` should create an MCL image. The source is in `MCL_specific/topmenu.lsp`.

2.7 Problems

Some of the likely error messages are covered in various places in this documentation, so if you see something you don't understand, try searching for significant word(s) from the error message.

In case of installation or other problems which don't seem to be covered in the documentation, please look at the instructions on the LKB Web Site. We will make fixes for known problems available there. The Web site also contains details of how to report bugs that you find.

2.7.1 Lisp specific problems

Allegro CL If you are using source files, note that there are various patches available for ACL 5.0 which are required to make the LKB run. Please contact Franz to obtain the patches.

If you are using an image which doesn't have CLIM built in, you need to load CLIM before loading `general/loadup`. If you don't, you will get the tty version of the LKB system.

2.7.2 Missing libraries

When you start the LKB from a downloaded image, you may get an error message that says a library is missing (e.g., `libXm.so.3`). The CLIM interface uses Motif libraries and on some systems these are not made available by default. You may be able to fix this by adding `/usr/dt/lib` to your `LD_LIBRARY_PATH`: if this doesn't work (or if this explanation is incomprehensible . . .), please talk to your system administrator (it's a standard difficulty with software that uses Motif).

2.7.3 Compilation: file writing problems

If you get an error while compiling the system to the effect that a fasl file cannot be written, this is probably because a directory it expects is missing. The system assumes that there is a directory tree named according to the type of system you have (search for `BINARY-DIR-NAME` in the `general` files). The source tree contains some empty fasl directory trees, but you may have to construct your own. If you don't do this in advance, Lisp will give error messages, but you can continue from these after creating the files.

2.7.4 Temporary directory missing

One likely error message is something like the following:

```
Failure to open temporary lexicon file
/user/bloggs/tmp/templex correctly.
Please create the appropriate directory
if it does not currently exist or redefine
the user functions lkb-tmp-dir and/or
set-temporary-lexicon-filenames.  Then reload grammar.
```

This is a problem with the temporary files: see §2.5.4.

2.7.5 Multiple grammars

You may get problems if you load a grammar into a non-fresh system (i.e., one into which an old grammar has already been loaded). While this should work with grammars which share the same parameters, it may not work in other cases. So if something seems to be going wrong, try restarting the LKB system and reloading the grammar.

Chapter 3

A first session

The following chapter takes the new user through an initial session with the LKB system. It assumes that you have a running LKB system, either using ACL/CLIM or MCL, installed as described in the previous chapter. It covers the basics of:

1. The LKB top menu
2. Loading an example grammar
3. Examining feature structures and type constraints
4. Parsing sentences
5. Adding a lexical entry
6. Adding a type with a constraint

The intention is that this chapter should be useful to readers who have no previous exposure to typed feature structure formalisms as well as to people who have some knowledge of typed feature structure formalisms and who want an introduction to the LKB's user interface and functionality. But if you are in the first category, you will probably find that you don't fully understand all the terminology and notation used here. A detailed introduction is contained in Chapter 4, but we expect that for most people that chapter will be easier to digest after this guided tour.

3.1 The LKB top menu

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The main way of interacting with the LKB is through the LKB top menu. The ACL/CLIM version is shown in Figure 3.1, the MCL version is on the top menu-bar. The main difference between the Mac and ACL/CLIM versions of the LKB is the appearance of the top-level interaction menu. The Mac version makes use of the Mac main menu-bar, and adds an LKB menu to that. LKB error messages etc appear in the MCL Listener window. For the ACL/CLIM version, there is a distinct top level interaction window, with the menu displayed using buttons across the top of the window. From now on, we will ignore these differences. We will use the term 'LKB top menu' for

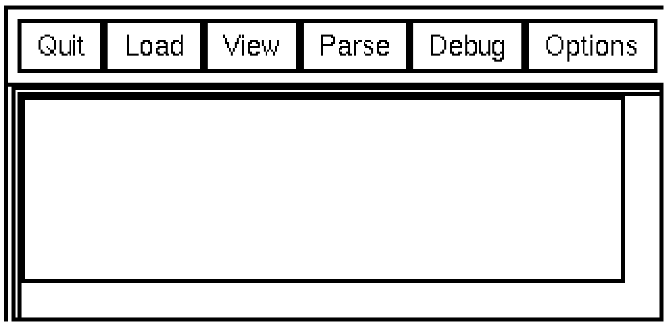


Figure 3.1: The LKB interaction window in ACL/CLIM

the menu and ‘LKB interaction window’ for the window in which messages appear for both the Mac and CLIM versions. The illustrations in the rest of this document show the CLIM interface.

Note that, in the ACL version, it is possible (though a little difficult) for the interaction window to be closed inadvertently. It may be reopened by evaluating (clim-user::restart-lkb-window) in Lisp (i.e., the `*common-lisp*` buffer in emacs). In both versions it is possible to end up in a state where most of the commands are unavailable because the system does not think a grammar has been loaded: to fix this, evaluate (enable-type-interactions).

3.2 Loading a grammar

The first step in this guided tour is to load an existing grammar: i.e., a set of files containing types and constraints, lexical entries, grammar rules etc. The LKB comes supplied with a series of grammars, all of which are in the directory `data`. There is a directory `esslli`, which contains a series of grammars of increasing complexity. In this section, we will assume that you are working with the smallest, which is called ‘toy’.

Select Complete grammar from the LKB Load menu, and choose the file `script` from the `toy` directory as shown in Figure 3.2 for ACL/CLIM, MCL uses a standard Mac file choice menu. The script file is responsible for loading the remainder of the files into the system. You should see various messages appearing in the interaction window, as shown in Figure 3.3 (the interaction window has been enlarged). If there are any errors in the grammar which the system can detect at this point, error messages will be displayed in this window. With the toy grammar, there should be no errors, unless there is a problem associated with the temporary directory (see §2.5.4). If you get another error message when trying to load `toy/script`, it is possible you have selected another file instead of script — try again.

Once a file is successfully loaded, the menu commands are all available and a type hierarchy window is displayed (as shown in Figure 3.4).

3.3 Examining feature structures and type constraints

In this section we will go through some of the ways in which you can look at the data structures in the grammar, such as the types, type constraints, lexical entries and grammar rules.

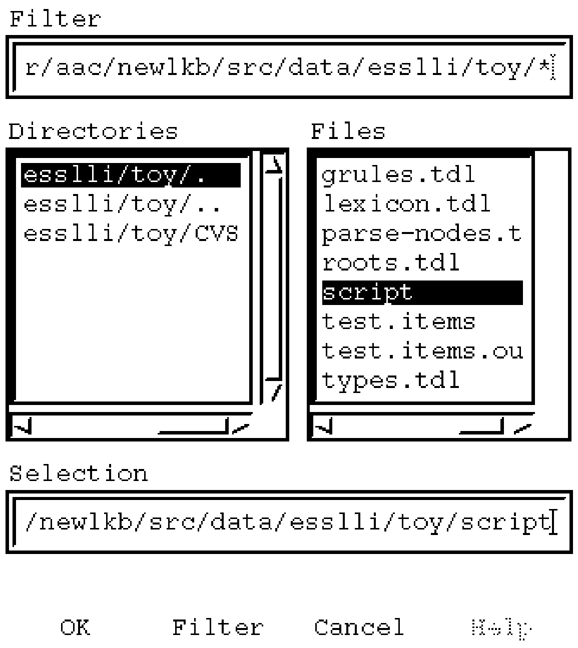
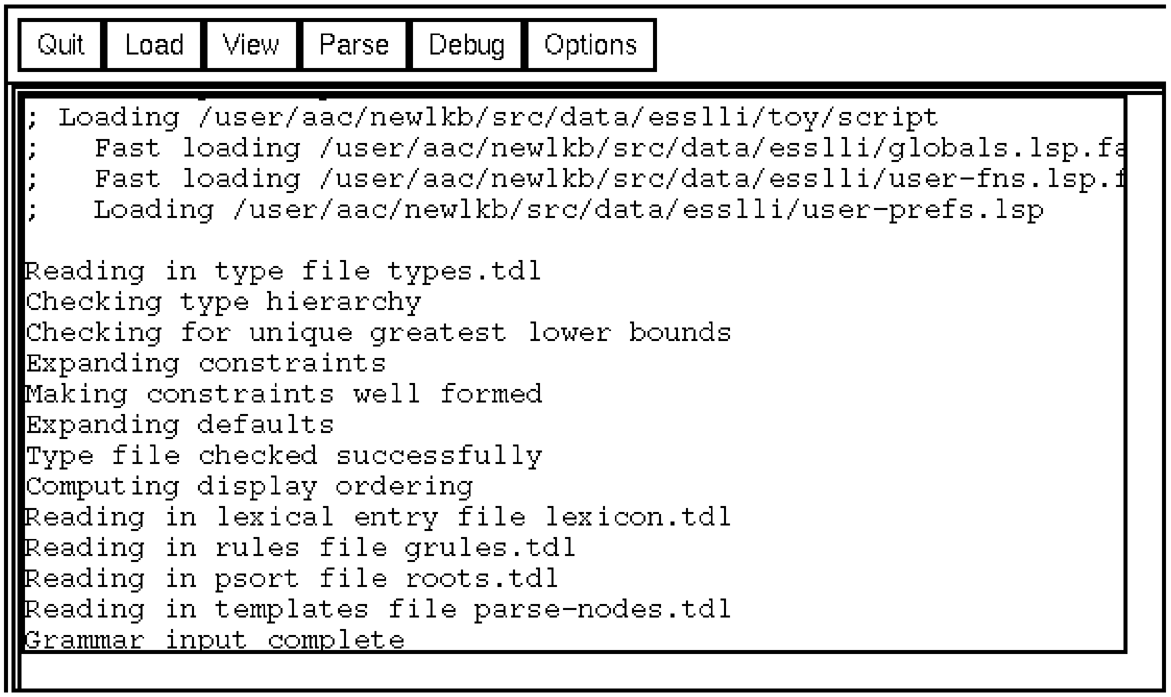


Figure 3.2: Selecting the script file in ACL/CLIM



```
; Loading /user/aac/newlkb/src/data/esslli/toy/script
;   Fast loading /user/aac/newlkb/src/data/esslli/globals.lsp.fa
;   Fast loading /user/aac/newlkb/src/data/esslli/user-fns.lsp.f
;   Loading /user/aac/newlkb/src/data/esslli/user-prefs.lsp

Reading in type file types.tdl
Checking type hierarchy
Checking for unique greatest lower bounds
Expanding constraints
Making constraints well formed
Expanding defaults
Type file checked successfully
Computing display ordering
Reading in lexical entry file lexicon.tdl
Reading in rules file grules.tdl
Reading in psort file roots.tdl
Reading in templates file parse-nodes.tdl
Grammar input complete
```

Figure 3.3: Loading a file

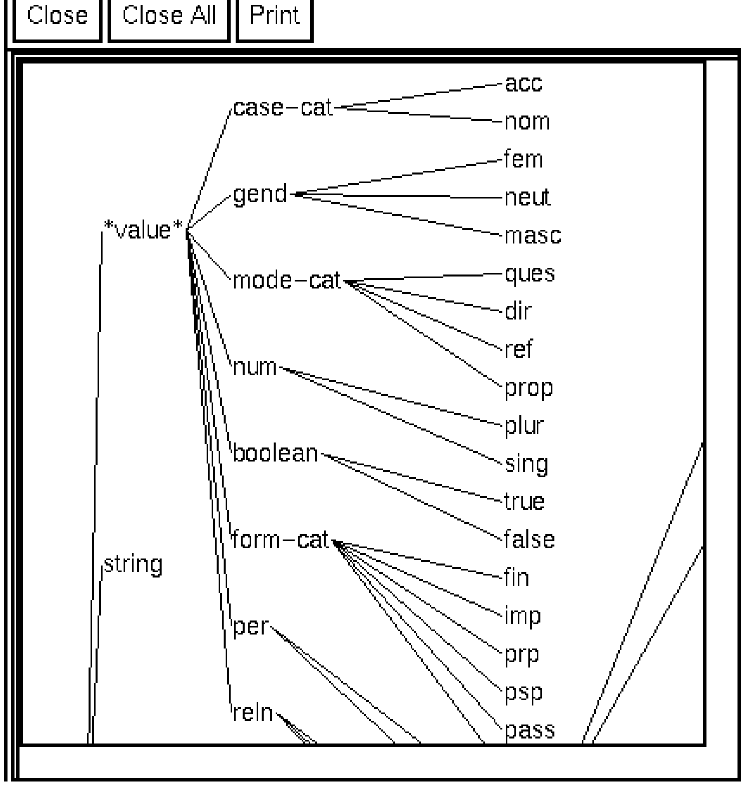
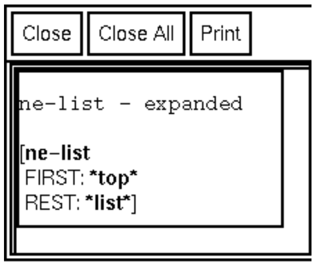


Figure 3.4: The type hierarchy window



ne-list - expanded

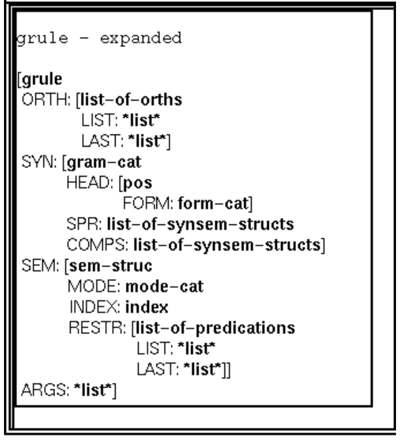
[ne-list
FIRST: *top*
REST: *list*]

Figure 3.5: An expanded type constraint window

3.3.1 The type hierarchy window

The backbone of any grammar in the LKB is the type system, which consists of a hierarchy of types, each of which has a constraint which is expressed as a feature structure. The type hierarchy allows for inheritance of constraints. In the LKB system, the type hierarchy window is shown with the most general type displayed at the left of the window. In the toy grammar, this is ***top***. You will notice that there is some multiple inheritance in the hierarchy (i.e., some types have more than one parent).

Click on the type **ne-list** which is a daughter of ***list***, which is a daughter of ***top***, and choose Expanded Type from the menu. A window will appear as shown in Figure 3.5. This window shows the constraint on type **ne-list**: it has two features, FIRST and REST. The value of FIRST is ***top***, which indicates it can unify with any feature structure. The value of REST is ***list*** which indicates it can only unify with something which is of type ***list*** or one of its subtypes. ***list*** and its daughters are important because they are used to implement list structures which are found in several places in the grammar.



```
grule - expanded

[grule
 ORTH: [list-of-orths
          LIST: *list*
          LAST: *list*]
 SYN: [gram-cat
        HEAD: [pos
                FORM: form-cat]
        SPR: list-of-synsem-structs
        COMPS: list-of-synsem-structs]
 SEM: [sem-struc
        MODE: mode-cat
        INDEX: index
        RESTR: [list-of-predications
                  LIST: *list*
                  LAST: *list*]]
 ARGS: *list*]
```

Figure 3.6: A complex type constraint

Look at the entry for the type **ne-list** in the actual source file `toy/types.tdl` (i.e., open that file in emacs, if you are running the ACL/CLIM version of the LKB, or in the MCL editor, if you are running the MCL version).

```
ne-list := *list* &
 [ FIRST *top*,
   REST *list* ].
```

The syntax of the language in which the type and its constraint are defined (the *description language*) is detailed in §5.3.1. The type definition obligatorily specifies the parent or parents of a type (in this case, ***list***) and optionally gives a constraint definition. In this particular case, the constraint described in the file corresponds very closely to the expanded constraint shown in the feature structure window, because the only parent of **ne-list** is ***list*** and this does not have any features in its constraint. However, in general, type constraints inherit a lot of information from the ancestors of the type so the description of a constraint is very compact compared to the expanded constraint.

To see a more complicated type constraint, click on **grule** (grammar rule) in the type hierarchy window (found via **feat-struc**, **synsem-struc**, **phrase** from ***top***) and again choose Expanded Type. The feature structure window is shown in Figure 3.6. **grule** illustrates that types can have complex constraints: that is the value of a feature in a constraint can be a feature structure. Look at the definition of **grule** in the source file:

```
grule := phrase &
 [ ARGS *list* ].
```

In contrast to **ne-list**, the constraint on **grule** has inherited a lot of information from types higher in the hierarchy: you can see how this inheritance operates by looking at the constraints of **grule**'s ancestors in the type hierarchy window.

You will find that you can click on the types within the feature structures to get menus and also on the description at the top of the window (e.g., `grule - expanded`). Details of the menu options in feature structure windows are given in §7.3. More details of the type hierarchy window, including an explanation of all the commands, are given in §7.2.

3.3.2 The View commands

The view commands let you get at entities such as lexical entries which cannot be accessed from the type hierarchy window.

Select View from the LKB top menu and then select Word entries. You will be prompted for a word which corresponds to a lexical entry. Enter `kim` (case doesn't matter), deleting the default that is specified (unless of course the default is `KIM`, in which case just select `OK`). You should get a feature structure window corresponding to the entry which has orthography "kim" in the toy grammar. If there were multiple entries with the spelling 'kim' they would all be displayed.

You can also access lexical entries by entering an identifier: to do this you select View Lex Entry. To try this out, try entering `kim_1`. An identifier will always give a unique lexical entry.

You might like to compare the feature structures shown with the actual lexical entries in the file toy/lexicon.tdl, to see how the inheritance from type constraints operates. For instance, the actual entry for *Kim* is simply:

```
kim_1 := pn-lxm &
 [ ORTH <! "kim" !>,
   SEM [ RESTR <! [ NAME 'Kim ] !> ] ].
```

Now try View Grammar rule and enter the identifier `head-specifier-rule` (or choose it from the selections if a menu is displayed). You will see the the grammar rule is also a typed feature structure as shown in Figure 3.7. We do not reproduce it in full here, because it will not fit on one page, but the boxes indicate which parts of the structure have been 'shrunk' (this is done by clicking on a node, and choosing the menu option Shrink/expand). A feature structure that encodes a rule can be thought of as consisting of a number of 'slots', into which the phrases for the daughters and the mother fit. To see how this works, we will next describe how to parse a sentence.

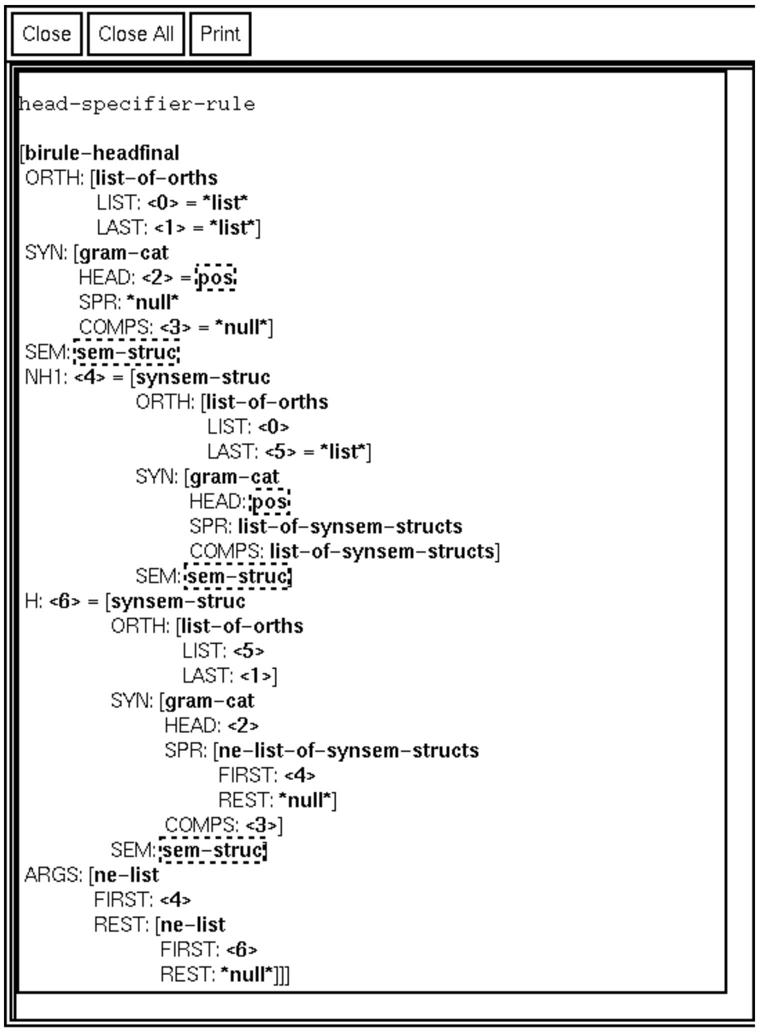
3.4 Parsing

To parse a sentence, click on Parse / Parse input. Unless you have been parsing other things already, the default selection is `Kim sleeps`. Click `OK` to accept this default. In ACL/CLIM you will get a window with one tiny parse tree, as shown in Figure 3.8.[1] If you click on the parse tree itself you will get a menu with an option to Show enlarged tree. If you choose this, you will see a window with a more readable version of the tree, as shown in Figure 3.9. In MCL you will just get the large tree immediately.

In a linguistic framework such as HPSG, a parse tree is just a convenient user interface device, which is shorthand for a much larger typed feature structure. Click on the uppermost (S) node of the enlarged parse tree and choose the option Feature structure — Edge 3. You will see a large feature structure, which is shown in Figure 3.10. As before, we have 'shrunk' some parts of the structure so that it can be displayed on the page. This structure represents the entire sentence. It is an instantiation of the `head-specifier-rule` shown in Figure 3.7.

Note that the mother node in the parse tree corresponds to the root node of the feature structure shown in Figure 3.10. The structure for the word *Kim* is the node which is the value of the feature

[1]The reason for the small size is that with non-trivial grammars and sentences, the parse trees can be very large and numerous . . .



```
head-specifier-rule

[birule-headfinal
 ORTH: [list-of-orths
        LIST: <0> = *list*
        LAST: <1> = *list*]
 SYN: [gram-cat
       HEAD: <2> = pos
       SPR: *null*
       COMPS: <3> = *null*]
 SEM: sem-struc
 NH1: <4> = [synsem-struc
             ORTH: [list-of-orths
                    LIST: <0>
                    LAST: <5> = *list*]
             SYN: [gram-cat
                   HEAD: pos
                   SPR: list-of-synsem-structs
                   COMPS: list-of-synsem-structs]
             SEM: sem-struc
 H: <6> = [synsem-struc
           ORTH: [list-of-orths
                  LIST: <5>
                  LAST: <1>]
           SYN: [gram-cat
                 HEAD: <2>
                 SPR: [ne-list-of-synsem-structs
                       FIRST: <4>
                       REST: *null*]
                 COMPS: <3>]
           SEM: sem-struc
 ARGS: [ne-list
        FIRST: <4>
        REST: [ne-list
               FIRST: <6>
               REST: *null*]]]
```

Figure 3.7: The head specifier rule

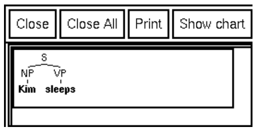


Figure 3.8: The parse result window in ACL/CLIM

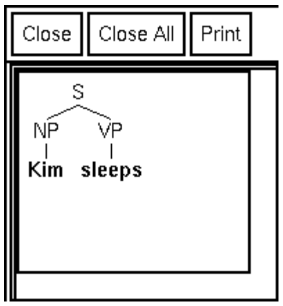


Figure 3.9: A parse tree window

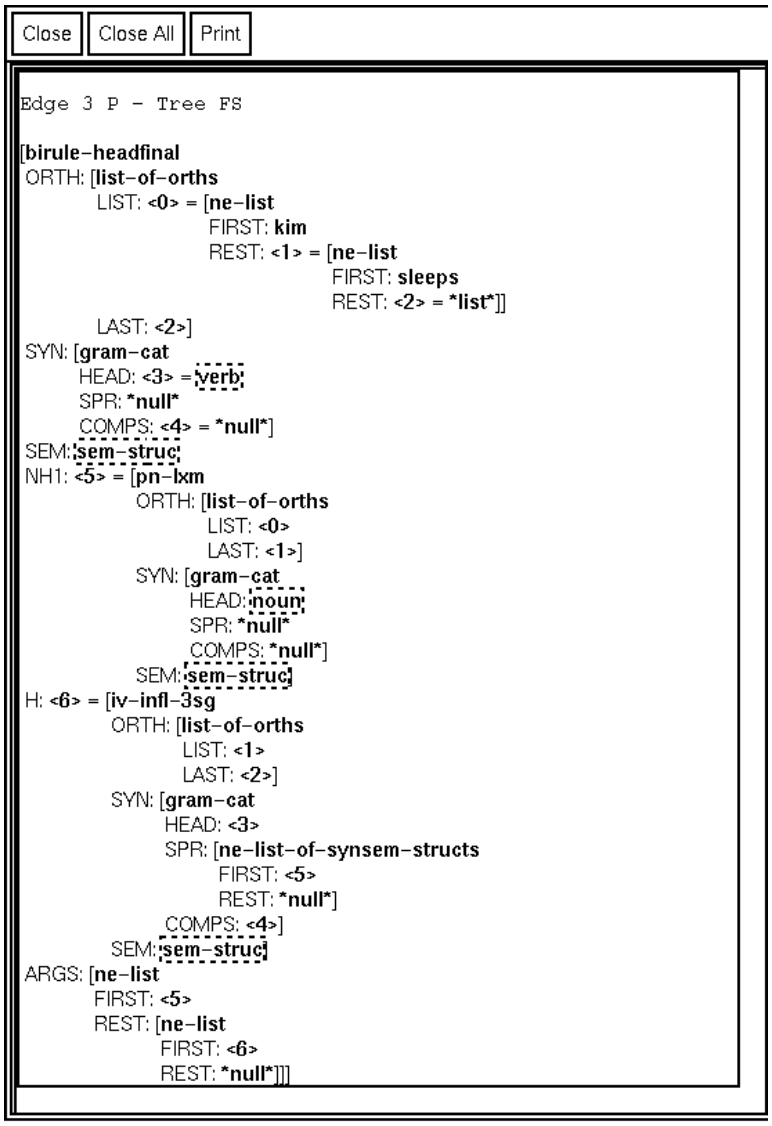
NH1. The structure for the verb *sleeps* is the value of H. The parse trees are created from the feature structures by matching these substructures against a set of node specifiers defined in the file `parse-nodes.tdl`. If you now try parsing the sentence *Kim likes Sandy* and examining the trees and the feature structures as before, you will see that the daughter structures may themselves have daughters. We will go into a lot more detail about how grammar rules work in the next chapter.

Now try Parse / Batch Parse. You will be prompted for the name of a file which contains a test suite: i.e. a list of sentences which either should or should not parse in a grammar. A suitable file, `test.items`, already exists in the toy directory. Select `test.items` and enter the name of a new file for the output, e.g., `test.items.out`. When you open the output file in the editor, it should show the following for each sentence:

1. the number of the sentence
2. the sentence itself delimited by `"`
3. the number of parses (0 if there were no parses)
4. the number of edges (roughly speaking an edge is a phrase constructed while attempting to parse)

Note that we have marked ungrammatical sentences with an asterisk in the test suite file, and though the parser strips off the asterisk before attempting to parse, the results file shows the sentence in the form in which it was input. The results file also contains a time for the total processing.

The toy grammar can parse exactly four sentences. In the next sections, we'll expand that coverage slightly.



```
Edge 3 P - Tree FS

[birule-headfinal
 ORTH: [list-of-orths
           LIST: <0> = [ne-list
                           FIRST: kim
                           REST: <1> = [ne-list
                                          FIRST: sleeps
                                          REST: <2> = *list*]]
           LAST: <2>]
 SYN: [gram-cat
        HEAD: <3> = verb
        SPR: *null*
        COMPS: <4> = *null*]
 SEM: sem-struc
 NH1: <5> = [pn-lxm
               ORTH: [list-of-orths
                        LIST: <0>
                        LAST: <1>]
               SYN: [gram-cat
                      HEAD: noun
                      SPR: *null*
                      COMPS: *null*]
               SEM: sem-struc
 H: <6> = [iv-infl-3sg
            ORTH: [list-of-orths
                     LIST: <1>
                     LAST: <2>]
            SYN: [gram-cat
                   HEAD: <3>
                   SPR: [ne-list-of-synsem-structs
                          FIRST: <5>
                          REST: *null*]
                   COMPS: <4>]
            SEM: sem-struc
 ARGS: [ne-list
          FIRST: <5>
          REST: [ne-list
                   FIRST: <6>
                   REST: *null*]]]
```

Figure 3.10: A feature structure representing the sentence *Kim sleeps*

3.5 Adding a lexical entry

In this section and the next one, we illustrate the basics of how you can modify an existing grammar. In this section, we describe how to add a new lexical entry.[2] First open the file `toy/lexicon.tdl` in your text editor. You will see that the toy grammar has four lexical entries: two proper names and two verbs. Suppose you want to add another proper name, perhaps your own first name. The entry will look exactly like the entry for *Kim*, but with the orthography and value of the semantic feature NAME replaced with your name.[3] Add such an entry to the end of the file. For instance:

```
ann_1 := pn-lxm &
 [ ORTH <! "ann" !>,
   SEM [ RESTR <! [ NAME 'ann ] !> ] ].
```

Save the file, and then select Load followed by Reload grammar. This will reload the script file that you loaded before, this time loading the changed version of the lexicon. You may get some error messages in the LKB interaction window at this point, if you have left out a character, for example. If you cannot see what is wrong, the description of the error messages in §6.2.1 may help you track it down. When you have successfully reloaded the system, you should be able to parse some additional sentences, such as:

```
Ann sleeps
```

If you find that a sentence won't parse, and you do not understand why a grammar rule is not applying to a particular lexical item, there are some tools to help you. In particular, §7.3.1 describes an interactive tool for showing why unification is failing.

Once you have successfully parsed some new sentences, you could add them to the list of test sentences for batch parsing.

3.6 Adding a type and its constraint description

The way the toy grammar is set up, although you could add a lexical entry for a proper name by just adding a description to the lexicon file, in order to add a new verb to the lexicon, you have to first add a type representing its relation. Suppose you want to add a new entry for the intransitive verb *snores*. First you have to add a type such as **snore_rel**. Open the file `toy/types.tdl`. Search the file for the entry for the relation for sleeps, **r_sleep**. Then add a new entry for **r_snore**. You can then save the file, and add a new entry to the lexicon file. As with the previous entry, you can basically do this by copying the existing entry for *sleeps*, but this time you have to change the relation to be the type you have just added. Change the orthography and the identifier for the entry as before. Save the file. Then select Reload grammar. As before, check the LKB interaction window to make sure reloading was successful and try parsing some new sentences.

[2]You may want to make a backup copy of the toy directory at this point before you start editing the files.

[3]If your name has spaces in it, please write it without a space for now. The LKB can deal with words with spaces in them, see §8.4, but discussing this would take us too far afield at the moment. If your name contains diacritical marks etc, like é, then you can enter these using the normal Macintosh sequences in the MCL text editor. For emacs, `M-x iso-accents-mode` allows you to enter accented characters. However, there are some problems — see §8.6 for a more detailed discussion.

3.7 Next steps

If you have worked through this chapter, and are a beginner to the use of typed feature structure systems, we have now to admit that we've led you gently to the edge of a small but steep cliff and are not going to provide much in the way of climbing equipment.[4] A basic introduction to the notion of typed feature structure grammars, avoiding formal notation, is in the next chapter (Chapter 4). Alternatively, the formal exposition of types and typed feature structures as used in the LKB is in Chapter 5. Chapter 5 is designed for readers who have some familiarity with feature structures and are happy with a fairly technical exposition. Many people will be happier investigating the properties of the system informally first and then checking Chapter 5 to understand the precise behaviour. With the exception of those chapters, the rest of this document is intended as a reference manual.

Ideally, once you understand the basics of the formalism to the level presented in Chapter 4, you would investigate the capabilities of the LKB further by working through some of the details of the example grammars, and try extending them, first by adding lexical entries as we did in this chapter, and then by extending the coverage by adding new lexical types. You should refer to the relevant sections in chapters 5, 6 and 7 when problems arise or when you need to know the details of some facility. Then §8.1 gives some hints as to how to go about building your own grammar. Some of the advanced capabilities discussed in Chapter 8 will become relevant at this point.

If you want to learn more about a linguistic framework that uses the typed feature structure formalism, then Sag and Wasow (1999) is an introductory textbook. Some of the grammars provided with the LKB system implement the grammars described there. Sag and Wasow use a somewhat different (and much less tractable) formalism from the version of the typed feature structure logic used in the LKB system and their terminology also differs. Most importantly, they use the term *typed feature structure description* where we talk about typed feature structures. However, Sag and Wasow make only limited use of the extra power of the formalism they describe, so most of the grammars they discuss can be encoded in the LKB.

[4]There is the possibility of Copestake and Flickinger (next millennium), which would be an introduction to linguistic engineering using typed feature structure systems, and the LKB in particular. If you think this would be a worthwhile enterprise, please send encouraging email, cash donations etc to us at CSLI.

Chapter 4

Typed feature structures made simple

If you have worked through the previous chapter, you should have gained an intuitive idea of the components of a typed feature structure grammar, how to write feature structure descriptions for lexical entries etc, and how grammar rules work. In this chapter we will go over the underlying concepts in more detail, to give you a more precise (though still relatively informal) description of typed feature structures. This chapter could be read without access to a running LKB system, although having the system available will be necessary to work with the sample grammars and to do some of the exercises. If you have some familiarity with typed feature structure formalisms, you should read Chapter 5 instead of this one. In the case of any apparent conflict between this chapter and Chapter 5, Chapter 5 should be taken as definitive. However the description in this chapter is precise. It roughly follows the definitions in Chapter 5 — here, however, we have used many more examples and far fewer mathematical symbols (*squiggly bits*).

Cautionary note There are several slightly different variants of typed feature structure formalisms. Here we are describing the version used in the LKB system, and since this is an informal introduction, we will not discuss the differences with other approaches in this chapter. Some of these differences are mentioned in Chapter 5, which gives more formal definitions. We also omit references to previous work — again, see Chapter 5. The terminology in the literature is also confusing, to say the least. Rather than trying to explain all the alternatives in the main text, we have just given the terminology used elsewhere in this documentation, with a couple of comments about the differences from Sag and Wasow (1999), since this is probably the most likely source of possible confusion. (Note, eventually we will produce a glossary which will make the relationships between the terminology clearer. This chapter is a first draft: comments are very welcome, especially from members of the target audience.)

Some sections in this chpater are followed by exercises. It's important to attempt at least those which aren't marked as optional. They shouldn't take more than a few minutes and sometimes we will use them to introduce new material.

Before we start describing the details of the formalism, we are going to introduce a really tiny grammar, both in order to make the concept of encoding a grammar in feature structures clearer, and also to give us concrete examples that can be used in the discussion of the typed feature structures themselves.

```
Start symbol: S                   Lexicon:

Rules:                            dog : N
                                  dogs: N
S -> NP VP                        this : Det
NP -> Det N                       these: Det
                                  sleeps : VP
                                  sleep: VP
```

Figure 4.1: A tiny grammar encoded using atomic symbols

4.1 A really really simple grammar

We expect that readers have some familiarity with grammars defined in terms of atomic symbols. For instance, Figure 4.1 shows a very simple grammar and lexicon, with just two grammar rules and six lexical entries. The specification of the *start symbol* as `S` means that the grammar will accept as complete strings “these dogs sleep” and “this dog sleeps”, but not “sleep” and “this dog”, because these cannot be assigned the category S.

Grammars in general can be viewed abstractly as mappings between a set of descriptive structures and a set of strings of characters. For a very simple grammar like that in Figure 4.1, we can use a labelled bracket notation as the description. For instance:

```
(S (NP (Det this) (N dog)) (VP sleeps))
```

This labelled bracketing can equivalently be drawn as a tree, as shown in Figure 4.2.

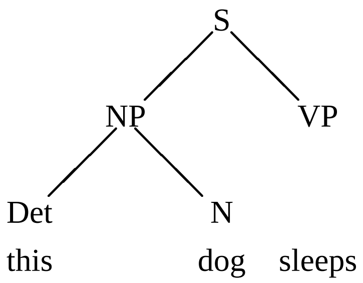


Figure 4.2: Tree for *this dog sleeps* with the tiny grammar using atomic symbols

Grammars can also be viewed as specifications that allow parsing and generation of strings given partial information. For instance, given the input string:

```
these dogs sleep
```

we could derive the single labelled bracketing:

```
(S (NP (Det these) (N dogs)) (VP sleep))
```

Given the partial bracketed structure:

```
(S (NP (Det ?) (N ?)) (VP sleeps))
```

(where we are just using `?` as a placeholder) the corresponding strings are:

```
this dog sleeps
these dog sleeps
this dogs sleeps
these dogs sleeps
```

As this example shows, this grammar allows sentences which are not grammatical English, such as:

(1) these dog sleeps

The problem is that the grammar does not include any specification of agreement. It could be fixed by increasing the number of atomic symbols, for instance as shown in Figure 4.3. But this approach would soon become very tedious as we expanded the grammar.

```
Start symbol: S                  Lexicon:

Rules:                           dog : N-sg
                                 dogs: N-pl
S -> NP-sg VP-sg                 this : Det-sg
S -> NP-pl VP-pl                 these: Det-pl
NP-sg -> Det-sg N-sg             sleeps : VP-sg
NP-pl -> Det-pl N-pl             sleep: VP-pl
```

Figure 4.3: An atomic symbol grammar encoding subject verb agreement

Feature structures are one way of allowing extra information to be encoded to deal with agreement and more complex phenomena. Some approaches to representation use such feature structures to augment a backbone of rules expressed using atomic symbols. However, in other approaches, including that implemented in the LKB, we instead make everything be a (typed) feature structure, including lexical entries and grammar rules.

Figure 4.4 shows how a grammar equivalent to the very simple grammar shown above can be written using typed feature structures. This is the grammar that is in the directory `tiniest/grammar1` distributed with the LKB. You should load this grammar into the LKB system in order to experiment. Figure 4.4 looks much more complex than the grammar given in Figure 4.1, but the additional initial complexity of feature structure grammars pays off with more complex grammars.[1] Please note that this isn't intended to be in any way a linguistically interesting grammar (unlike the toy grammar used in the last chapter, which does have theoretically motivated fundamentals, but which is somewhat too complex to use for our current purposes).

[1]In fact this grammar is a bit more complex than it needed to be to simply simulate the starting grammar in the LKB system, but we've done this in order to be consistent with some of the other grammars distributed with the LKB, such as the toy grammar discussed in the previous chapter. As we'll see in a lot of detail later on, although the LKB system can process any grammar that can be expressed in this variant of the typed feature structure formalism, there are a few parameters which control the interface between the grammar and the system which have to be declared. For simplicity, we've kept most of those parameters the same in the sample grammars supplied with the system.

```
;;; Types
string := *top*.

*list* := *top*.

*ne-list* := *list* &
 [ FIRST *top*,
   REST *list* ].

*null* := *list*.

synsem-struc := *top* &
[ CATEGORY cat ].

cat := *top*.

s := cat.

np := cat.

vp := cat.

det := cat.

n := cat.

phrase := synsem-struc &
[ ARGS *list* ].

lexeme := synsem-struc &
[ ORTH string ].

root := phrase &
[ CATEGORY s ].
```

```
;;; Lexicon
this := lexeme &
[ ORTH "this",
  CATEGORY det ].

these := lexeme &
[ ORTH "these",
  CATEGORY det ].

sleep := lexeme &
[ ORTH "sleep",
  CATEGORY vp ].

sleeps := lexeme &
[ ORTH "sleeps",
  CATEGORY vp ].

dog := lexeme &
[ ORTH "dog",
  CATEGORY n ].

dogs := lexeme &
[ ORTH "dogs",
  CATEGORY n ].

;;; Rules
s_rule := phrase &
[ CATEGORY s,
  ARGS [ FIRST [ CATEGORY np ],
         REST [ FIRST [ CATE-
GORY vp ],
                REST *null* ]]] .

np_rule := phrase &
[ CATEGORY np,
  ARGS [ FIRST [ CATEGORY det ],
         REST [ FIRST [ CATE-
GORY n ],
                REST *null* ]]] .
```

Figure 4.4: Tiny typed feature structure grammar

We will not go through the operation of the grammar here, but rely on the intuitive correspondence with the grammar in Figure 4.1. The details will emerge as we discuss the formalism. For now, you should just note that the basic components of the grammar are:

The type system (left column of Figure 4.4)
The type system acts as the defining framework for the rest of the grammar. For instance, it determines which structures are mutually compatible and which features can occur, and it sets up an inheritance system which allows generalisations to be expressed. For this particular grammar, for example, all the basic linguistic entities are of type **synsem-struc** which the type system defines to have the feature CATEGORY. The information which was conveyed by the simple atomic categories in the grammar in Figure 4.1 is kept in this feature. The categories themselves, **s**, **np** and so on, are also represented as types. All types must be explicitly defined, except for string types such as `"these"`.

Lexical entries (top two-thirds of right column of Figure 4.4)
These are typed feature structures which the grammar writer constructs in order to encode the words of the language. Lexical entries define a relationship between a string representing the characters in a word and some linguistic description of the word (or, more precisely, of a particular sense of a word). In this grammar, the ORTH (orthography) feature is used to encode the string in lexical entries.

Grammar rules (bottom third of right column of Figure 4.4)
Grammar rules are typed feature structures that describe how to combine lexical entries and phrases to make further phrases. In the atomic category grammar, we expressed the idea of a rule in a conventional way by specifying a category for a phrase to the left of an arrow, and the daughter categories, in their expected linear order, to the right of the arrow. For this feature structure grammar we have made the mother structure actually include the daughters.[2] Thus, the rules are actually partial descriptions of phrases. The daughters of the phrase are contained in the feature ARGS. This takes as its value a list where the order of the list elements corresponds to the linear order of the daughters. Note that we will sometimes collectively refer to lexical entries and grammar rules as *entries*.

Start symbol The equivalent of the start symbol in the atomic category grammar is represented by the type **root**.

For this grammar, we could still derive the same labelled bracketing for *this dog sleeps* as we saw before, by simply taking the values of the category feature from the lexical entries and from each phrase. But with a feature structure grammar, a tree with atomic labels is just an abbreviation for the complete representation. For this style of grammar, where the mother of a rule is reprsented as a feature structure that contains all its daughters, the complete representation for the derivation is given by the feature structure for the sentence. This structure is shown in Figure 4.5.

In the next few sections, we will use examples from this grammar, and some slightly more complex variants of it, in order to explain typed feature structures in detail. We'll start off this detailed explanation of typed feature structures by discussing *type system*s, which form the backbone of

[2]This isn't a requirement of the LKB system but it's an approach used in most grammars in the HPSG framework.

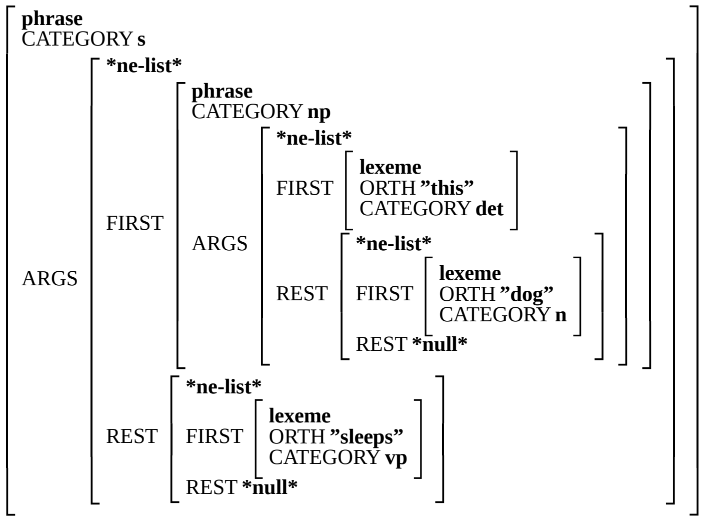


Figure 4.5: AVM for *this dog sleeps* from the tiny grammar using feature structures

grammars. A type system consists of a *type hierarchy*, which indicates specialisation and consistency of types, plus a set of *constraint*s on types which determined which typed feature structures are *well-formed*. The next section describes the type hierarchy.

4.2 The type hierarchy

Figure 4.6 shows the type hierarchy corresponding to our simple grammar (with the string types omitted). As in all type hierarchies, there is a unique most general type, which we will refer to as

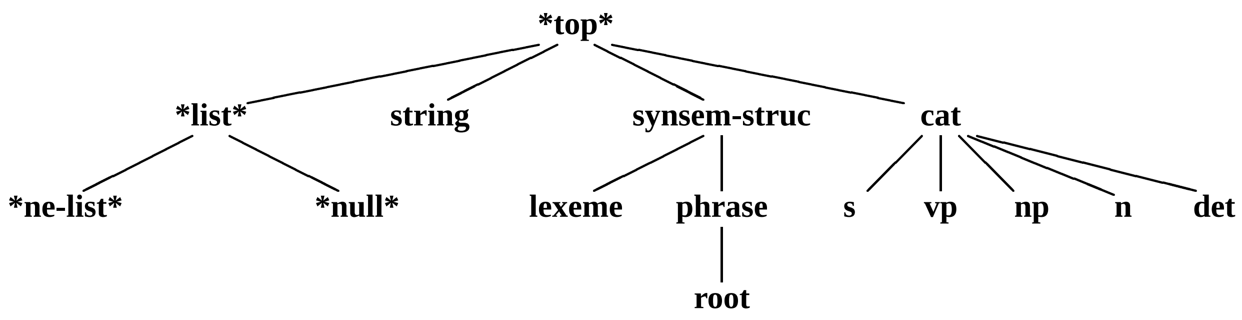


Figure 4.6: Type hierarchy for the tiny grammar

the top type, ***top***. The way that type files are written in the LKB means that the descriptions of types contain a specification of their parents together with the constraint (see Figure 4.4, where, for instance, ***ne-list*** is defined as having the parent ***list***). It is the specification of the parents that defines the type hierarchy. Note that ***top*** is not defined in the grammar specification. The hierarchy determines how constraints are inherited, although we won't get to the details until later in the chapter. This particular hierarchy is a tree, it is possible for a type to have more than one parent: this is usually referred to as *multiple inheritance* and we'll see some examples of it shortly.

Below is a short summary of the properties of type hierarchies in general. (Later on, we'll give summaries of typed feature structures, constraints and so on.) All type hierarchies in the LKB system must obey these conditions.

Properties of type hierarchies

Unique top There is a single hierarchy containing all the types with a unique top type.

No cycles There are no cycles in the hierarchy.

Unique greatest lower bounds Any two types in the hierarchy must either be incompatible, in which case they will not share any descendants, or they must have a unique highest common descendant (referred to as the unique *greatest lower bound*).

In order to make the last restriction a bit clearer, we will use an artificial example of a hierarchy (shown in Figure 4.7). This is a formally valid hierarchy, since if we look at any pair of types, the

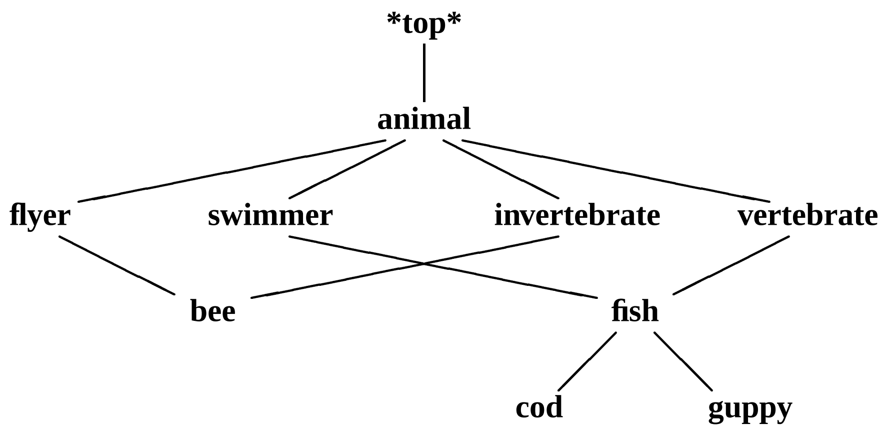


Figure 4.7: Valid hierarchy with multiple inheritance

relationship between them falls one of the following categories:

1. The types have no descendents in common (e.g., **vertebrate** and **invertebrate**)
2. The types have a hierarchical relationship (e.g., **animal** and **bee**), in which case the unique greatest common descendant is trivially the lower in the hierarchy.
3. There is a third type which is a unique greatest common descendant. For instance, **vertebrate** and **swimmer** have **fish** as a common descendant: **cod** and **guppy** are also common descendants, but **fish** is above both of them in the hierarchy.

Crucially, the assumption is made that all the types that exist have a specified position in the hierarchy (sometimes referred to as a *closed world* assumption) and that, if two types are compatible, there must be a single type which represents their combination. So if we know something is of type **vertebrate** and also of type **swimmer**, given this hierarchy, we can conclude it is of type **fish** (though we don't know whether it is a **cod** or a **guppy**).

An example of an invalid hierarchy is given in Figure 4.8, where we have added **mammal** under **vertebrate** and **whale** as inheriting from **mammal** and **swimmer**. Now both **fish** and **whale** inherit from the types **vertebrate** and **swimmer**, but aren't related to eachother through an inheritance relationship. This invalidates the hierarchy because it violates the unique greatest lower bounds condition. If **vertebrate** and **swimmer** are compatible there must be a single type for their combination, but both **whale** and **fish** independently inherit from them. Note that it is irrelevant that the node **mammal** intervenes between **vertebrate** and **whale** while **fish** is a direct daughter of **vertebrate**: **whale** is not a descendant of **fish**, so **fish** isn't the greatest lower bound of **vertebrate** and **swimmer**.

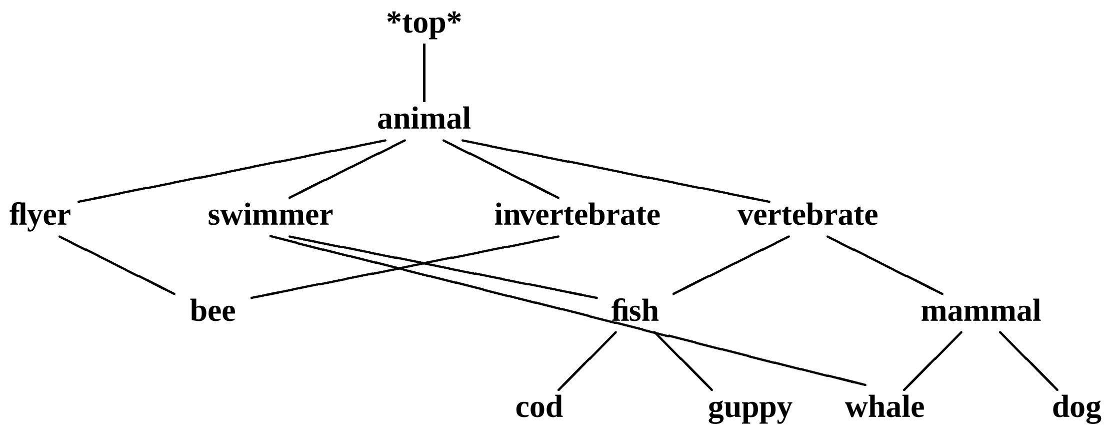


Figure 4.8: Invalid hierarchy

This hierarchy can be fixed straightforwardly, if somewhat uninterestingly, by adding a new node **vertebrate-swimmer**. This is shown in Figure 4.9. In the LKB, if a type hierarchy does not conform to the greatest lower bound (glb) condition, the system will automatically create types in order to satisfy the condition (the created types are referred to as *glbtypes*). More details of this are given in 6.2.3. However in this chapter we will assume that all type hierarchies obey the glb condition.

Having described the restrictions on the type hierarchy, we should mention the slight complication of strings. As we mentioned above, strings such as `"these"` are an exception to the requirement that all types have to be explicitly defined by the user. Any arbitrary string (i.e. sequence of characters starting and ending with `"`) is conventionally considered to be a subtype of

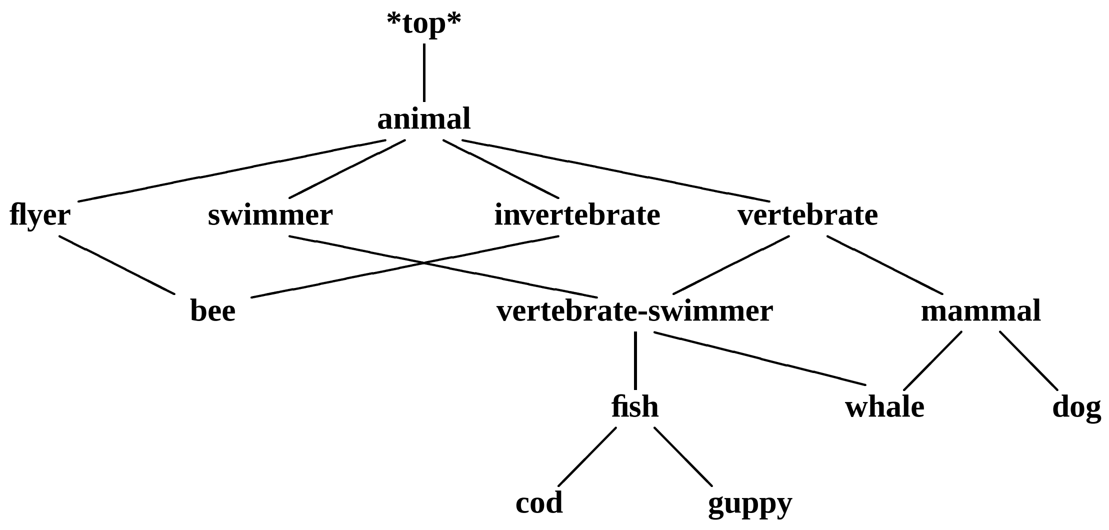


Figure 4.9: Corrected hierarchy

the type **string**. No strings have subtypes, which means that different strings are incompatible. So string types actually obey all the conditions on the type hierarchy, but we usually don't show them in diagrams or in the type hierarchy display, since they have no interesting interrelationships.

You should note that, in the LKB system, despite the requirement that all types must be defined, it is valid to specify that a type has exactly one daughter. For instance, **root** is the unique daughter of **phrase** in the sample grammar. The system does not infer that something of type **phrase** is also of type **root**. This is one point of fundamental difference between typed feature structure formalisms — the approach assumed by Sag and Wasow, for instance, would in effect require that this inference be possible — but it would be far too much of a digression to discuss it here. The LKB system's form of the closed world assumption just requires the grammar writer to always specify, for any pair of types, whether or not they are compatible, and if they are compatible, what the result of combining them is. As we'll see below, this requirement makes it straightforward to define combination of typed feature structures, that is, *unification*.

4.2.1 Exercises

1. Draw the hierarchy corresponding to the following type file (where `x := a & b` means that **x** has parents **a** and **b**):

```
a := *top*.
b := *top*.
x := a & b.
```

```
y := a & b & c.
z := a & b & c.
```

What's wrong with it? How could you fix it?

2. (Optional) Inheritance hierarchies are often introduced using examples from taxonomies. Biological taxonomies classify organisms according to categories such as phylum, class, order, family, genus, species and so on. In what respects are type hierarchies similar to and different from such biological taxonomies? Could a representation of a taxonomy be implemented using a type hierarchy?

4.2.2 Answers

1. The problems are:

   (a) Lack of connectivity: **c** is not defined.

   (b) Multiple greatest lower bounds

   In order to fix the lack of connectivity, we can define **c** to inherit from ***top***. In order to fix the multiple greatest lower bound problem, we have to introduce new types: a minimal solution is:

   ```
   a := *top*.
   b := *top*.
   c := *top*.
   ab := a & b.
   abc := ab & c.
   x := ab.
   y := abc.
   z := abc.
   ```

   If you came up with another solution, and want to check it in the LKB system, replace the type file in the directory `tiniest/answers` with your own type file and load the script in that directory as usual. It should load without any messages that say it is fixing glb problems. In general there is no unique way of adding types to turn a hierarchy into one that conforms to the greatest lower bound condition.

2. Taxonomies and type hierarchies both encode a notion of specificity: for instance, the phylum *Chordata* contains the classes *Mammalia* and *Reptilia* (among others). They also share the property that the specificity relationship is transitive and cannot be overridden: there is no way to say that, for instance **bird** is a subtype of **vertebrate** and that **penguin** is a subtype of **bird** but to cancel the inference that **penguin** is a subtype of **vertebrate**. But there are differences, for one thing there is no cross-classification in conventional biological taxonomies, so they can be represented as trees. Furthermore, taxonomies use distinct levels of classification, although there are some categories which may not be instantiated for a particular organism, such as sub-species. So a taxonomy could be partially represented

in a type hierarchy: the specialisation relationships could be captured, but the categories of classification, such as genus, cannot be represented, since there is nothing in the formalism which allows one to talk about the levels in the hierarchy, or to restrict the hierarchy to a fixed number of levels.

There's also something of a difference with respect to the notion of completeness: although organisms are discovered which can, for example, be classified with respect to genus but not to a particular species, a biologist is unlikely to be content to leave them underspecified for long. So it might be reasonable to assume that if there was only one species in a given genus, that if an organism was classified as belonging to that genus, it automatically also belonged to that species. An LKB description of a taxonomy would also be deficient in this respect.

Of course, whether the deficiencies actually matter depends on what the system is supposed to do …

4.3 Typed feature structures

We now move on to talking about typed feature structures. We'll make a distinction between typed feature structures in general, which we'll discuss in this section, and the subset of typed feature structures which are *well-formed* with respect to a set of type constraints, which are described in §4.5.

Typed feature structures can be thought of as graphs, which have exactly one type on each node, and which have labelled arcs connecting nodes (except for the case of the simplest feature structures, which consist of a single node with a type but with no arcs). The labels on the arcs are referred to as *feature*s. Arcs are regarded as having a direction, conventionally regarded as pointing into the structure. For instance, in the structure below, there are two arcs, labelled with FIRST and REST, and three nodes, with types ***ne-list***, ***list*** and ***top***:

$$\begin{tikzcd} \textbf{*ne-list*}\ \bullet \arrow[r, "\text{FIRST}"] \arrow[dr, "\text{REST}"] & \textbf{*top*}\ \bullet \\ & \textbf{*list*}\ \bullet \end{tikzcd}$$

Properties of typed feature structures

Connectedness and unique root A typed feature structure must have a unique root node: apart from the root, all nodes have one or more parent nodes.

Unique features Any node may have zero or more arcs leading out of it, but the label on each (that is, the feature) must be unique.

No cycles No node may have an arc that points back to the root node or to a node that intervenes between it and the root node[3]

[3]Formally, in fact, both type hierarchies and typed feature structures are *directed acyclic graphs* (DAGs). However, directional arcs in typed feature structures do not encode specificity in any way. It would not make much sense for type hierarchies to contain cycles, since intuitively it cannot be the case that x is more specific than y and that y is also

Types Each node must have a single type, which must be present in the type hierarchy.

Finiteness A feature structure must have a finite number of nodes.

The more complex example in Figure 4.10 represents the structure for the rule `np_rule` from the grammar shown in Figure 4.4, where the first daughter position (ARGS FIRST) has been unified with the feature structure corresponding to *these*. We will describe unification in detail in §4.4, but intuitively it just refers to combining two typed feature structures, retaining all the information in each of them.

It is very important to realize that any non-root node in a feature structure can be considered as the root of another feature structure. For instance, the following is the feature structure rooted at the node reached by starting at the root of the structure in Figure 4.10 then following the arc labelled ARGS and then the arc labelled FIRST.

$$\begin{tikzcd}
\textbf{lexeme} \arrow[r, "\text{ORTH}"] \arrow[dr, "\text{CATEGORY}"] & \textbf{"these"} \\
 & \textbf{det}
\end{tikzcd}$$

Because this graph notation is cumbersome (and difficult to draw in LaTeX ...), it is usual to illustrate feature structures with an alternative notation, known as an *attribute value matrix* or AVM. The AVM corresponding to Figure 4.10 is shown in Figure 4.11.

The *description language* used in the grammar files is similar to the AVM notation: a description which would correspond to Figure 4.10 is shown in Figure 4.12. The main differences are that the AVM notation we're using has the types inside the square brackets, while this description language puts them outside, and that the description language requires conjunction symbols &.[4] Note that, although this is a perfectly valid description syntactically, it's not usual to write something like this, both because there's no reason generally to write a description that corresponds to a partially instantiated rule, and because it makes explicit a lot of information that is inferred automatically via the process of making a structure well-formed, as we'll discuss in §4.5.

There is no significance to the order in which features are drawn. The following two AVMs represent exactly the same structure.

$$\begin{bmatrix} \textbf{phrase} & \\ \text{CATEGORY} & \textbf{np} \\ \text{ARGS} & \begin{bmatrix} \textbf{*ne-list*} \\ \text{FIRST } \textbf{lexeme} \\ \text{REST } \textbf{*null*} \end{bmatrix} \end{bmatrix} \qquad \begin{bmatrix} \textbf{phrase} & \\ \text{ARGS} & \begin{bmatrix} \textbf{*ne-list*} \\ \text{REST } \textbf{*null*} \\ \text{FIRST } \textbf{lexeme} \end{bmatrix} \\ \text{CATEGORY} & \textbf{np} \end{bmatrix}$$

However, it is obviously easier to read AVMs if the features appear in a consistent order (the way the LKB allows the user to define display order is described in §7.3 and §C.1.2).

It is often useful to talk about *path*s into feature structures, by which we mean sequences of features that can be followed from the root node. In the example above, for instance, the path

more specific than x. But since the arcs in typed feature structures don't have this sort of interpretation, cycles are not intuitively ruled out, and some variants of the typed feature structure formalism allow them.

[4]It would clearly be better if the description language mirrored the AVMs, but this is something we are stuck with for historical reasons, just like the QWERTY keyboard. The description language actually has a rather complex syntax that doesn't simply mirror an AVM — for instance it uses various abbreviatory notations. But we won't discuss these in any detail in this chapter.

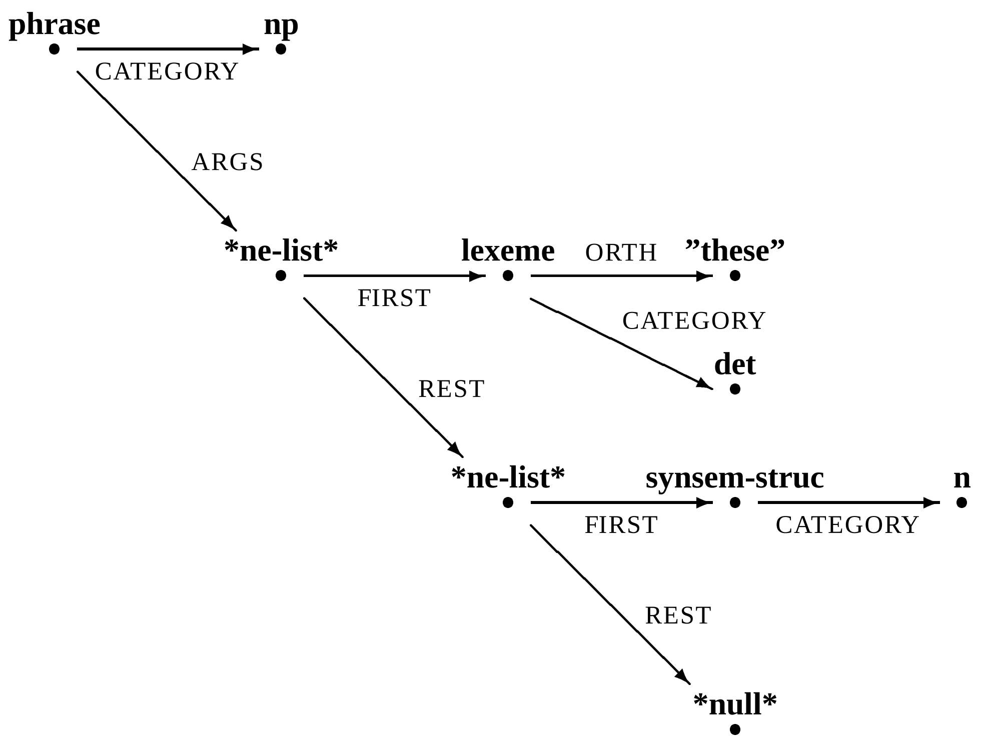


Figure 4.10: Graph representation of a feature structure

$$\begin{bmatrix}\textbf{phrase} & \\ \text{CATEGORY }\textbf{np} & \\ \text{ARGS} & \begin{bmatrix}\textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix}\textbf{lexeme}\\ \text{ORTH }\textbf{"these"}\\ \text{CATEGORY }\textbf{det}\end{bmatrix}\\ \text{REST} & \begin{bmatrix}\textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix}\textbf{synsem-struc}\\ \text{CATEGORY }\textbf{n}\end{bmatrix}\\ \text{REST }\textbf{*null*} & \end{bmatrix}\end{bmatrix}\end{bmatrix}$$

Figure 4.11: AVM representation of a feature structure

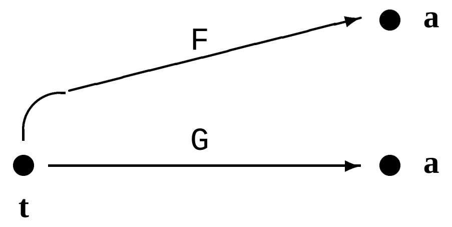
```
example := phrase &
[ CATEGORY np,
  ARGS  *ne-list* &
        [ FIRST lexeme &
                [ ORTH "these",
                  CATEGORY det ],
          REST  *ne-list* &
                [ FIRST synsem-struc &
                        [ CATEGORY n ],
                  REST *null* ]]] .
```

Figure 4.12: Description language representation of a feature structure

CATEGORY.ARGS leads to a node with the type ***ne-list***. The *value* of a path is the feature structure whose root is the node led to by the path. The root node is the value of the *empty path*. We will sometimes use this terminology loosely however, and say that the value of a path is a type, when strictly speaking what we mean is that the value of the path is a feature structure with a root node labelled with that type.

The graph in Figure 4.10 is a tree: there are no cases where two arcs point to the same node. But *reentrancy*, as the non-tree situation is called, is required to build up more interesting feature structure grammars. Figure 4.13 illustrates two feature structures: the first is not reentrant, while the second is. We use structures with features like F and G at this point, to abstract away from the details of encoding in the grammar. (We assume that the types **t**, **a**, **b** and so on are all defined in some hierarchy.)

	Graph	AVM	description

Non-reentrant		$\begin{bmatrix}\textbf{t}\\ \text{F}\ \textbf{a}\\ \text{G}\ \textbf{a}\end{bmatrix}$	`t &`
			`[ F a,`
			`  G a ].`

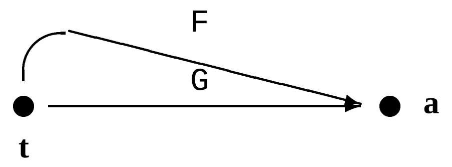
Reentrant		$\begin{bmatrix}\textbf{t}\\ \text{F}\ \boxed{0}\ \textbf{a}\\ \text{G}\ \boxed{0}\end{bmatrix}$	`t &`
			`[ F #1 & a,`
			`  G #1 ].`

Figure 4.13: Reentrant structures

If two paths point to the same node, we say the paths are *equivalent*. Reentrancy is conventionally indicated by boxed integers in the AVM diagrams, and by tags beginning with # in the descriptions. The particular integer or tag used is of no significance: their only function is to indicate that the paths lead to the same node. We should also note at this point that it is conventional to distinguish between features and types typographically by putting the former in uppercase, and the latter in lowercase. Although the case isn't significant, there is nothing to prevent the same name being used for a type and for a feature, since the syntax of the descriptions always allows them to be distinguished.

To see reentrancy at work in a grammar, look at the grammar shown in Figure 4.14, where we have augmented the grammar in Figure 4.4 with information about agreement. Try parsing the sentences *this dog sleeps*, *these dog sleeps* and so on in the LKB system (the grammar is in `tiniest/grammar2`) and look at the trees which result from the sentences which are admitted. The reentrancies which are specified on the rules ensure:

1. that the information about agreement in the lexical entries is passed up to the phrases

2. that the determiner and noun have compatible agreement specifications in the rule `np_rule` and that the noun phrase and the verb phrase have compatible agreement specifications in the rule `s_rule`

However, we can't fully describe this here, because haven't discussed unification yet, so we will return to the details of how this works later.

4.3.1 Exercises

1. Which of the following are valid typed feature structures (assuming all the types used are defined)?

   (a) $\begin{bmatrix}\textbf{det}\end{bmatrix}$

   (b) $\begin{bmatrix}\textbf{t}\\ \text{F}\ \boxed{0}\\ \text{G}\ \boxed{0}\end{bmatrix}$

   (c) $\begin{bmatrix}\textbf{phrase}\\ \text{CATEGORY}\ \textbf{np}\\ \text{ORTH}\ \textbf{"these"}\\ \text{CATEGORY}\ \textbf{cat}\end{bmatrix}$

   (d) $\begin{bmatrix}\textbf{t}\\ \text{F}\ \boxed{0}\begin{bmatrix}\textbf{u}\\ \text{F}\ \boxed{1}\,\textbf{a}\\ \text{H}\ \boxed{1}\end{bmatrix}\\ \text{G}\ \boxed{1}\\ \text{J}\ \boxed{0}\end{bmatrix}$

   (e) $\begin{bmatrix}\textbf{t}\\ \text{F}\ \boxed{0}\begin{bmatrix}\textbf{u}\\ \text{F}\ \boxed{1}\,\textbf{a}\\ \text{H}\ \boxed{0}\end{bmatrix}\\ \text{G}\ \boxed{1}\\ \text{J}\ \boxed{0}\end{bmatrix}$

2. Draw the graph and the AVM for the structure for *this dog sleeps* in the version of the grammar with agreement.

3. List all the valid paths in the following structure, and the types of the corresponding nodes. Also list all pairs of paths which lead to the same node.

$$\begin{bmatrix}\textbf{t}\\ \text{F}\ \boxed{0}\begin{bmatrix}\textbf{u}\\ \text{F}\ \boxed{1}\,\textbf{a}\\ \text{H}\ \boxed{1}\end{bmatrix}\\ \text{G}\ \boxed{1}\\ \text{J}\ \boxed{0}\end{bmatrix}$$

4.3.2 Answers

1. (a) Valid. There are no arcs, but a feature structure need only have a single node.

   (b) Valid, but only because of a notational convention which we haven't told you about. The structure looks invalid, since here is no explicit type associated with the inner node, and a type must be associated with every node in a valid structure. But there is a convention when writing AVMs that it is OK to omit the type on a node when showing a reentrant structure if the type is ***top***. So this structure is just shorthand for:
   $\begin{bmatrix}\textbf{t}\\ \text{F}\ \boxed{0}\,\textbf{*top*}\\ \text{G}\ \boxed{0}\end{bmatrix}$
   (In fact, later on we will often omit the type on reentrant or non-terminal nodes when it can be inferred from the type constraints.)

```
;;; Types
string := *top*.

*list* := *top*.

*ne-list* := *list* &
 [ FIRST *top*,
   REST *list* ].

*null* := *list*.

synsem-struc := *top* &
[ CATEGORY cat,
  NUMAGR agr ].

cat := *top*.

s := cat.

np := cat.

vp := cat.

det := cat.

n := cat.

agr := *top*.

sg := agr.

pl := agr.

phrase := synsem-struc &
[ ARGS *list* ].

lexeme := synsem-struc &
[ ORTH string ].

sg-lexeme := lexeme &
[ NUMAGR sg ].

pl-lexeme := lexeme &
[ NUMAGR pl ].

root := phrase &
[ CATEGORY s ].
```

```
;;; Lexicon
this := sg-lexeme &
[ ORTH "this",
  CATEGORY det ].

these := pl-lexeme &
[ ORTH "these",
  CATEGORY det ].

sleep := pl-lexeme &
[ ORTH "sleep",
  CATEGORY vp ].

sleeps := sg-lexeme &
[ ORTH "sleeps",
  CATEGORY vp ].

dog := sg-lexeme &
[ ORTH "dog",
  CATEGORY n ].

dogs := pl-lexeme &
[ ORTH "dogs",
  CATEGORY n ].

;;; Rules
s_rule := phrase &
[ CATEGORY s,
  NUMAGR #1,
  ARGS [ FIRST [ CATEGORY np,
                 NUMAGR #1 ],
         REST [ FIRST [ CATE-
GORY vp,
                        NU-
MAGR #1 ],
                REST *null* ]]] .

np_rule := phrase &
[ CATEGORY np,
  NUMAGR #1,
  ARGS [ FIRST [ CATEGORY det,
                 NUMAGR #1 ],
         REST [ FIRST [ CATE-
GORY n,
                        NU-
MAGR #1 ],
                REST *null* ]]] .
```

Figure 4.14: Tiny grammar with number agreement

(c) Invalid. The structure has two features CATEGORY coming from the same node.

(d) Valid. The reentrancy is fairly complex, but there are no cycles. Note that it is OK to have multiple cases of the feature F since they do not come from the same node.

(e) Invalid. There is a cycle in the structure: the path F.H leads to the same node as the path F does.

2. Load the grammar in `tiniest/grammar2` into the LKB, parse *this dog sleeps* and check the AVM against your answer. The graph you drew should have a single node in every place where the AVM shows a boxed integer. If you created the AVM using the LKB in the first place, award yourself one bonus point . . .

3.

path	type
empty path	**t**
F	**u**
F.F	**a**
F.H	**a**
G	**a**
J	**u**

path	path
F	G
F.F	F.H
F.F	G
F.H	G

One can regard these pairings as comprising the individual pieces of information that are encapsulated in the single structure. Each of these pairs can be represented as a single feature structure, as shown below (we have omitted the type ***top*** from the nodes):

$$\begin{bmatrix}\mathbf{t}\end{bmatrix} \quad \begin{bmatrix}\text{F}\ \mathbf{u}\end{bmatrix} \quad \begin{bmatrix}\text{F}\begin{bmatrix}\text{F}\ \mathbf{a}\end{bmatrix}\end{bmatrix} \quad \begin{bmatrix}\text{F}\begin{bmatrix}\text{H}\ \mathbf{a}\end{bmatrix}\end{bmatrix} \quad \begin{bmatrix}\text{G}\ \mathbf{a}\end{bmatrix} \quad \begin{bmatrix}\text{J}\ \mathbf{u}\end{bmatrix}$$

$$\begin{bmatrix}\text{F}\ \boxed{1}\ \text{G}\ \boxed{1}\end{bmatrix} \quad \begin{bmatrix}\text{F}\begin{bmatrix}\text{F}\ \boxed{1}\\ \text{H}\ \boxed{1}\end{bmatrix}\end{bmatrix} \quad \begin{bmatrix}\text{F}\begin{bmatrix}\text{F}\ \boxed{1}\end{bmatrix}\\ \text{G}\ \boxed{1}\end{bmatrix} \quad \begin{bmatrix}\text{F}\begin{bmatrix}\text{H}\ \boxed{1}\end{bmatrix}\\ \text{G}\ \boxed{1}\end{bmatrix}$$

When we come to talk about unification in the next section, it will be useful to think in terms of the individual pieces of information that make up a feature structure and the formalisation in Chapter 5 also makes use of this idea.

4.4 Unification

We have seen some examples of unification aleady, but now we will discuss it in more detail. Unification is the combination of two typed feature structures to give the most general feature structure which retains all the information which they individually contain. If there is no such feature structure, unification is said to fail.

To make this description precise, we must first discuss the idea of generality with respect to typed feature structures. Typed feature structures can be regarded as being ordered by specificity. Unlike the type hierarchy, where specificity is stipulated by the grammar writer, feature structure specificity can be determined automatically, based on a notion of the amount of information they contain. For instance, the feature structure we just used in the last example, repeated here as (2), contains more information than the structure in (3)

(2) $$\begin{bmatrix} \textbf{t} \\ \text{F}\ \boxed{0} \begin{bmatrix} \textbf{u} \\ \text{F}\ \boxed{1}\ \textbf{a} \\ \text{H}\ \boxed{1} \end{bmatrix} \\ \text{G}\ \boxed{1} \\ \text{J}\ \boxed{0} \end{bmatrix}$$

(3) $$\begin{bmatrix} \textbf{t} \\ \text{F}\ \boxed{0} \begin{bmatrix} \textbf{u} \\ \text{F}\ \boxed{1}\ \textbf{a} \\ \text{H}\ \boxed{1} \end{bmatrix} \\ \text{G}\ \textbf{a} \\ \text{J}\ \boxed{0} \end{bmatrix}$$

The information about the equivalence betwen the path G and the paths F.F etc, which was present in the first structure is missing in the second structure, and the second structure contains no extra information. Thus the second structure is strictly more general that the first. The technical term for this is that the more general structure *subsumes* the less general one. Consider the path-value and path-path equivalences we discussed in the last exercise. If you construct the equivalences for the second structure, you will find they are a strict subset of the ones for the first structure.

The more specific structure will always have all the paths of the more general structure, and may have additional paths. The subsumption relationship is also controlled by the types on the paths. The more general structure must have types for its paths that are either equal to or more general than those for the corresponding paths on the more specific structure. For instance:

(4) $$\begin{bmatrix} \textbf{t} \\ \text{G}\ \textbf{a} \\ \text{J}\ \textbf{*top*} \end{bmatrix}$$

is more general than (subsumes)

(5) $$\begin{bmatrix} \textbf{t} \\ \text{G}\ \textbf{a} \\ \text{J}\ \textbf{b} \end{bmatrix}$$

The most general feature structure of all is always $\begin{bmatrix} \textbf{*top*} \end{bmatrix}$.

We could revise our decomposition process so that we listed not just the path and the type of its node, but also all the supertypes of that type. For instance (assuming **a** and **b** are each direct subtypes of ***top***) the following structure would be the decomposition of the structure shown in (5):

(6)

path	type
empty path	**t**
empty path	***top***
G	**a**
G	***top***
J	**b**
J	***top***

If we did this, then the subsumption order would always correspond to the superset relationship between the decomposed elements.

We can now describe subsumption more formally and concisely.

Properties of subsumption A feature structure F subsumes another feature structure G if and only if the following conditions hold:

Path values For every path P in F with a value of type **t**, there is a corresponding path P in G with a value which is either **t** or a subtype of **t**.

Path equivalences Every pair of paths P and Q which are reentrant in F (i.e., which lead to the same node in the graph) are also reentrant in G.

Unification can now be defined very concisely in terms of subsumption.

Properties of unification The unification of two typed feature structures F and G is the most general typed feature structure which is subsumed by both F and G, if it exists.

It follows from this definition that if one of the structures specifies that a node at the end of some path P has a type **a**, and in the other structure path P leads to a node of type **b**, the structures will only unify if **a** and **b** are compatible types. If they are compatible, the node in the result will have the type which is the greatest lower bound of **a** and **b**. Thus unification of typed feature structures is always defined with respect to a particular type hierarchy.

Another way of putting this definition is that if we take a hierarchy of feature structures ordered by subsumption, the result of unification corresponds to the greatest lower bound of the structures being unified. Or an alternative way of looking at it, in terms of the decomposition of structures, is that unification corresponds to taking the union of the sets of path-type and path-path equivalences from each of the structures to be unified and trying to form the resulting set of structures into a single typed feature structure (see exercise 2 at the end of this section).

The symbol we will use for unification is $\sqcap$.[5] For instance, assuming the type hierarchy from Figure 4.6:

(7) $$\begin{bmatrix}\textbf{lexeme}\\ \text{ORTH }\textbf{"these"}\end{bmatrix} \sqcap \begin{bmatrix}\textbf{lexeme}\\ \text{CATEGORY }\textbf{np}\end{bmatrix} = \begin{bmatrix}\textbf{lexeme}\\ \text{ORTH }\textbf{"these"}\\ \text{CATEGORY }\textbf{np}\end{bmatrix}$$

The root nodes of the two structures being unified always correspond to the root node of the result but arcs with different features always give distinct arcs in the result. Constrast this example with:

(8) $$\begin{bmatrix}\textbf{lexeme}\\ \text{ORTH }\textbf{"these"}\\ \text{CATEGORY }\textbf{*top*}\end{bmatrix} \sqcap \begin{bmatrix}\textbf{lexeme}\\ \text{CATEGORY }\textbf{np}\end{bmatrix} = \begin{bmatrix}\textbf{lexeme}\\ \text{ORTH }\textbf{"these"}\\ \text{CATEGORY }\textbf{np}\end{bmatrix}$$

Here both the feature structures being unified have an arc labelled CATEGORY and this must give a single arc in the result (since feature structures may only have one arc with a given feature from any node). The first structure says that the value of CATEGORY is ***top***, the second that it is **np**,

[5]Some other authors, including Sag and Wasow (1999), use $\sqcup$. The reason for the difference in directionality basically dates back to authors who used alternative ways of formalising unification, some of which roughly correspond to the alternative viewpoints we just mentioned. The LKB documentation has always used $\sqcap$ simply because it's more consistent with drawing type hierarchies with the most general type topmost, which most people seem to find the most natural direction.

but since these types are consistent, the type on the node in the result is simply their greatest lower bound: that is **np**.

Unification, like other mathematical operations, can be regarded procedurally or statically. For instance, one can equivalently say ‘the result of adding 2 and 3 is 5’ which suggests a procedure, or ‘5 is the sum of 2 plus 3’, or $5 = 2+3$. With respect to unification, terms like ‘failure’ are somewhat procedural. Because of this, it is useful to introduce a symbol that stands for inconsistency, $\bot$ (bottom). For instance, the unification of the following two structures is $\bot$.

(9) $$\begin{bmatrix}\textbf{synsem-struc}\\ \text{CATEGORY }\textbf{vp}\end{bmatrix} \sqcap \begin{bmatrix}\textbf{synsem-struc}\\ \text{CATEGORY }\textbf{np}\end{bmatrix} = \bot$$

The inconsistency arises because of the inconsistent types for the path CATEGORY (i.e., **np** and **vp** don’t have a glb).

We now use some further examples to illustrate unification in more detail.

4.4.1 Examples of unification

(10) $$\begin{bmatrix}\textbf{synsem-struc} & \\ \text{CATEGORY} & \textbf{np}\\ \text{ARGS} & \begin{bmatrix}\textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix}\textbf{synsem-struc}\\ \text{CATEGORY }\textbf{*top*}\end{bmatrix}\end{bmatrix}\end{bmatrix} \sqcap \begin{bmatrix}\textbf{phrase} & \\ \text{ARGS} & \begin{bmatrix}\textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix}\textbf{phrase}\\ \text{CATEGORY }\textbf{vp}\end{bmatrix}\\ \text{REST} & \textbf{lexeme}\end{bmatrix}\end{bmatrix}$$
$$= \begin{bmatrix}\textbf{phrase} & \\ \text{CATEGORY} & \textbf{np}\\ \text{ARGS} & \begin{bmatrix}\textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix}\textbf{phrase}\\ \text{CATEGORY }\textbf{vp}\end{bmatrix}\\ \text{REST} & \textbf{lexeme}\end{bmatrix}\end{bmatrix}$$

In this example, we have to consider paths of length greater than one, but unification of the substructures works in exactly the same way. For instance, the root node of the result has the type **phrase** because **phrase** is the glb of **phrase** and **synsem-struc**. Similarly, the node at the end of the path ARGS.FIRST also has the type **phrase**.

(11) $$\begin{bmatrix}\textbf{phrase} & \\ \text{CATEGORY} & \textbf{np}\\ \text{ARGS} & \begin{bmatrix}\textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix}\textbf{synsem-struc}\\ \text{CATEGORY }\textbf{det}\end{bmatrix}\\ \text{REST} & \begin{bmatrix}\textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix}\textbf{synsem-struc}\\ \text{CATEGORY }\textbf{n}\end{bmatrix}\\ \text{REST} & \textbf{*null*}\end{bmatrix}\end{bmatrix}\end{bmatrix} \sqcap \begin{bmatrix}\textbf{phrase} & \\ \text{ARGS} & \begin{bmatrix}\textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix}\textbf{lexeme}\\ \text{ORTH }\textbf{"dogs"}\\ \text{CATEGORY }\textbf{n}\end{bmatrix}\end{bmatrix}\end{bmatrix} = \bot$$

Here the value of the path ARGS.FIRST.CATEGORY is **det** in the first structure and **n** in the second. These types are not compatible, so unification fails.

(12)

$$\begin{bmatrix} \textbf{phrase} & \\ \text{CATEGORY } \textbf{np} & \\ \text{ARGS} & \begin{bmatrix} \textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix} \textbf{synsem-struc} \\ \text{CATEGORY } \textbf{det} \end{bmatrix} \end{bmatrix} \end{bmatrix} \sqcap \begin{bmatrix} \textbf{phrase} & \\ \text{ARGS} & \begin{bmatrix} \textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix} \textbf{synsem-struc} \\ \text{CATEGORY } \textbf{cat} \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

$$= \begin{bmatrix} \textbf{phrase} & \\ \text{CATEGORY } \textbf{np} & \\ \text{ARGS} & \begin{bmatrix} \textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix} \textbf{synsem-struc} \\ \text{CATEGORY } \textbf{det} \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

The point about this example is to illustrate that if one of the input structures subsumes the other, the result is the most specific structure. As we mentioned above, the most general feature structure of all is $\begin{bmatrix} \textbf{*top*} \end{bmatrix}$: the result of unifying this with an arbitrary feature structure F will always be F. Note also that if two identical feature structures G are unified, the result will be G.

(13)

$$\begin{bmatrix} \textbf{phrase} & \\ \text{ARGS} & \begin{bmatrix} \textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix} \textbf{lexeme} \\ \text{ORTH } \textbf{"these"} \\ \text{CATEGORY } \textbf{det} \end{bmatrix} \end{bmatrix} \end{bmatrix} \sqcap \begin{bmatrix} \textbf{phrase} & \\ \text{CATEGORY } \textbf{np} & \\ \text{ARGS} & \begin{bmatrix} \textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix} \textbf{synsem-struc} \\ \text{CATEGORY } \textbf{det} \end{bmatrix} \\ \text{REST} & \begin{bmatrix} \textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix} \textbf{synsem-struc} \\ \text{CATEGORY } \textbf{n} \end{bmatrix} \\ \text{REST } \textbf{*null*} & \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

$$= \begin{bmatrix} \textbf{phrase} & \\ \text{CATEGORY } \textbf{np} & \\ \text{ARGS} & \begin{bmatrix} \textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix} \textbf{lexeme} \\ \text{ORTH } \textbf{"these"} \\ \text{CATEGORY } \textbf{det} \end{bmatrix} \\ \text{REST} & \begin{bmatrix} \textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix} \textbf{synsem-struc} \\ \text{CATEGORY } \textbf{n} \end{bmatrix} \\ \text{REST } \textbf{*null*} & \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

The result in this example is the feature structure we showed in 4.11. This is a partial structure which might be created in the course of parsing with the tiniest grammar, because it illustrates a partial application of the np rule to the lexical entry for *these*. Because the structure corresponding to the lexical entry has to go in the ARGS.FIRST position, the first argument to the unification is a sort of skeleton structure with the lexical structure at the end of the ARGS.FIRST path.

(14)
$$\left[\begin{array}{ll}\textbf{phrase} & \\ \text{CATEGORY }\textbf{np} & \\ \text{ARGS} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{FIRST} & \left[\begin{array}{l}\textbf{lexeme}\\ \text{ORTH }\textbf{”these”}\\ \text{CATEGORY }\textbf{det}\end{array}\right] \\ \text{REST} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{FIRST} & \left[\begin{array}{l}\textbf{synsem-struc}\\ \text{CATEGORY }\textbf{n}\end{array}\right] \\ \text{REST }\textbf{*null*} & \end{array}\right]\end{array}\right]\end{array}\right] \sqcap \left[\begin{array}{ll}\textbf{phrase} & \\ \text{ARGS} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{REST} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{FIRST} & \left[\begin{array}{l}\textbf{lexeme}\\ \text{ORTH }\textbf{”dogs”}\\ \text{CATEGORY }\textbf{n}\end{array}\right]\end{array}\right]\end{array}\right]\end{array}\right]$$

$$= \left[\begin{array}{ll}\textbf{phrase} & \\ \text{CATEGORY }\textbf{np} & \\ \text{ARGS} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{FIRST} & \left[\begin{array}{l}\textbf{lexeme}\\ \text{ORTH }\textbf{”these”}\\ \text{CATEGORY }\textbf{det}\end{array}\right] \\ \text{REST} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{FIRST} & \left[\begin{array}{l}\textbf{lexeme}\\ \text{ORTH }\textbf{”dogs”}\\ \text{CATEGORY }\textbf{n}\end{array}\right] \\ \text{REST }\textbf{*null*} & \end{array}\right]\end{array}\right]\end{array}\right]$$

Here we have taken the result from the previous example and unified it with a structure representing a second daughter for the rule, corresponding to the lexical entry for *dogs*. The result is a structure which is a complete representation of the phrase *these dogs*. At this point we must emphasize a crucial property of unification, which is that the result is independent of the order in which we combine the structures (i.e., more formally, unification is commutative and transitive). For instance, if we take the two daughter structures first, unify them together, and then unify them with the rule structure, the result will be identical to that above.

(15)
$$\left(\left[\begin{array}{ll}\textbf{phrase} & \\ \text{ARGS} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{FIRST} & \left[\begin{array}{l}\textbf{lexeme}\\ \text{ORTH }\textbf{”these”}\\ \text{CATEGORY }\textbf{det}\end{array}\right]\end{array}\right]\end{array}\right] \sqcap \left[\begin{array}{ll}\textbf{phrase} & \\ \text{ARGS} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{REST} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{FIRST} & \left[\begin{array}{l}\textbf{lexeme}\\ \text{ORTH }\textbf{”dogs”}\\ \text{CATEGORY }\textbf{n}\end{array}\right]\end{array}\right]\end{array}\right]\end{array}\right] \right)$$

$$\sqcap \left[\begin{array}{ll}\textbf{phrase} & \\ \text{CATEGORY }\textbf{np} & \\ \text{ARGS} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{FIRST} & \left[\begin{array}{l}\textbf{synsem-struc}\\ \text{CATEGORY }\textbf{det}\end{array}\right] \\ \text{REST} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{FIRST} & \left[\begin{array}{l}\textbf{synsem-struc}\\ \text{CATEGORY }\textbf{n}\end{array}\right] \\ \text{REST }\textbf{*null*} & \end{array}\right]\end{array}\right]\end{array}\right]$$

$$= \left[\begin{array}{ll}\textbf{phrase} & \\ \text{CATEGORY }\textbf{np} & \\ \text{ARGS} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{FIRST} & \left[\begin{array}{l}\textbf{lexeme}\\ \text{ORTH }\textbf{”these”}\\ \text{CATEGORY }\textbf{det}\end{array}\right] \\ \text{REST} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{FIRST} & \left[\begin{array}{l}\textbf{lexeme}\\ \text{ORTH }\textbf{”dogs”}\\ \text{CATEGORY }\textbf{n}\end{array}\right] \\ \text{REST }\textbf{*null*} & \end{array}\right]\end{array}\right]\end{array}\right]$$

The effect of this is that we can guarantee that different parsing strategies will always give the same result with a typed feature structure grammar (if the parsing process ever terminates and does not run into an infinite loop). However some strategies may be more efficient than others, since if unifying a set of structures results in failure, the process of determining this is quicker if the failures occur as one of the early unification steps.

(16) $$\left[\begin{array}{l}\textbf{t}\\ \text{F}\ \boxed{1}\ \textbf{*top*}\\ \text{G}\ \boxed{1}\end{array}\right] \sqcap \left[\begin{array}{l}\textbf{t}\\ \text{F}\left[\begin{array}{l}\textbf{u}\\ \text{J}\ \textbf{a}\end{array}\right]\\ \text{G}\left[\begin{array}{l}\textbf{u}\\ \text{J}\ \textbf{*top*}\\ \text{K}\ \textbf{b}\end{array}\right]\end{array}\right] = \left[\begin{array}{l}\textbf{t}\\ \text{F}\ \boxed{0}\left[\begin{array}{l}\textbf{u}\\ \text{J}\ \textbf{a}\\ \text{K}\ \textbf{b}\end{array}\right]\\ \text{G}\ \boxed{0}\end{array}\right]$$

This example involves reentrancy. (Again, we use abstract feature structures for simplicity and assume a flat type hierarchy, where **t**, **u**, **a** and **b** are all incompatible daughters of ***top***.) Note that the information on the reentrant node in the result all comes from the second structure: effectively the result of unification has been to combine two nodes which were distinct in the input structure.

(17) $$\left[\begin{array}{l}\textbf{t}\\ \text{F}\ \boxed{1}\ \textbf{*top*}\\ \text{G}\ \boxed{1}\end{array}\right] \sqcap \left[\begin{array}{l}\textbf{t}\\ \text{F}\left[\begin{array}{l}\textbf{u}\\ \text{J}\ \textbf{a}\end{array}\right]\\ \text{G}\left[\begin{array}{l}\textbf{u}\\ \text{J}\ \textbf{b}\\ \text{K}\ \textbf{b}\end{array}\right]\end{array}\right] = \perp$$

Here we modified the example above slightly, so that the value on G.J is **b** instead of **a**. Since **a** and **b** are incompatible, unification fails.

(18) $$\left[\begin{array}{l}\textbf{t}\\ \text{F}\left[\begin{array}{l}\textbf{u}\\ \text{G}\ \boxed{1}\end{array}\right]\\ \text{H}\ \boxed{1}\end{array}\right] \sqcap \left[\begin{array}{l}\textbf{t}\\ \text{F}\ \boxed{1}\\ \text{H}\ \boxed{1}\end{array}\right] = \perp$$

This unification results in failure because the result would be a cyclic structure. Note that cyclic structures are the only cases where unification failure can occur without incompatible types.

4.4.2 Exercises

These exercises involve more examples of unification. You could also try using the LKB system to investigate unification, by specifying entries, viewing the feature structures, and unifying the results according to the instructions in §7.3.1. Be warned, however, that if you do this you will probably find that some of the entries you specify get expanded with additional information because of the well-formedness conditions. For instance, if you write the following description:

```
ex1 := lexeme &
[ CATEGORY np ].
```

the structure displayed will be

$$\left[\begin{array}{l}\textbf{lexeme}\\ \text{ORTH}\ \textbf{string}\\ \text{CATEGORY}\ \textbf{np}\end{array}\right]$$

We will explain how this happens in detail in the next section.

1. Give the results of the following unifications, assuming that the types **t**, **u**, **a** and **b** are incompatible daughters of ***top***.

   (a) $$\left[\begin{array}{l}\textbf{t}\\ \text{F}\ \boxed{1}\ \textbf{a}\\ \text{G}\ \boxed{1}\end{array}\right] \sqcap \left[\begin{array}{l}\textbf{t}\\ \text{G}\ \textbf{b}\end{array}\right]$$

   (b) $$\left[\begin{array}{l}\textbf{t}\\ \text{F}\ \boxed{1}\\ \text{G}\ \boxed{1}\\ \text{H}\ \boxed{2}\\ \text{J}\ \boxed{2}\end{array}\right] \sqcap \left[\begin{array}{l}\textbf{t}\\ \text{F}\ \boxed{1}\\ \text{J}\ \boxed{1}\end{array}\right]$$

   (c) $$\left[\begin{array}{ll}\textbf{t} & \\ \text{F} & \left[\begin{array}{l}\textbf{u}\\ \text{G}\ \boxed{1}\end{array}\right]\\ \text{H}\ \boxed{1} & \end{array}\right] \sqcap \left[\begin{array}{ll}\textbf{t} & \\ \text{F}\ \boxed{2} & \\ \text{H} & \left[\begin{array}{l}\textbf{u}\\ \text{J}\ \boxed{2}\end{array}\right]\end{array}\right]$$

2. Consider the following example involving reentrancy:

$$\left[\begin{array}{l}\textbf{t}\\ \text{F}\ \boxed{1}\,\textbf{*top*}\\ \text{G}\ \boxed{1}\end{array}\right] \sqcap \left[\begin{array}{l}\textbf{t}\\ \text{F}\ \boxed{2}\,\textbf{a}\\ \text{H}\ \boxed{2}\end{array}\right] = \left[\begin{array}{l}\textbf{t}\\ \text{F}\ \boxed{3}\,\textbf{a}\\ \text{G}\ \boxed{3}\\ \text{H}\ \boxed{3}\end{array}\right]$$

   Write down the path-path and the path-value equivalences for each structure (assume the types **t** and **a** are immediate subtypes of ***top***). What can you say about the relationship between the set of equivalences for the result compared with those for the arguments to unification?

3. Assume the type hierarchy given for the grammar with agreement shown in Figure 4.14.

   (a) What is the result of the following:

$$\left[\begin{array}{ll}\textbf{phrase} & \\ \text{CATEGORY}\ \textbf{np} & \\ \text{NUMAGR}\ \boxed{1}\,\textbf{agr} & \\ \text{ARGS} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{FIRST} & \left[\begin{array}{l}\textbf{synsem-struc}\\ \text{CATEGORY}\ \textbf{det}\\ \text{NUMAGR}\ \boxed{1}\end{array}\right]\\ \text{REST} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{FIRST} & \left[\begin{array}{l}\textbf{synsem-struc}\\ \text{CATEGORY}\ \textbf{n}\\ \text{NUMAGR}\ \boxed{1}\end{array}\right]\\ \text{REST}\ \textbf{*null*} & \end{array}\right]\end{array}\right]\end{array}\right] \sqcap \left[\begin{array}{ll}\text{ARGS} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{FIRST} & \left[\begin{array}{l}\textbf{pl-lexeme}\\ \text{ORTH}\ \textbf{”these”}\\ \text{CATEGORY}\ \textbf{det}\\ \text{NUMAGR}\ \textbf{pl}\end{array}\right]\end{array}\right]\end{array}\right]$$

   (b) What happens when you unify the result obtained above with the following structure?

$$\left[\begin{array}{ll}\text{ARGS} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{REST} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{FIRST} & \left[\begin{array}{l}\textbf{pl-lexeme}\\ \text{ORTH}\ \textbf{”dogs”}\\ \text{CATEGORY}\ \textbf{n}\\ \text{NUMAGR}\ \textbf{pl}\end{array}\right]\end{array}\right]\end{array}\right]\end{array}\right]$$

   (c) What about this one?

$$\left[\begin{array}{ll}\text{ARGS} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{REST} & \left[\begin{array}{ll}\textbf{*ne-list*} & \\ \text{FIRST} & \left[\begin{array}{l}\textbf{lexeme}\\ \text{ORTH}\ \textbf{”dogs”}\\ \text{CATEGORY}\ \textbf{n}\\ \text{NUMAGR}\ \textbf{agr}\end{array}\right]\end{array}\right]\end{array}\right]\end{array}\right]$$

(d) And this?

$$\begin{bmatrix} \text{ARGS} & \begin{bmatrix} \textbf{*ne-list*} & \\ \text{REST} & \begin{bmatrix} \textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix} \textbf{sg-lexeme} \\ \text{ORTH } \textbf{"dog"} \\ \text{CATEGORY } \textbf{n} \\ \text{NUMAGR } \textbf{sg} \end{bmatrix} \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

4. Assume that **t** is an immediate daughter of ***top***. Consider the following structure:

$$\begin{bmatrix} \textbf{t} \\ \text{F } \boxed{1}\,\textbf{*top*} \\ \text{G } \boxed{1} \end{bmatrix}$$

How many structures are there which subsume it? Draw these structures in a subsumption hierarchy, with the most general structure at the top, the intermediate structures arranged in order of generality and the full structure at the bottom.

(Optional) Suppose we are told that

$$FS1 \sqcap FS2 = \begin{bmatrix} \textbf{t} \\ \text{F } \boxed{1}\,\textbf{*top*} \\ \text{G } \boxed{1} \end{bmatrix}$$

but we don't know the structures FS1 and FS2. How many different pairs of feature structures FS1 and FS2 satisfy the equation? Why might this sort of question be relevant to language processing?

4.4.3 Answers

1. (a) $\perp$

   (b) $\begin{bmatrix} \textbf{t} \\ \text{F } \boxed{1} \\ \text{G } \boxed{1} \\ \text{H } \boxed{1} \\ \text{J } \boxed{1} \end{bmatrix}$

   (c) $\perp$ (cyclic structure).

2. (a)

path	type
empty path	**t**
empty path	***top***
F	***top***
G	***top***

path	path
F	G

   (b)

path	type
empty path	**t**
empty path	***top***
F	***top***
F	**a**
H	***top***
H	**a**

path	path
F	H

(c)

path	type
empty path	**t**
empty path	***top***
F	***top***
F	**a**
G	***top***
G	**a**
H	***top***
H	**a**

path	path
F	G
F	H
G	H

The result contains all the equivalences from the arguments plus one extra path-value equivalence between G and **a** and one extra path-path equivalence between G and H. The extra pieces arise because of the reentrancy. In general, the path-value plus path-path equivalences for the feature structure which is the result of a successful unification are a superset of the union of those of the arguments.

3. (a)

$$\left[\begin{array}{ll}
\multicolumn{2}{l}{\textbf{phrase}}\\
\multicolumn{2}{l}{\text{CATEGORY } \textbf{np}}\\
\multicolumn{2}{l}{\text{NUMAGR } \boxed{1}\,\textbf{pl}}\\
\text{ARGS} & \left[\begin{array}{ll}
\multicolumn{2}{l}{\textbf{*ne-list*}}\\
\text{FIRST} & \left[\begin{array}{l}\textbf{pl-lexeme}\\ \text{ORTH } \textbf{"these"}\\ \text{CATEGORY } \textbf{det}\\ \text{NUMAGR } \boxed{1}\end{array}\right]\\
\text{REST} & \left[\begin{array}{ll}
\multicolumn{2}{l}{\textbf{*ne-list*}}\\
\text{FIRST} & \left[\begin{array}{l}\textbf{synsem-struc}\\ \text{CATEGORY } \textbf{n}\\ \text{NUMAGR } \boxed{1}\end{array}\right]\\
\multicolumn{2}{l}{\text{REST } \textbf{*null*}}
\end{array}\right]
\end{array}\right]
\end{array}\right]$$

(b)

$$\left[\begin{array}{ll}
\multicolumn{2}{l}{\textbf{phrase}}\\
\multicolumn{2}{l}{\text{CATEGORY } \textbf{np}}\\
\multicolumn{2}{l}{\text{NUMAGR } \boxed{1}\,\textbf{pl}}\\
\text{ARGS} & \left[\begin{array}{ll}
\multicolumn{2}{l}{\textbf{*ne-list*}}\\
\text{FIRST} & \left[\begin{array}{l}\textbf{pl-lexeme}\\ \text{ORTH } \textbf{"these"}\\ \text{CATEGORY } \textbf{det}\\ \text{NUMAGR } \boxed{1}\end{array}\right]\\
\text{REST} & \left[\begin{array}{ll}
\multicolumn{2}{l}{\textbf{*ne-list*}}\\
\text{FIRST} & \left[\begin{array}{l}\textbf{pl-lexeme}\\ \text{ORTH } \textbf{"dogs"}\\ \text{CATEGORY } \textbf{n}\\ \text{NUMAGR } \boxed{1}\end{array}\right]\\
\multicolumn{2}{l}{\text{REST } \textbf{*null*}}
\end{array}\right]
\end{array}\right]
\end{array}\right]$$

(c)

$$\left[\begin{array}{ll}
\multicolumn{2}{l}{\textbf{phrase}}\\
\multicolumn{2}{l}{\text{CATEGORY } \textbf{np}}\\
\multicolumn{2}{l}{\text{NUMAGR } \boxed{1}\,\textbf{pl}}\\
\text{ARGS} & \left[\begin{array}{ll}
\multicolumn{2}{l}{\textbf{*ne-list*}}\\
\text{FIRST} & \left[\begin{array}{l}\textbf{pl-lexeme}\\ \text{ORTH } \textbf{"these"}\\ \text{CATEGORY } \textbf{det}\\ \text{NUMAGR } \boxed{1}\end{array}\right]\\
\text{REST} & \left[\begin{array}{ll}
\multicolumn{2}{l}{\textbf{*ne-list*}}\\
\text{FIRST} & \left[\begin{array}{l}\textbf{lexeme}\\ \text{ORTH } \textbf{"dogs"}\\ \text{CATEGORY } \textbf{n}\\ \text{NUMAGR } \boxed{1}\end{array}\right]\\
\multicolumn{2}{l}{\text{REST } \textbf{*null*}}
\end{array}\right]
\end{array}\right]
\end{array}\right]$$

(d) $\perp$

As you have probably realized, this demonstrates how reentrancy ensures that the daughters

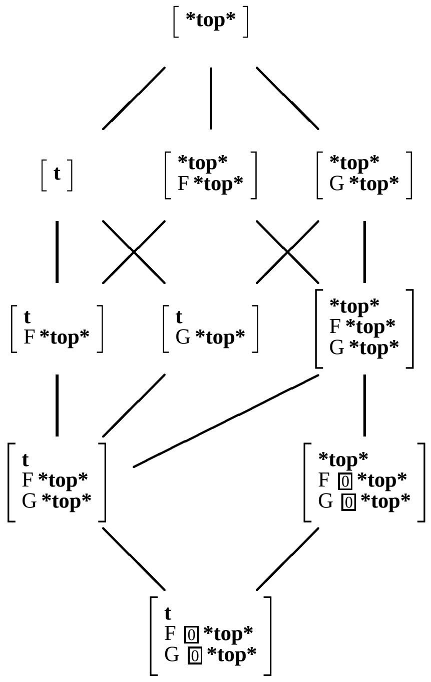


Figure 4.15: Subsumption hierarchy

of the np rule have consistent values for agreement. Note that when unification succeeds, the resulting phrase has a value for NUMAGR which is the unification of the values of NUMAGR on the daughters. This ensures that there is also agreement with the verb phrase. With respect to the last example, notice that the three feature structures which were unified were all pairwise compatible: it was only the combination of all three which fails. Thus the np rule itself works equally well for both singular and plural cases.

4. On the assumption that **t** is an immediate daughter of ***top***, there are 10 feature structures that subsume
$\begin{bmatrix} \textbf{t} \\ \text{F } \boxed{1}\,\textbf{*top*} \\ \text{G } \boxed{1} \end{bmatrix}$
(including the structure itself). These are shown in Figure 4.15. If you examine this hierarchy, you will see that any two feature structures always have a unique greatest lower bound, which is equal to their unification. You should also be able to see that every pair of structures has a unique lowest upper bound (lub). This corresponds to finding a feature structure which represents the pieces of information that common to both structures. This operation is called *generalisation* — it is currently relevant in the LKB only with respect to the treatment of defaults, which we are not going to discuss in this chapter.

   Answer to optional part: There are 14 possible pairs of structures (or 27 if you count ordered pairs) which can be combined to give this structure. We won't list them all here, but briefly go through the argument. We know the only structures that can be involved are those that subsume the full structure. We can consider each of these 10 possibilities for FS1 and see how many possible structures for FS2 there are in each case, ignoring any that duplicate those we have already found. If FS1 is the full structure, there are 10 possibilities for FS2. If FS1 is:

$$\left[\begin{array}{l}\textbf{*top*}\\ \text{F}\ \boxed{1}\,\textbf{*top*}\\ \text{G}\ \boxed{1}\end{array}\right]$$

there are 5 possibilities for FS2 (all the structures which specify that the root node is of type **t**), but one of these is the case where FS2 is the full structure, which is equivalent to a pair we have already considered. Of the other 8 possibilities for FS1, none contain any information about reentrancy, thus they must be combined with a reentrant structure, but we've already considered all these cases.

In general, if $F \sqcap G = H$, then we know that both F and G subsume (or are equal to) H, and that they mutually contain all the information in H, but we have no way of knowing which information is in which structure. There will be a finite number of possible candidate feature structure pairs (assuming H is a finite structure), but there could be a very large number of possibilities. Even if we also know F, we still cannot in general determine G, because while we know that it must contain all the information that is in H which is not in F, it may also contain some of the same information as F. The only exception to this is if F is the most general structure $\left[\,\textbf{*top*}\,\right]$, then G must be equal to H.

The relevance of this concerns processing strategies. While we can deterministically and efficiently unify two structures, we cannot, in general, reverse the operation efficiently. The claim is often made that unification-based grammars are *reversible*: what is meant by this is that they can be used for parsing and generation. To be accurate this statement has to be qualified in multiple ways — it certainly isn't true that all unification-based grammars are suitable for generation. But the point here is just that efficient grammar reversibility does not involve reversing unifications.

4.5 Type constraints and inheritance

We finally arrive at a detailed description of the operation of the type constraints. In the previous sections, we have been discussing feature structures in general, but now we want to concentrate on those which are well-formed with respect to a set of type constraints. Usually the feature structures corresponding directly to descriptions (e.g., of lexical entries) won't be well-formed: the process of inheriting/inferring information, which we've alluded to a couple of times informally so far, is precisely the process of making the structure well-formed. The primary purpose of type constraints as far as the grammar writer is concerned is that they can be used to allow generalisations to be expressed, so that lexical entries and other descriptions can be kept succinct. Their secondary purpose is to avoid errors creeping into a grammar, such as misspelt feature names.

In the LKB system, the constraint on a type is expressed as a typed feature structure. We will start off by defining well-formedness of feature structures in general with respect to a set of type constraints, and talk about how the system converts a non-well-formed structure to a well-formed one, via type inference. Then we'll look at how unification operates on well-formed feature structures. Finally we will describe the internal conditions on a set of type constraints, and discuss how the definitions of types we have seen in the examples so far (e.g. in Figure 4.4) give rise to the actual type constraints.

type	constraint	appropriate features
top	$\begin{bmatrix}\textbf{*top*}\end{bmatrix}$	
string	$\begin{bmatrix}\textbf{string}\end{bmatrix}$	
list	$\begin{bmatrix}\textbf{*list*}\end{bmatrix}$	
ne-list	$\begin{bmatrix}\textbf{*ne-list*}\\ \text{FIRST } \textbf{*top*}\\ \text{REST } \textbf{*list*}\end{bmatrix}$	FIRST REST
null	$\begin{bmatrix}\textbf{*null*}\end{bmatrix}$	
synsem-struc	$\begin{bmatrix}\textbf{synsem-struc}\\ \text{CATEGORY } \textbf{cat}\end{bmatrix}$	CATEGORY
cat	$\begin{bmatrix}\textbf{cat}\end{bmatrix}$	
s	$\begin{bmatrix}\textbf{s}\end{bmatrix}$	
np	$\begin{bmatrix}\textbf{np}\end{bmatrix}$	
vp	$\begin{bmatrix}\textbf{vp}\end{bmatrix}$	
det	$\begin{bmatrix}\textbf{det}\end{bmatrix}$	
n	$\begin{bmatrix}\textbf{n}\end{bmatrix}$	
phrase	$\begin{bmatrix}\textbf{phrase}\\ \text{CATEGORY } \textbf{cat}\\ \text{ARGS } \textbf{*list*}\end{bmatrix}$	CATEGORY ARGS
lexeme	$\begin{bmatrix}\textbf{lexeme}\\ \text{ORTH } \textbf{string}\\ \text{CATEGORY } \textbf{cat}\end{bmatrix}$	CATEGORY ORTH
root	$\begin{bmatrix}\textbf{root}\\ \text{CATEGORY } \textbf{s}\\ \text{ARGS } \textbf{*list*}\end{bmatrix}$	CATEGORY ARGS

Figure 4.16: Constraints and appropriate features for the tiny grammar

4.5.1 Well-formedness

First let's say that the *substructure*s of a feature structure are the feature structures rooted at each node in the structure. Then we can describe well-formedness in terms of conditions on each substructure. We'll also talk about the features which label arcs starting from the root node of a structure as the *top-level* features of a structure. The top-level features of a type constraint are referred to as the *appropriate features* for that type.

Properties of a well-formed feature structure

Constraint Each substructure of a well-formed feature structure must be subsumed by the constraint corresponding to the type on the substructure's root node.

Appropriate features The top-level features for each substructure of a well-formed feature structure must be the appropriate features of the type on the substructure's root node.

Figure 4.16 shows the full constraint and the appropriate features for all the types in the simplest grammar. Note that the constraints on some types, such as **phrase**, contain some information which was not in their description: this is because they have inherited information from types higher in the hierarchy, as we'll see in detail in §4.5.4.

Some types, such as **cat**, **n** and **vp** in the example grammar, have no appropriate features. This means that in any well-formed feature structure, they can only label terminal nodes. We refer to types which have no appropriate features and which have no descendants with appropriate features as *atomic* types. The type ***top*** has no appropriate features itself, but some of its descendants do, so it is not an atomic type.

The following examples are all well-formed typed feature structures given these type constraints (note that not all well-formed structures are sensible!):

1. $\left[\begin{array}{l}\textbf{phrase}\\ \text{CATEGORY } \textbf{s}\\ \text{ARGS } \textbf{*list*}\end{array}\right]$

2. $\left[\begin{array}{l}\textbf{lexeme}\\ \text{ORTH } \textbf{"on"}\\ \text{CATEGORY } \textbf{s}\end{array}\right]$

3. $\left[\begin{array}{l}\textbf{*ne-list*}\\ \text{FIRST } \boxed{1}\,\textbf{*list*}\\ \text{REST } \boxed{1}\end{array}\right]$

4. $\left[\begin{array}{ll}\multicolumn{2}{l}{\textbf{phrase}}\\ \multicolumn{2}{l}{\text{CATEGORY } \textbf{np}}\\ \text{ARGS} & \left[\begin{array}{ll}\multicolumn{2}{l}{\textbf{*ne-list*}}\\ \text{FIRST} & \left[\begin{array}{l}\textbf{lexeme}\\ \text{ORTH } \textbf{"these"}\\ \text{CATEGORY } \textbf{det}\end{array}\right]\\ \text{REST} & \left[\begin{array}{ll}\multicolumn{2}{l}{\textbf{*ne-list*}}\\ \text{FIRST} & \left[\begin{array}{l}\textbf{synsem-struc}\\ \text{CATEGORY } \textbf{n}\end{array}\right]\\ \multicolumn{2}{l}{\text{REST } \textbf{*null*}}\end{array}\right]\end{array}\right]\end{array}\right]$

The following examples are not well-formed and do not subsume well-formed structures:

1. $\left[\begin{array}{l}\textbf{phrase}\\ \text{CATEGORY } \textbf{lexeme}\\ \text{ARGS } \textbf{*list*}\end{array}\right]$
   Wrong type on CATEGORY.

2. $\left[\begin{array}{l}\textbf{synsem-struc}\\ \text{CATEGORY } \textbf{s}\\ \text{AGS } \textbf{*list*}\end{array}\right]$
   AGS is not an appropriate feature for **synsem-struc** (or for anything else).

3. $\left[\begin{array}{l}\textbf{synsem-struc}\\ \text{CATEGORY } \textbf{s}\\ \text{FIRST } \textbf{lexeme}\end{array}\right]$
   FIRST is not an appropriate feature for **synsem-struc**.

The following examples are not well-formed but they subsume well-formed structures which can be constructed by the type inference process which we will discuss below:

1. $\left[\begin{array}{l}\textbf{phrase}\\ \text{CATEGORY } \textbf{*top*}\\ \text{ARGS } \textbf{*list*}\end{array}\right]$
   Wrong type on CATEGORY, but it is compatible with a valid type.

2. $\left[\begin{array}{l}\textbf{synsem-struc}\\ \text{CATEGORY } \textbf{s}\\ \text{ARGS } \textbf{*list*}\end{array}\right]$
   ARGS is not an appropriate feature for **synsem-struc** but it is appropriate for **phrase** which is compatible with **synsem-struc**.

3. $\begin{bmatrix}\textbf{phrase}\\ \text{CATEGORY } \textbf{s}\end{bmatrix}$
   The ARGS feature is missing, so the constraint on **phrase** does not subsume this structure, but it is compatible with it.

Exercises on well-formedness

1. For each of the following, specify whether it is well-formed or not (assuming the constraints given in Figure 4.16). For the non-well-formed structures which subsume some well-formed structures, list the most general such well-formed structure.

   (a) $\begin{bmatrix}\textbf{*null*}\\ \text{FIRST } \textbf{synsem-struc}\end{bmatrix}$

   (b) $\begin{bmatrix}\textbf{*top*}\\ \text{FIRST } \textbf{synsem-struc}\end{bmatrix}$

   (c) $\begin{bmatrix}\textbf{*top*}\\ \text{REST } \begin{bmatrix}\text{REST } \textbf{*null*}\end{bmatrix}\end{bmatrix}$

   (d) $\begin{bmatrix}\textbf{*top*}\\ \text{CATEGORY } \boxed{0}\\ \text{ARGS } \begin{bmatrix}\text{REST } \boxed{0} \begin{bmatrix}\textbf{*top*}\\ \text{REST } \textbf{*top*}\end{bmatrix}\end{bmatrix}\end{bmatrix}$

2. Consider the subsumption hierarchy you constructed in the answers to the exercises in §4.4.2. Which of the structures are well-formed feature structures under the assumption that the type **t** is an immediate daughter of ***top***, and has the following constraint:
   $\begin{bmatrix}\textbf{t}\\ \text{F } \textbf{*top*}\\ \text{G } \textbf{*top*}\end{bmatrix}$

Answers to exercises on well-formedness

1. (a) not well formed — FIRST isn't an appropriate feature for ***null***.

   (b) not well formed, but subsumes:
   $\begin{bmatrix}\textbf{*ne-list*}\\ \text{FIRST } \begin{bmatrix}\textbf{synsem-struc}\\ \text{CATEGORY } \textbf{cat}\end{bmatrix}\\ \text{REST } \textbf{*list*}\end{bmatrix}$

   (c) not well formed, but subsumes:
   $\begin{bmatrix}\textbf{*ne-list*}\\ \text{FIRST } \textbf{*top*}\\ \text{REST } \begin{bmatrix}\textbf{*ne-list*}\\ \text{FIRST } \textbf{*top*}\\ \text{REST } \textbf{*null*}\end{bmatrix}\end{bmatrix}$

   (d) not well formed — CATEGORY's value must be of type **cat** but this node is reentrant with a node that must be of type ***ne-list***, which isn't compatible with **cat**.

2. The only well-formed structures are the following (shown in a subsumption hierarchy):

$$\begin{tikzcd}
\begin{bmatrix}\textbf{*top*}\end{bmatrix} \arrow[d, dash] \\
\begin{bmatrix}\textbf{t}\\ \text{F }\textbf{*top*}\\ \text{G }\textbf{*top*}\end{bmatrix} \arrow[d, dash] \\
\begin{bmatrix}\textbf{t}\\ \text{F }\boxed{0}\,\textbf{*top*}\\ \text{G }\boxed{0}\,\textbf{*top*}\end{bmatrix}
\end{tikzcd}$$

In general, we can talk about a subsumption hierarchy of well-formed feature structures, and define well-formed unification as determining the glb within that hierarchy.

4.5.2 Type inference

Type inference takes a non-well-formed typed feature structure and returns the most general well-formed structure which it subsumes. Thus it always preserves the information in the initial structure. It is always possible to find a unique most general well-formed structure from a non-well-formed structure if the latter subsumes any well-formed structures. The LKB system carries out type inference on all entries. It is an error to define an entry which cannot be converted into a well-formed feature structure.

The first part of type inference consists of specialising the types on each node in the structure to the most general type for which all the node's features are appropriate. For instance, in the following structure, ARGS is not an appropriate feature for **synsem-struc** but it is appropriate for **phrase**, which is a subtype of **synsem-struc**.

(19) $$\begin{bmatrix}\textbf{synsem-struc}\\ \text{CATEGORY }\textbf{s}\\ \text{ARGS }\textbf{*top*}\end{bmatrix}$$

The result is therefore

(20) $$\begin{bmatrix}\textbf{phrase}\\ \text{CATEGORY }\textbf{s}\\ \text{ARGS }\textbf{*top*}\end{bmatrix}$$

Both ARGS and CATEGORY are also appropriate for the type **root** but this is a subtype of **phrase**. If the initial structure had been:

(21) $$\begin{bmatrix}\textbf{*top*}\\ \text{CATEGORY }\textbf{s}\\ \text{FIRST }\textbf{lexeme}\end{bmatrix}$$

we could not have found a possible type, because there are no types for which both CATEGORY and FIRST are appropriate. If it had been:

(22) $$\begin{bmatrix}\textbf{*list*}\\ \text{CATEGORY }\textbf{s}\end{bmatrix}$$

we also could not have found a possible type, because although CATEGORY is an appropriate feature for **synsem-struc**, this is not a subtype of ***list***. There is a condition on how features are introduced in the type constraints that guarantees there will always be a unique most general type for any set of features if that set of features is appropriate for any types. We will discuss this in §4.5.4.

The second stage in type inference consists of ensuring that all nodes are subsumed by their respective type constraints. This involves unifying each node with the constraint of the type on each node (using well-formed unification, described below in §4.5.3). So from

(23) $$\begin{bmatrix}\textbf{phrase}\\ \text{CATEGORY } \textbf{s}\\ \text{ARGS } \textbf{*top*}\end{bmatrix}$$

we obtain

(24) $$\begin{bmatrix}\textbf{phrase}\\ \text{CATEGORY } \textbf{s}\\ \text{ARGS } \textbf{*list*}\end{bmatrix}$$

Type inference may also fail at this point. For instance, given the structure:

(25) $$\begin{bmatrix}\textbf{phrase}\\ \text{CATEGORY } \textbf{*list*}\\ \text{ARGS } \textbf{*top*}\end{bmatrix}$$

we find that the type on CATEGORY ***list*** is inconsistent with the constraint on **phrase**, which stipulates that the value of CATEGORY must be the type **cat**.

4.5.3 Unification revisited

We want unification of well-formed feature structures to give a well-formed result. We can achieve this by giving a definition of the unification of well-formed feature structures which parallels unification of typed feature structures in general.

Properties of well-formed unification The well-formed unification of two typed feature structures F and G is the most general well-formed typed feature structure which is subsumed by both F and G, if it exists.

This makes sense because we can talk about a subsumption hierarchy of well-formed typed feature structures which is a subpart of the hierarchy of typed feature structures in general. In most cases, this gives exactly the same result as we've seen from unification previously. However, there is a complication which arises only in some cases where there is multiple inheritance, specifically when there is a constraint on a glb type which is more specific than the constraints of the two ancestor types.

To illustrate this, consider the corrected animal hierarchy shown in Figure 4.9, and suppose it also contains the type **boolean**, as a daughter of ***top***, and **true** and **false** inheriting from **boolean**. Suppose that the constraint on the type **swimmer** is
$\begin{bmatrix}\textbf{swimmer}\\ \text{FINS } \textbf{boolean}\end{bmatrix}$ the constraint on **mammal** is
$\begin{bmatrix}\textbf{mammal}\\ \text{FRIENDLY } \textbf{boolean}\end{bmatrix}$
and the constraint on **whale** is

$$\begin{bmatrix}\textbf{whale}\\ \text{HARPOONED } \textbf{boolean}\\ \text{FINS } \textbf{true}\\ \text{FRIENDLY } \textbf{boolean}\end{bmatrix}$$

Consider what happens when we unify the following feature structures (both of which are well-formed):

$$\begin{bmatrix}\textbf{mammal}\\ \text{FRIENDLY } \textbf{true}\end{bmatrix} \sqcap_{wf} \begin{bmatrix}\textbf{swimmer}\\ \text{FINS } \textbf{boolean}\end{bmatrix}$$

If we ignored the requirement for well-formedness, the result would be:

$$\begin{bmatrix}\textbf{whale}\\ \text{FINS } \textbf{boolean}\\ \text{FRIENDLY } \textbf{true}\end{bmatrix}$$

but this isn't well-formed — it lacks the feature HARPOONED, and the value of FINS isn't **true**. To get a well-formed feature structure, we also have to add the constraint information on **whale**, to get:

$$\begin{bmatrix}\textbf{whale}\\ \text{HARPOONED } \textbf{boolean}\\ \text{FINS } \textbf{true}\\ \text{FRIENDLY } \textbf{true}\end{bmatrix}$$

This result is the most general well-formed structure that contains all the information in the structures being unified, but of course it also contains additional information, derived from the type system.

If the constraint on the glb type is inconsistent with the given information, unification fails. For instance:

$$\begin{bmatrix}\textbf{mammal}\\ \text{FRIENDLY } \textbf{true}\end{bmatrix} \sqcap_{wf} \begin{bmatrix}\textbf{swimmer}\\ \text{FINS } \textbf{false}\end{bmatrix} = \perp$$

From now on, when we talk about unification of well-formed structures, we'll always be referring to this operation.

4.5.4 Conditions on type constraints

The final part of the description of the typed feature structure formalism concerns the construction of the full type constraints from the descriptions and the conditions on the type constraints. This will show precisely how we get from the descriptions shown in Figure 4.4 to the constraints shown in Figure 4.16. We will refer to the feature structures which are directly specified in the descriptions as the *local constraints*. There are a series of conditions on full type constraints which determine how the local constraints are expanded into the full constraints.

Properties of type constraints

Type The type of the feature structure expressing the constraint on a type is always that type.

Consistent inheritance The constraint on a type must be subsumed by the constraints on all its parents. This means that any local constraint specification must be compatible with the inherited information, and that in the case of multiple inheritance, the parents' constraints must unify.

Maximal introduction of features Any feature must be introduced at a single point in the hierarchy. That is, if a feature, F, is an appropriate feature for some type, t, and not an appropriate feature for any of its ancestors, then F cannot be appropriate for a type which is not a descendant of t. Note that the consistent inheritance condition guarantees that the feature will be appropriate for all descendants of t.

Well-formedness of constraints All full constraint feature structures must be well-formed as described in §4.5.1.

You should check Figure 4.16 and Figure 4.4 to make sure you follow how this applies to the tiny grammar.

Although the constraints in the grammars we've been looking at are all very simple, constraints can in general be arbitrarily complex feature structures. For instance, taking the version of the grammar with agreement, shown in Figure 4.14, we could have simplified the description of the rules that was given there by making them inherit from a subtype of **phrase** with the following description:

(26)
```
agr-phrase := phrase &
[ NUMAGR #1,
  ARGS [ FIRST [ NUMAGR #1 ],
         REST [ FIRST [  NUMAGR #1 ],
                REST *null* ]]] .
```

There is one non-obvious consequence of the conditions on type constraints, which is that they disallow type descriptions such as the following:

(27)
```
list := *top* &
[ FIRST *top*,
  REST list ].
```

The reason is that this description would have to result in an infinite constraint structure when we tried to make it well-formed. That is, it would be expanded so that the feature structure which is the value of REST would have features FIRST and REST and that value of REST would be of type **list** which would be expanded in the same way, and so on. The solution to this problem is to define lists in the way we've done in the example grammars, so that there are distinct subtypes for empty and non-empty lists, with the latter having no appropriate features.

4.5.5 Exercises

1. What would be the full constraint on **agr-phrase** if it was defined as shown in (26)? What would the revised entry for `s_rule` look like?

2. Considering the corrected animal hierarchy, Figure 4.9, augmented as described in §4.5.3. Write type definitions which would result in the full constraints described. Is it necessary that there be any local constraint on **whale**?

3. Suppose I change the definition of **phrase** in the tiniest grammar to:

```
phrase := synsem-struc &
[ ORTH *top*,
  ARGS *list* ].
```

What else would I have to do to the type system to keep it valid?

4.5.6 Answers

1. The full constraint would be the following:

$$\begin{bmatrix} \textbf{agr-phrase} & \\ \text{CATEGORY } \textbf{cat} & \\ \text{NUMAGR } \boxed{1}\ \textbf{agr} & \\ \text{ARGS} & \begin{bmatrix} \textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix} \textbf{synsem-struc} \\ \text{CATEGORY } \textbf{cat} \\ \text{NUMAGR } \boxed{1} \end{bmatrix} \\ \text{REST} & \begin{bmatrix} \textbf{*ne-list*} & \\ \text{FIRST} & \begin{bmatrix} \textbf{synsem-struc} \\ \text{CATEGORY } \textbf{cat} \\ \text{NUMAGR } \boxed{1} \end{bmatrix} \\ \text{REST } \textbf{*null*} & \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

   The revised entry for `s_rule` would be:

```
s_rule := phrase &
[ CATEGORY s,
  ARGS [ FIRST [ CATEGORY np ],
         REST [ FIRST [ CATEGORY vp ]]]].
```

2. One possible set of constraint definitions is:

```
swimmer := animal &
[ FINS boolean ].

vertebrate := animal &
[ FRIENDLY boolean ].

vertebrate-swimmer := vertebrate &
[ HARPOONED boolean,
  FINS true ].
```

   so there need be no local constraint on **whale**.

3. ORTH would also have to be added to the type **synsem-struc** so it was only introduced in one place.

4.6 Grammar rules, lexical entries and parsing

We have now completed the description of the typed feature structure formalism. At least in principle, typed feature structures could be used to model things other than linguistic entities, but since our interest is in grammar modelling, we now turn to describing how parsing works. We will concentrate on parsing, since talking about generation really requires that we talk about semantic representation, and we don't want to go into that here.

For the parser to work, in addition to the grammar it just needs two extra pieces of information, which in the LKB are specified in the globals and user-fns files:

1. The location of orthographic information in lexical structures (here the feature ORTH). This is needed so the system can go from an input string to a set of lexical structures.

2. The location of the daughters and the mother structure in grammar rules. In the grammars we have looked at, the daughters are the elements of the ARGS list and the mother is the entire structure. The application of a grammar rule can then be implemented by unification, in the way that we saw in §4.4.2.

The normal assumption is that the input to the parser is a string which can be regarded as a list of word strings. For instance *this dog sleeps* is treated as `‘‘this’’ ‘‘dog’’ sleeps’’`. We want to define parsing itself as an operation on typed feature structures, so we have to assume that there is an initial lexical lookup phase, where the system goes from this list of words strings to a list of sets of lexical structures. We have to think about sets of lexical structures because of lexical ambiguity: a valid parse is going to involve exactly one structure from each set. For the tiniest grammar, we simply assume that the word strings are delimited by spaces, and that a structure corresponding to a lexical entry is added to the set for a word string if the value of its ORTH feature matches the string. In realistic grammars, lexical lookup is complicated by morphology and *multiword entries*, but we will ignore that here. The list of sets of (well-formed) typed feature structures found for `"this" "dog" "sleeps"` in the initial grammar is shown below (note there is no lexical ambiguity).

$$\left\{\begin{bmatrix}\textbf{lexeme}\\ \text{ORTH }\textbf{"this"}\\ \text{CATEGORY }\textbf{det}\end{bmatrix}\right\}, \left\{\begin{bmatrix}\textbf{lexeme}\\ \text{ORTH }\textbf{"dog"}\\ \text{CATEGORY }\textbf{n}\end{bmatrix}\right\}, \left\{\begin{bmatrix}\textbf{lexeme}\\ \text{ORTH }\textbf{"sleeps"}\\ \text{CATEGORY }\textbf{vp}\end{bmatrix}\right\}$$

We will also assume that each phrase is associated with a string which is formed by concatenating the strings associated with its daughters in a fixed order (which in this grammar corresponds to the order of the elements on the ARGS list of the rule). This is one of the assumptions we made without much discussion at the beginning of the chapter, although it's not, in general, a necessary assumption for grammar writing with typed feature structures. However, since the parser supplied with the LKB depends on this condition for its operation, we will continue to assume it here. We'll see at the end of the chapter that we can actually implement this condition in the grammar rules.

So, at the start of parsing we have a list of sets of lexical structures, with associated strings, and an initial structure, which is a typed feature structure corresponding to the start symbol. The string associated with the initial structure corresponds to the string for the complete sentence. So in this case the structure plus string is:

$$\begin{bmatrix}\textbf{root}\\ \text{CATEGORY }\textbf{s}\\ \text{ARGS }\textbf{*list*}\end{bmatrix}$$

```
"this" "dog" "sleeps"
```

Parsing then essentially involves throwing in as many structures corresponding to grammar rules as are needed to link the lexical structures to the initial structure. To make this a little more

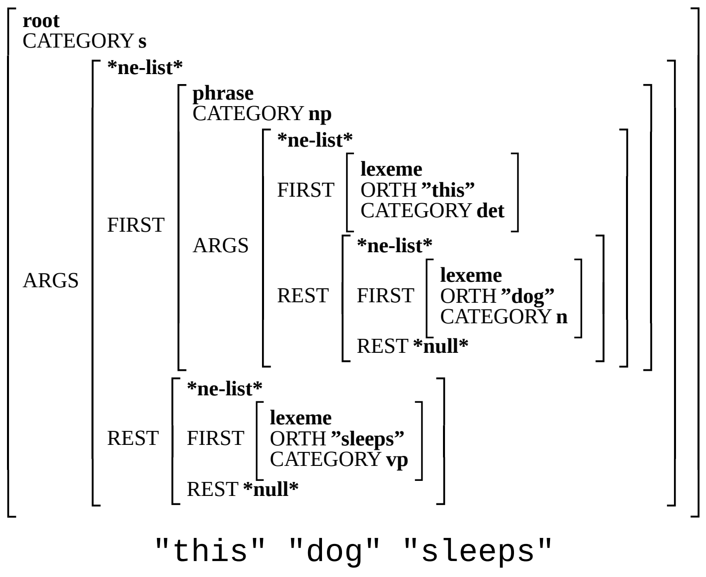


Figure 4.17: Complete structure for a sentence with associated string

precise, let us say that a *valid link* is a well-formed typed feature structure which is subsumed by a grammar rule and which has structures in the daughter positions which are each either subsumed by a member of the set of lexical structures or are themselves valid links. We then count as a solution any valid link which is also subsumed by the initial structure and which has the same string as it does (i.e., the string for the sentence).[6]

For the example we've been using, there is only one valid link, shown as Figure 4.17. It corresponds to the application of the `s_rule` and the `np_rule`.

Although formally parsing in the LKB corresponds to the description given above, for practical purposes we need something rather more efficient. The approach used is known as *chart parsing*, where the *chart* is the data structure which records the partial results, known as *edges*. Edges correspond to phrases with their associated string. In the case of the LKB, processing proceeds *bottom-up*. This means the parser initially combines lexical structures to form phrases, and then combines these phrases with one another, or with other lexical structures. The information embodied in the initial structure is not checked till the end. We will not go through chart parsing in detail here, but if you open a window showing the chart in the LKB, you will see all the edges that are constructed during an attempt to parse a string.

4.7 The description language

For completeness, we should make a few remarks about the description language. The purpose of the description language is, of course, to allow the grammar designer to write definitions of types and of feature structures in a way which is readable by a machine. The same grammar could be described using different description languages. As discussed so far, the description language almost

[6]This statement gets more complex if the mothers of rules are not the complete structures, but nothing essential changes.

looks like just an ASCIIised version of the AVM syntax. However, description languages generally allow various abbreviations — for instance, we can encode lists without explicitly mentioning FIRST and REST. For instance, the following two descriptions are equivalent:

```
example := phrase &
[ CATEGORY np,
  ARGS  < lexeme &
          [ ORTH "these",
            CATEGORY det ],
          synsem-struc &
          [ CATEGORY n ] > ].

example := phrase &
[ CATEGORY np,
  ARGS  *ne-list* &
        [ FIRST lexeme &
                [ ORTH "these",
                  CATEGORY det ],
          REST  *ne-list* &
                [ FIRST synsem-struc &
                        [ CATEGORY n ],
                  REST *null* ]]] .
```

However a valid feature structure description always results in a single typed feature structure.

We think that it's not really useful to try and give a non-formal account of the description language used in the LKB which explains exactly where to put the &'s etc. The section on the description language in Chapter 5 (§5.3) goes through a series of examples which you may find useful, but most people find it easiest to proceed by modifying existing examples. You may find the discussion of the error messages in Chapter 6 is helpful.

One thing we would like to make sure is clear is the distinction between the definitions of types and everything else (i.e., what we've been calling the entries). The type definitions package together two distinct pieces of information: the location of the type in the hierarchy, and the definition of the constraint on that type. So the following description of the type **a**:

```
a := b & c.
```

is read as stating that the type **a** is a lower bound of **b** and **c** in the hierarchy. Elsewhere in the description language, & can be read as effectively equivalent to unification, but here it must be read as an operation on the type hierarchy. It follows from this definition that the constraint on **a** will be the unification of the constraints on **b** and **c**, but as we've seen we need to know what the type hierarchy is before we can talk about unification, so the statement about the hierarchy is logically prior.

Note that the same description used in an entry (e.g., in the description of a lexical entry or grammar rule) must be read quite differently. In this context, it means that the feature structure named `a` is the unification of the feature structures $[\,\mathbf{b}\,]$ and $[\,\mathbf{c}\,]$. [7] Since this is only valid if there

[7] If you read Chapter 5, you will notice that we overload the same operator there so it stands for both unification and greatest-lower bound (join) in the type hierarchy. In that context, however, there is no ambiguity as to whether we

is some type **d** which is the greatest lower bound of **b** and **c**, it isn't usual to write descriptions of entries like this, since it's clearer to simply write:

```
a := d.
```

4.8 Some grammar engineering techniques

This section will probably be expanded at some future date.

The types ***top***, **string**, ***list***, ***null*** and ***ne-list*** are ones we will see over and over again in different grammars. And as we have mentioned, the method of encoding rules with the feature ARGS is used in several grammars. But the grammars in this chapter are not to be taken as examples of linguistically good grammar design. So this final section in this chapter is simply structured as a series of examples which introduce various encoding techniques. You may find it useful to go through these before going back to working with a more linguistically interesting grammar, such as the toy grammar.

4.8.1 Encoding information with types vs with features

You may have started to wonder what the criteria are for encoding information with types or with features. In some cases, they are more or less interchangeable, and the choice made by a particular grammar writer may be more or less a matter of aesthetics. But in a lot of cases there is a distinct formal difference. We will illustrate this by going back to the agreement example.

The reason that the simple agreement example works out more nicely with typed feature structures than with the atomic category grammar is because of the use of features to encode agreement, because that allows the specification of reentrancy between parts of the structure. If we had used subtypes of category instead, there would have been little advantage over the atomic category version, because we could not have encoded the fact that we want the structures to match on agreement, but not on nouniness or verbiness, for instance. So features are used when we needs to use reentrancy.

In the agreement example, we only considered number agreement. Of course, person is also relevant. One way of encoding this would have been to use a feature AGR instead of NUMAGR which takes the type **pernum** and to have NUM and PER as appropriate features for **pernum**. For instance:

$$\begin{bmatrix}\textbf{agr}\\ \text{PER }\textbf{3rd}\\ \text{NUM }\textbf{sg}\end{bmatrix}$$

We can then stipulate the reentrancy between the value of AGR on verbs and their subjects for instance, and ensure that they are consistent with respect to both number and person.

However, although this encoding has frequently been used, it may not be the most perpicuous way to treat agreement in English. The problem is that for most English verbs, the distinction in morphological form is between third person singular forms and everything else. While we can represent third person singular simply enough, as above, expressing the generalisation 'everything

are referring to types or feature structures. Unfortunately the description language we're using does not distinguish between a type, **t**, and the feature structure consisting of a single node labelled with that type, which we write as $\begin{bmatrix}\textbf{t}\end{bmatrix}$ in the AVM notation. This means that a syntactically identical description is understood quite differently if it is the description of a type as opposed to the description of an entry. QWERTY keyboards again.

else', is not so easy.[8] With the LKB system, we could do this by making use of the type hierarchy, so that **pernum** has subtypes **3sg** and **non3sg**, where **3sg** has the constraint shown above, and all the other combinations are represented as subcases of **non3sg**. This is shown below (we have omitted the definition of the types **per** and **num** and their subtypes).

```
pernum := *top* &
[ PER per,
  NUM num ].

non3sg := pernum.

1sg := non3sg &
[ PER 1st,
  NUM sg ].

1pl := non3sg &
[ PER 1st,
  NUM pl ].

2sg := non3sg &
[ PER 2cd,
  NUM sg ].

2pl := non3sg &
[ PER 2cd,
  NUM pl ].

3sg := pernum &
[ PER 3rd,
  NUM sg ].

3pl := non3sg &
[ PER 3rd,
  NUM pl ].
```

This sort of encoding is used in the toy grammar. However it still isn't very elegant because nothing blocks the following structure:

(28) $$\begin{bmatrix} \textbf{non3sg} \\ \text{PER } \textbf{3rd} \\ \text{NUM } \textbf{sg} \end{bmatrix}$$

[8]One option is to add negation to the formalism, and indeed this has been done with some variants of constraint-based formalisms, but it turns out to have lots of formal consequences that we find unpleasant. Rather than go through the formal issues here, we will simply observe that we in general take the position that the formalism should only be expanded when there's a real gain in expressiveness and naturalness for a reasonable number of linguistic examples, and negation on our view fails this test, since it's unusual to find examples of its use in the literature other than the 'not third person singular' case . . .

The reason for this is that the notion of well-formedness used in the LKB is actually quite weak and it does not preclude a feature structure of a type **t** being well-formed even if it is not compatible with any of the subtypes of **t**.[9]

At this point, however, we have now almost duplicated the feature information in the type hierarchy and we should ask ourselves what the justification is for the use of the features PER and NUM. If you look at the toy grammar and its successors in the LKB data files, you will discover that there is never a case where the grammar uses reentrancies between number information separately from person information. If there is no reason in the grammar to make these pieces of information be independently accessible, we can simply drop that part of the structure, and use a hierarchy of atomic types instead, as shown below.

```
pernum := *top*.
non3sg := pernum.
1sg := non3sg.
1pl := non3sg.
2sg := non3sg.
2pl := non3sg.
3sg := pernum.
3pl := non3sg.
```

We have thus removed the problem of the inconvenient feature structure shown in (28), but the expedient of removing the internal structure. A somewhat more complicated version of this hierarchy is in fact used in the large-scale English resource grammar.

4.8.2 Difference lists

Suppose we added the following type to the type system in Figure 4.4:

```
*diff-list* := *top* &
 [ LIST *list*,
   LAST *list* ].
```

and redefined **synsem-struc**, **lexeme** and **phrase** as follows:

```
synsem-struc := *top* &
[ ORTH *diff-list*,
  CATEGORY cat ].

phrase :=  synsem-struc &
 [ ORTH [ LIST #first,
          LAST #last ],
   ARGS [ FIRST [ ORTH [ LIST #first,
                         LAST #middle ] ],
```

[9]Again, there are feature structure formalisms in which this could be ruled out, but there's a potentially high cost in computational efficiency.

```
          REST [ FIRST [ ORTH [ LIST #middle,
                                LAST #last ]]]]].
lexeme := synsem-struc &
[ ORTH [ LIST [ FIRST string,
                REST #end ],
         LAST #end ]].
```

We also would have to redefine the lexical entries so their orthography goes in the right place, for instance:

```
this := lexeme &
[ ORTH [ LIST [ FIRST "this"]],
  CATEGORY det ].
```

A grammar with these modifications is in the directory `difflist`. Experiment with parsing some sentences and look at the values for the ORTH of the phrases.

Structures like these, where a pointer is maintained to the end of the list (the LAST feature), are known as *difference lists*. They have a special abbreviation in the description language, for instance:

```
this := lexeme &
[ ORTH <! "this" !>,
  CATEGORY det ].
```

They can be used in general in grammars as a way of appending lists simply using unification. The way we have used them here, to allow the orthography to be built up on phrases, means that the grammar itself encodes the way that phrases correspond to strings. If we make the assumption that the feature structures themselves encode orthography, the description of parsing that we gave in §6.7 can be made general enough to include grammars which do not make the assumptions about word order and concatenation that we started off with. But we won't explore this further here, since the LKB chart parser builds in these assumptions.

With this last piece of notation, we have covered everything that you need to know to understand the full details of the `esslli/toy` grammar we used in the previous chapter, and most of what is needed to understand the more complex grammars. One way of proceeding would be to attempt the exercises used in teaching the ESSLLI course which are in `data/esslli/exercises`. Grammars which embody answers to the exercises are in `data/esslli/enddayone` etc.

Chapter 5

Feature structures and types in the LKB system

This chapter contains a (fairly) formal description of the notion of feature structures and types used in the LKB system.[1] It also defines the description language used in the TDL compatibility mode. The following chapter gives details of how the descriptions are evaluated and checked by the system, including error messages and so on.

It is intended to be comprehensible to someone who has a knowledge of feature structures, as used in PATR, for instance, and some formal background. The LKB system uses typed feature structures, but we start off by giving definitions for untyped feature structures, since the typed feature structure definitions will build on these.

5.1 Untyped feature structures

In this section we briefly recapitulate some of the basic definitions of untyped feature structures, including subsumption, unification and generalisation. We will use a notation in which more specific entities (feature structures and, later on, types) are uniformly described as being lower in some hierarchy. (This is the opposite direction to that used by Shieber (1986) and Carpenter (1992).)

A feature structure is either basic, in which case it must be an *atomic value*, or it is complex, in which case it provides values for one or more *feature*s. These values in turn are either atomic or complex feature structures. The set Feat of features and set Atom of atomic values are assumed to be finite. Feature structures can be defined in terms of labelled finite-state automata following Kasper and Rounds (1986, 1990). The version of the definitions given here follows Carpenter (1993).

Definition 1 (Feature Structure) *A feature structure is a tuple* $F = \langle Q, q_0, \delta, \alpha \rangle$ *where:*

- Q*: a finite set of nodes*
- $q_0 \in Q$*: the root node*
- $\delta : \mathsf{Feat} \times Q \to Q$ *: the partial feature value function (transition function)*

[1]This chapter is based on earlier documents, in particular Copestake (1993). Defaults are not discussed here, see §8.10.

- $\alpha : Q \rightarrow \mathsf{Atom}$ *: the partial atomic value function*

with the following constraints:

Connectedness *There must be some* path *from the root to every node.*
Paths are defined as sequences of zero or more features. Let $\mathsf{Path} = \mathsf{Feat}^*$ *and* ϵ *be the empty path. The definition of the transition function can be extended to paths by taking* $\delta(\epsilon, q) = q$ *and* $\delta(f \cdot \pi, q) = \delta(\pi, \delta(f, q))$. *Then the connectedness condition can be expressed as stating that there must be a path* π *such that* $q = \delta(\pi, q_0)$ *for all* $q \in Q$

Atomic values *Only nodes without features can be atomic values, so that if* $\alpha(q)$ *is defined then* $\delta(f, q)$ *is undefined for every* $f \in \mathsf{Feat}$ (But note that some nodes without features may not have values.)

Acyclicity *The resulting graph is acyclic in that there is no path* π *and non-empty path* π' *such that* $\delta(\pi, q_0) = \delta(\pi \cdot \pi', q_0)$.
(Although it is not formally necessary to rule out cycles in untyped or typed feature structures, doing so makes some definitions simpler and the implementation more straightforward and efficient.)

5.1.1 Subsumption

Feature structures can be regarded as being ordered by information content — a feature structure is said to *subsume* another if the latter carries extra information. Subsumption can be formalised by assuming that a pair of sets is associated with each feature structure which determine the path equivalences that hold and the atomic values assigned to paths. Let $\equiv_F$ be the equivalence relation induced between paths by the structure sharing in F and $\mathcal{P}_F$ be the partial function induced by F which maps paths in F to atomic values.

Definition 2 (Abstract Feature Structure) *If* $F = \langle Q, q_0, \delta, \alpha \rangle$ *is a feature structure, we let* $\equiv_F \subseteq \mathsf{Path} \times \mathsf{Path}$ *and* $\mathcal{P}_F : \mathsf{Path} \rightarrow \mathsf{Atom}$ *be such that:*

- *(Path Equivalence)*
  $\pi \equiv_F \pi'$ *if and only if* $\delta(\pi, q_0) = \delta(\pi', q_0)$

- *(Path Value)*
  $\mathcal{P}_F(\pi) = \sigma$ *if and only if* $\alpha(\delta(\pi, q_0)) = \sigma$.

The pair $\langle \mathcal{P}, \equiv_F \rangle$ *is called the abstract feature structure corresponding to* F.

A feature structure F subsumes another feature structure F' if and only if the information in F is contained in the information in F'; that is, if F' provides at least as much information about path values and structure sharing as F. The abstract feature structure corresponding to F is sufficient to determine its information content and thus subsumption.

Definition 3 (Subsumption) *F subsumes F', written* $F' \sqsubseteq F$, *iff:*

- *if* $\pi \equiv_F \pi'$ *then* $\pi \equiv_{F'} \pi'$

- *if $\mathcal{P}_F(\pi) = \sigma$ then $\mathcal{P}_{F'}(\pi) = \sigma$*

Thus F subsumes F' if and only if every piece of information in F is contained in F'. For un-typed feature structures, $\top$ is defined to be the single node feature structure with no atomic value assigned. Thus $\pi \equiv_\top \pi'$ if and only if $\pi = \pi' = \epsilon$ and $\mathcal{P}(F)$ is undefined everywhere. Note that $F \sqsubseteq \top$ for every feature structure F. $\top$ is used in attribute-value matrices to denote the lack of any known value.

5.1.2 Unification

Unification corresponds to conjunction of information, and thus can be defined in terms of subsumption, which is a relation of information containment. The unification of two feature structures is defined to be the most general feature structure which contains all the information in both of the feature structures.

Definition 4 (Unification) *The unification $F \sqcap F'$ of two feature structures F and F' is taken to be the greatest lower bound of F and F' in the collection of feature structures ordered by subsumption.*

Thus $F \sqcap F' = F''$ if and only if $F'' \sqsubseteq F$, $F'' \sqsubseteq F'$ and for every F''' such that $F''' \sqsubseteq F$ and $F''' \sqsubseteq F'$ it is also the case that $F''' \sqsubseteq F''$.

5.1.3 Generalisation

Generalisation is the opposite of unification in which the lowest upper bound of two feature structures is taken. The generalisation of two feature structures is defined to be the most specific feature structure which contains only information found in both feature structures.

Definition 5 (Generalisation) *The generalisation $F \sqcup F'$ of two feature structures is defined to be their greatest lower bound in the subsumption ordering.*

Thus $F \sqcup F' = F''$ if and only if $F \sqsubseteq F''$, $F' \sqsubseteq F''$ and for every F''' such that $F \sqsubseteq F'''$ and $F' \sqsubseteq F'''$ then $F'' \sqsubseteq F'''$. Although unification corresponds to conjunction, generalisation does not correspond to disjunction but is more like information intersection. In systems which support it, disjunction of feature structures will give a result which is either more specific than that produced by generalisation (defined as an operation which produces a non-disjunctive feature structure) or equal to it.

5.2 Typed feature structures

A type system can be described as having three components; a fixed finite set of features Feat, a fixed type hierarchy $\langle \mathsf{Type}, \sqsubseteq \rangle$ with a finite set of types, and a constraint function C which associates a constraint feature structure with every type. The constraints determine which feature structures are *well-formed*. The definition of types in the LKB system follows Carpenter (1992) quite closely, although the type constraints are somewhat different.

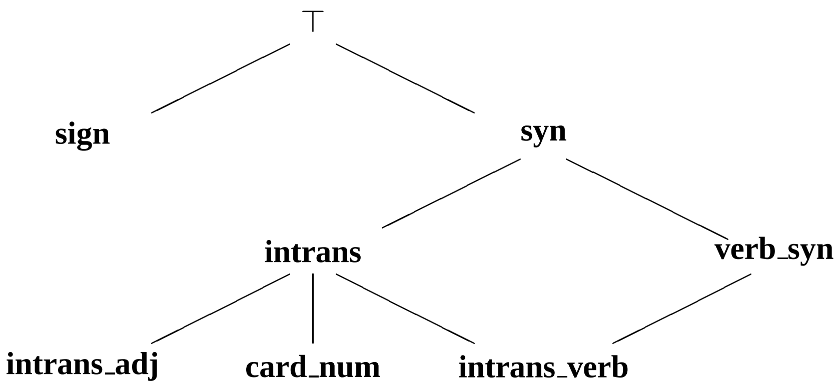


Figure 5.1: A fragment of a type hierarchy

5.2.1 The type hierarchy

The type hierarchy $\langle \mathsf{Type}, \sqsubseteq \rangle$ defines a partial order (notated $\sqsubseteq$, “is more specific than”) on the types and specifies which types are *consistent*. A set of types is said to be consistent if the members of the set share a common subtype. That is the subset $S \subseteq \mathsf{TYPE}$ is consistent iff there is some t_0 in TYPE such that $t_0 \sqsubseteq t$ for any t in S. The significance of this is that only feature structures with mutually consistent types can be unified. Two types which are unordered in the hierarchy are assumed to be inconsistent unless a common subtype has been explicitly specified (this is sometimes referred to as a *closed world assumption*). It is a condition on the type hierarchy that every *consistent* set of types $S \subseteq \mathsf{TYPE}$ must have a unique greatest lower bound or meet (notation $\sqcap S$). The unique greatest lower bound condition on consistent types allows feature structures to be typed deterministically; if two feature structures of types **a** and **b** are unified the type of the result will be $\mathbf{a} \sqcap \mathbf{b}$, which must be unique if it exists. If $\mathbf{a} \sqcap \mathbf{b}$ does not exist unification fails. Thus, in the fragment of a type hierarchy shown in Figure 5.1, **intrans** and **verb_syn** are consistent; $\mathbf{intrans} \sqcap \mathbf{verb\_syn} = \mathbf{intrans\_verb}$. We will use a very simple type system at this point for ease of exposition.

Because the type hierarchy is a partial order it has properties of reflexivity, transitivity and anti-symmetry (from which it follows that the type hierarchy cannot contain cycles). Note that the empty set is (vacuously) consistent, as for any t_0 in TYPE it satisfies the condition that $t_0 \sqsubseteq t$ for all t’s in the empty set. The maximal element $\top$ of $\langle \mathsf{TYPE}, \sqsubseteq \rangle$ is defined as the meet of the empty set, $\top = \sqcap\emptyset$. This element $\top$ is such that $t \sqsubseteq \top$ for any t in TYPE. Thus the join operation on the type hierarchy is total.

The meet $\sqcap$ operation can be made total by adding the join of the empty-set $\bot = \sqcup\emptyset$ to $\langle \mathsf{TYPE}, \sqsubseteq \rangle$. But even if $\bot$ is added to make $\langle \mathsf{TYPE}, \sqsubseteq \rangle$ a lattice, this lattice need not be distributive. For example, given the type hierarchy in Figure 5.1 $(\mathbf{intrans\_adj} \sqcup \mathbf{card\_num}) \sqcap \mathbf{verb\_syn} = \mathbf{intrans\_verb}$ but $(\mathbf{intrans\_adj} \sqcap \mathbf{verb\_syn}) \sqcup (\mathbf{card\_num} \sqcap \mathbf{verb\_syn}) = \bot$. Although meet will be taken as corresponding to conjunction, join does not correspond to disjunction. There is thus a symmetry with the behaviour of feature structures, where generalisation and disjunction are not equivalent. Nothing in what follows depends on whether the existence of a bottom element in the type hierarchy, $\bot$, is assumed or not. We use $\bot$ as a notational convenience to indicate inconsistency, just as $\bot$ is used to indicate unification failure for feature structures.

5.2.2 Typed feature structures

Initially we will define the set $\mathcal{F}$ of typed feature structures to include both those which are, and those which are not, well-formed with respect to a particular type system. A typed feature structure is defined as a tuple $F = \langle Q, q_0, \delta, \alpha \rangle$ where the only significant difference from the definition in the untyped case is that instead of α being a partial atomic value function it is a total node typing function, $\alpha : Q \rightarrow \mathsf{TYPE}$. Thus every node has a type.

Definition 6 (Typed Feature Structure) *A typed feature structure is a tuple* $F = \langle Q, q_0, \delta, \alpha \rangle$ *where:*

- Q*: a finite set of (connected, acyclic) nodes*
- $q_0 \in Q$*: the root node*
- $\delta : \mathsf{Feat} \times Q \rightarrow Q$ *: the partial feature value function*
- $\alpha : Q \rightarrow \mathsf{Type}$ *: the total node typing function*

with connectedness and acyclicity being defined as in the untyped case.

Consider the following example of a feature structure:

$$F_1 = \begin{bmatrix} \textbf{sign} & \\ \text{SEM} & \begin{bmatrix} \textbf{vsem} & \\ \text{RELN} & \textbf{r\_die} \\ \text{CORPSE} & \textbf{index} \end{bmatrix} \end{bmatrix}$$

As every feature structure has a unique initial node, q_0, the type of a feature structure can be said to be the type of its initial node, that is:

Definition 7 (Type of a feature structure) *If* $F = \langle Q, q_0, \delta, \alpha \rangle$ *then* $Typeof(F) = \alpha(q_0)$.

Thus the type of feature structure F_1 is **sign**.

The definition of subsumption of typed feature structures is very similar to that for untyped feature structures, with the additional proviso that the ordering must be consistent with the ordering on their types. The symbol $\sqsubseteq$ ("is-more-specific-than", "is-subsumed-by") is overloaded to express subsumption of feature structures as well as the ordering on the type hierarchy. Thus if F_1 and F_2 are feature structures of types t_1 and t_2 respectively, then $F_1 \sqsubseteq F_2$ only if $t_1 \sqsubseteq t_2$. If two feature structures are identical except for their types then the subsumption ordering on the feature structures will be equivalent to the ordering on their types.

Definition 8 (Abstract Typed Feature Structure) *If* $F = \langle Q, q_0, \delta, \alpha \rangle$ *is a feature structure, we let* $\equiv_F \subseteq \mathsf{Path} \times \mathsf{Path}$ *and* $\mathcal{P}_F : \mathsf{Path} \rightarrow \mathsf{Type}$ *be such that:*

- *(Path Equivalence)*
  $\pi \equiv_F \pi'$ *if and only if* $\delta(\pi, q_0) = \delta(\pi', q_0)$
- *(Path Value)*
  $\mathcal{P}_F(\pi) = t$ *if and only if* $\alpha(\delta(\pi, q_0)) = t$.

Definition 9 (Subsumption of typed feature structures) *F subsumes F', written $F' \sqsubseteq F$, iff:*

- *if $\pi \equiv_F \pi'$ then $\pi \equiv_{F'} \pi'$*
- *if $\mathcal{P}_F(\pi) = t$ then $\mathcal{P}_{F'}(\pi) = t'$ where $t' \sqsubseteq t$*

Unification of typed feature structures is defined in the same way as for untyped feature structures, that is the unification of two typed feature structures will be their greatest lower bound in the subsumption ordering. Since if F and F' are feature structures of types t and t' respectively, their unification $F \sqcap F'$ has to have type $t \sqcap t'$, unification will fail if $t \sqcap t'$ does not exist. Generalisation can also be defined in the same way as for untyped feature structures, that is as the lowest upper bound of two feature structures in the subsumption ordering.

Thus the type hierarchy makes a finer grained differentiation of feature structures possible, because the ordering is dependent on the type hierarchy as well as the order of untyped feature structure subsumption. For example, if F_1 and F_2 are the two feature structures given below, then $F_2 \sqsubset F_1$ assuming that **obj** $\sqsubset$ **index**:

$$F_1 = \begin{bmatrix} \textbf{sign} & \\ \text{SEM} & \begin{bmatrix} \textbf{vsem} \\ \text{RELN } \textbf{r\_die} \\ \text{CORPSE } \textbf{index} \end{bmatrix} \end{bmatrix} \quad F_2 = \begin{bmatrix} \textbf{sign} & \\ \text{SEM} & \begin{bmatrix} \textbf{vsem} \\ \text{RELN } \textbf{r\_die} \\ \text{CORPSE } \textbf{obj} \end{bmatrix} \end{bmatrix}$$

This is in itself useful; for example it allows selectional restrictions to be encoded as sorts in a way which is extremely cumbersome with untyped feature structures (cf. Moens *et al.*, 1989). However the type system also specifies a set of *well-formed* feature structures, which satisfy a constraint function, and this gives the system a functionality which includes the properties of inheritance, error-checking and classification.

5.2.3 Constraints

The constraint function C defines the set of feature structures $\mathcal{WF}$ which are well-formed with respect to the type system. In the LKB system every type must have exactly one associated feature structure which acts as a constraint on all feature structures of that type by subsuming all well-formed feature structures of that type. The constraint also defines which features are *appropriate* for a particular type. In a well-formed feature structure each node must have all the features appropriate to its type and no others. Constraints are inherited by all subtypes of a type, but a constraint on a subtype may introduce new features (which will be inherited as appropriate features by all its subtypes). A constraint on a type is a well-formed feature structure of that type; all constraints must therefore be mutually consistent.

For example, considering some of the types shown in Figure 5.1, the constraint associated with the type **verb_syn** might be:

$$\begin{bmatrix} \textbf{verb\_syn} & \\ \text{HEAD} & \begin{bmatrix} \textbf{head} \\ \text{POS } \textbf{verb} \\ \text{INV } \textbf{boolean} \end{bmatrix} \end{bmatrix}$$

This constraint states that any feature structure of type **verb_syn** must have a feature structure of type **head** as the value for its HEAD feature. This constraint must be consistent with the constraints on all of its subparts, i.e. it must itself be a well-formed feature structure. In this case, for example, the constraint on **head** is:

$$\begin{bmatrix}\textbf{head} \\ \text{POS } \textbf{pos} \\ \text{INV } \textbf{boolean}\end{bmatrix}$$

and thus the constraint on **verb_syn** is well-formed, given that **verb** $\sqsubseteq$ **pos**. Here **verb**, **pos** and **boolean** are atomic types, and have no appropriate features. So, for example, the constraint on **pos** is simply the atomic feature structure [**pos**].

The type **intrans** might have the constraint:

$$\begin{bmatrix}\textbf{intrans} & \\ \text{VAL} & \begin{bmatrix}\textbf{val} & \\ \text{SPR} & \begin{bmatrix}\textbf{ne-list} \\ \text{HD } \textbf{np} \\ \text{TL } \textbf{e-list}\end{bmatrix} \\ \text{COMPS } \textbf{e-list} & \end{bmatrix}\end{bmatrix}$$

(Note: we will pretend for the sake of this example that **np** is an atomic type. Of course this wouldn't really work, **np** would have to be a subtype of **sign** with a constraint such that the value of POS was **noun** and so on.)

The constraint on **intrans_verb** will contain information inherited from both parents, thus:

$$\begin{bmatrix}\textbf{intrans\_verb} & \\ \text{HEAD} & \begin{bmatrix}\textbf{head} \\ \text{POS } \textbf{verb} \\ \text{INV } \textbf{boolean}\end{bmatrix} \\ \text{VAL} & \begin{bmatrix}\textbf{val} & \\ \text{SPR} & \begin{bmatrix}\textbf{ne-list} \\ \text{HD } \textbf{np} \\ \text{TL } \textbf{e-list}\end{bmatrix} \\ \text{COMPS } \textbf{e-list} & \end{bmatrix}\end{bmatrix}$$

Given that **true** is an atomic subtype of **boolean**, the feature structure below is well-formed since it contains all the appropriate features and no inappropriate ones, it is subsumed by the constraints on its type and all its substructures are well-formed.

$$\begin{bmatrix}\textbf{intrans\_verb} & \\ \text{HEAD} & \begin{bmatrix}\textbf{head} \\ \text{POS } \textbf{verb} \\ \text{INV } \textbf{true}\end{bmatrix} \\ \text{VAL} & \begin{bmatrix}\textbf{val} & \\ \text{SPR} & \begin{bmatrix}\textbf{ne-list} \\ \text{HD } \textbf{np} \\ \text{TL } \textbf{e-list}\end{bmatrix} \\ \text{COMPS } \textbf{e-list} & \end{bmatrix}\end{bmatrix}$$

Formally, the notion of appropriate features is defined as follows:

Definition 10 (Appropriate features) *If $C(t) = \langle Q, q_0, \delta, \alpha\rangle$ then the appropriate features of t are defined as $Appfeat(t) = Feat(\langle F, q_0\rangle)$ where $Feat(\langle F, q\rangle)$ is defined to be the set of features labelling transitions from the node q in some feature structure F i.e. $f \in Feat(\langle F, q\rangle)$ such that $\delta(f, q)$ is defined.*

We can then define the constraint function:

Definition 11 (Constraint function) *The constraint function which associates constraint feature structures with types is given by C: $\langle \mathsf{TYPE}, \sqsubseteq\rangle \rightarrow \mathcal{F}$.*
This must satisfy the following conditions:

Monotonicity *Given types t_1 and t_2 if $t_1 \sqsubseteq t_2$ then $C(t_1) \sqsubseteq C(t_2)$*

Type *For a given type t, if $C(t)$ is the feature structure $\langle Q, q_0, \delta, \alpha\rangle$ then $\alpha(q_0) = t$.*

Compatability of constraints *For all $q \in Q$ the feature structure $F' = \langle Q', q, \delta, \alpha\rangle \sqsubseteq C(\alpha(q))$ and $Feat(q) = Appfeat(\alpha(q))$.*

Maximal introduction of features *For every feature $f \in \mathsf{FEAT}$ there is a unique type $t = Maxtype(f)$ such that $f \in Appfeat(t)$ and there is no type s such that $t \sqsubset s$ and $f \in Appfeat(s)$. The maximal appropriate value of a feature $Maxappval(f)$ is the type t such that if $C(Maxtype(f)) = \langle Q, q_0, \delta, \alpha\rangle$ then $t = \alpha(\delta(f, q_0))$*

The compatibility condition implies that no constraint feature structure $C(t) = F$ can strictly contain a feature structure of type t or any subtype of t. That is, if F is given by $\langle Q, q_0, \delta, \alpha\rangle$, then for all non-initial nodes $q \in Q$ such that $q \neq q_0$ the type of the node $\alpha(q) \not\sqsubseteq t$. If such a node existed it would have to be the initial node of a feature structure F_q which was more specific than F, i.e. $F_q \sqsubseteq F$, and would therefore itself have to contain such a node, and so on. Thus such a constraint could only be satisfied by a cyclic or infinite structure, and we disallow both of these possibilities. This condition does not, however, rule out recursive structures such as lists, because the type **list** can be defined to have two subtypes **e-list** (empty list) and **ne-list**, where the former has no appropriate features and the latter has two, HD which can take any value, and TL, which will take a value of type **list**. The type **ne-list** does not violate the compatibility condition, since the structure can be terminated.

Definition 12 (Well-formed feature structures) *We say that a given feature structure $F = \langle Q, q_0, \delta, \alpha\rangle$ is a well-formed feature structure iff for all $q \in Q$, we have that $F' = \langle Q', q, \delta, \alpha\rangle \sqsubseteq C(\alpha(q))$ and $Feat(q) = Appfeat(\alpha(q))$.*

From these definitions it can be seen that all constraint feature structures are themselves well-formed feature structures.

Since the type system gives a concept of a well-formed feature structure, it follows that non-well-formed feature structures can be detected, allowing error checking. Typing also allows for a form of classification; a feature may only be introduced as appropriate at one point in the type hierarchy (and will be inherited as an appropriate feature by all subtypes of that type); it follows from this that there is a unique maximal type for any set of features, and therefore an untyped feature structure can always be typed deterministically. For example, assuming the type system introduced above, the description:

```
[ HEAD [ INV true ],
  VAL  [ COMPS e-list ] ].
```

would give rise to the following feature structure:

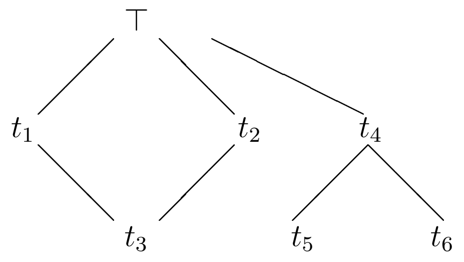
$$\begin{bmatrix} \textbf{intrans\_verb} & \\ \text{HEAD} & \begin{bmatrix} \textbf{head} \\ \text{POS } \textbf{verb} \\ \text{INV } \textbf{true} \end{bmatrix} \\ \text{VAL} & \begin{bmatrix} \textbf{val} & \\ \text{SPR} & \begin{bmatrix} \textbf{ne-list} \\ \text{HD } \textbf{np} \\ \text{TL } \textbf{e-list} \end{bmatrix} \\ \text{COMPS } \textbf{e-list} & \end{bmatrix} \end{bmatrix}$$

(Full details of the feature structure description language are given in section 5.3.1, below.) The type of the feature structure is determined automatically; since the features HEAD and VAL are specified, its type has to be **intrans_verb** (or some subtype of that type). The procedure for making a feature structure well-formed, WF, involves recursively unifying the constraints of the maximal types of the subparts of the feature structure; since we disallow cyclic feature structures, this operation terminates straightforwardly at the atomic feature structures.

5.2.4 Unification and well-formedness

The definition of subsumption for well-formed feature structures is exactly the same as that for typed feature structures. The result of well-formed unification of well-formed feature structures, $\langle \mathcal{WF}, \sqsubseteq \rangle$, is defined to be the greatest lower bound in the subsumption ordering of well-formed feature structures and is thus itself well-formed. This does however mean that the algorithm for unification involves an additional step, because it is potentially necessary to unify in the constraint feature structure associated with the meet of the types of the feature structures being unified.

If F_1 and F_2 are well-formed feature structures of types t_1 and t_2 respectively, then $F_1 \sqcap F_2$, if it exists, has type $t_1 \sqcap t_2$. Since F_1 and F_2 are well-formed, in particular we know that $F_1 \sqsubseteq C(t_1)$ and $F_2 \sqsubseteq C(t_2)$. Thus if F_1 and F_2 are consistent, $F_1 \sqcap F_2 \sqsubseteq C(t_1) \sqcap C(t_2)$. But to be well-formed $F_1 \sqcap F_2$ has to satisfy $F_1 \sqcap F_2 \sqsubseteq C(t_1 \sqcap t_2)$ and $C(t_1 \sqcap t_2)$ might be more specific than $C(t_1) \sqcap C(t_2)$. Consider the following example of a type hierarchy:



Assume that the types t_4, t_5 and t_6 are atomic (i.e. they have constraints $[t_4]$, $[t_5]$ and $[t_6]$, respectively) and the constraints on types t_1, t_2 and t_3 are:

$$C(t_1) = \begin{bmatrix} t_1 \\ \text{F}\, t_4 \end{bmatrix} \quad C(t_2) = \begin{bmatrix} t_2 \\ \text{G}\, \top \end{bmatrix} \quad C(t_3) = \begin{bmatrix} t_3 \\ \text{F}\, t_5 \\ \text{G}\, \top \\ \text{H}\, \top \end{bmatrix}$$

We then have: $C(t_1) \sqcap C(t_2) = \begin{bmatrix} t_3 \\ \text{F}\, t_4 \\ \text{G}\, \top \end{bmatrix}$

Then $t_3 = t_1 \sqcap t_2$ but $C(t_3) \sqsubset C(t_1) \sqcap C(t_2)$

Consider the following well-formed feature structures, F_1, F_2 and F_3:

$$F_1 = \begin{bmatrix} t_1 \\ \text{F}\, t_4 \end{bmatrix} \qquad F_2 = \begin{bmatrix} t_2 \\ \text{G}\, \top \end{bmatrix} \quad F_3 = \begin{bmatrix} t_1 \\ \text{F}\, t_6 \end{bmatrix}$$

$$F_1 \sqcap F_2 = \begin{bmatrix} t_3 \\ \text{F}\, t_4 \\ \text{G}\, \top \end{bmatrix}$$

$$F_2 \sqcap F_3 = \begin{bmatrix} t_3 \\ \text{F}\, t_6 \\ \text{G}\, \top \end{bmatrix}$$

$F_1 \sqcap F_2$ is not a well-formed feature structure of type t_3 as $F_1 \sqcap F_2 \not\sqsubseteq C(t_3)$. To extend it to a well-formed feature structure involves unifying in $C(t_3)$. $F_2 \sqcap F_3$ is also not a well-formed feature structure but it cannot be extended to a well-formed feature structure, because its value for F is inconsistent with the constraint for t_3.

To overcome this, we use the following definition for the operation of well-formed unification, $\sqcap_w$:

Definition 13 (Well-formed unification) *The well-formed unification of F_1 and F_2, $F_1 \sqcap_w F_2$ is given by $F_1 \sqcap F_2 \sqcap C(t_1 \sqcap t_2)$. This will be well-formed if it exists.*

No such complication arises with generalisation, since $F = F' \sqcup F''$ will always be well-formed if F' and F'' are well-formed. From now on, when talking about typed feature structures, we will use the term feature structure to mean well-formed typed feature structure and $\sqcap$ will be used to refer to well-formed unification, $\sqcap_w$, dropping the subscript.

5.3 Description language

In order to specify types, constraints, lexical entries and so on, we require a *description language*. The LKB allows a variety of description languages to be used: the one specified here adopts a simplified version of the TDL syntax from the PAGE system (Uszkoreit et al, 1994). We will introduce the syntax by going through some examples, in increasing order of complexity.

5.3.1 Syntax of type and constraint descriptions

Example 1

```
feat-struc := *top*.
```

or

```
feat-struc :< *top*.
```

In the LKB, these are alternative ways of defining the type **feat-struc** to inherit from the single parent ***top***, i.e., $\top$, which is the only built-in type in the LKB system (the name can be specified as a system parameter).[2] Since no constraint is specified for **feat-struc** and it is not possible to specify a constraint for ***top***, $C(\textbf{feat-struc}) = [\,\textbf{feat-struc}\,]$. Note that:

1. the type definition, and in fact all descriptions, is terminated by a '.'
2. new lines and spaces are not significant, except that spaces may not occur in identifiers, such as type names
3. case is not significant, though we follow the convention of expressing features in uppercase and types in lowercase

[2]In the full TDL syntax, the symbol :< is used to indicate simple inheritance from a single type when there is no constraint specification. In the LKB, :< is allowed in this situation (and only in this situation) but := may always be used instead.

4. the use of `*` in the type name ***top*** is a convention indicating this is a standard type, however the `*`s are not significant to the system

5. the following characters may not be used in identifiers: `< > ! = : . # & , [ ] ; @ $ ( ) ^ "`

Example 2

```
agr-cat := gen-agr-cat &
[ PER per,
  NUM num,
  GEND gend ].
```

(The symbol `:=` has to be used because the constraint is specified.) This description defines **agr-cat** to inherit from **gen-agr-cat** and to have a constraint specification which is equivalent to the following in the 'pretty' AVM notation:

$$\begin{bmatrix} \text{PER } \textbf{per} \\ \text{NUM } \textbf{num} \\ \text{GEND } \textbf{gend} \end{bmatrix}$$

The actual constraint on the type will be the following:

$$\begin{bmatrix} \textbf{agr-cat} \\ \text{PER } \textbf{per} \\ \text{NUM } \textbf{num} \\ \text{GEND } \textbf{gend} \end{bmatrix} \sqcap C(\textbf{gen-agr-cat})$$

Example 3

```
head-feature-principle := grule & head-dtr-type &
 [ SYN [ HEAD #head ],
   H [ SYN [ HEAD #head ] ] ].
```

The type **head-feature-principle** has two parents: **grule** and **head-dtr-type**. The structure shows the notation for reentrancy: the reentrant node is indicated by `#head`. Note that the name of the tag is not significant. The constraint on this type will be:

$$\begin{bmatrix} \textbf{head-feature-principle} \\ \text{SYN} \begin{bmatrix} \text{HEAD } \boxed{1}\ \textbf{*top*} \end{bmatrix} \\ \text{H} \begin{bmatrix} \text{SYN} \begin{bmatrix} \text{HEAD } \boxed{1} \end{bmatrix} \end{bmatrix} \end{bmatrix} \sqcap C(\textbf{grule}) \sqcap C(\textbf{head-dtr-type})$$

Note that the TDL syntax also allows an alternative notation to be used for concatenation of features:

```
 [ SYN.HEAD #head,
   H.SYN.HEAD #head ].
```

is equivalent to:

```
 [ SYN [ HEAD #head ],
   H [ SYN [ HEAD #head ] ] ].
```

5.3.2 A formal description of the syntax of type descriptions

To formally express the syntax of the description language, we use Backus-Naur Form (BNF) basically following the typographic conventions used in Aho et al (1982). As there, alternative right-hand sides of productions are indicated by |. However, we follow the convention that both non-terminals and terminal tokens are italicized: non-terminals are capitalized. For example *Avm-def* is a non-terminal, *identifier* is a terminal token that could match, for example, a type name such as 'head-dtr-type'. Using these conventions, the following is the basic syntax of the type specification language:

Type-def → *Type* *Avm-def* `.` | *Type* *Subtype-def* `.`
Type → *identifier*
Subtype-def → `:<` *Type*
Avm-def → `:=` *Conjunction*
Conjunction → *Term* | *Term* `&` *Conjunction*
Term → *Type* | *string* | *Feature-term* | *Coreference*
Feature-term → `[]` | `[` *Attr-val-list* `]`
Attr-val-list → *Attr-val* | *Attr-val* `,` *Attr-val-list*
Attr-val → *Attr-list* *Conjunction*
Attr-list → *Attribute* | *Attribute*`.`*Attr-list*
Attribute → *identifier*
Coreference → *#identifier*

This syntax is elaborated to allow for TDL templates, lists, and difference lists, as described in §5.3.7 and §5.3.6. Strings are are indicated by `"`: e.g., `"me"` or `'`: e.g., `'Kim`. They are discussed in the next section. The modification to allow for defaults is given in §8.10.

TDL also allows 'status' indications, e.g.,

```
:begin :type
```

These are allowed in LKB files for compatibility with the PAGE system, but are ignored.

Comments are allowed in LKB files, but only in between descriptions. Comments are either single lines beginning with `;` or they are bracketed by `#| |#`.

5.3.3 Lexical entries

The syntactic description for lexical entries is very similar to that for type constraint descriptions. For example:

```
me_1 := pron-lxm &
[ ORTH "me",
  SYN  [ HEAD noun &
              [ AGR non-3sing
                    & [ PER 1st ],
CASE acc ] ] ].
```

However the interpretation is different. Rather than stipulating that me_1 is a type in the hierarchy under the type **pron-lxm**, this definition states that me_1 is a feature structure which has the type **pron-lxm**. If the definition were simply:

```
me_1 := pron-lxm.
```

this should be read as stating that the feature structure named by me_1 is $\begin{bmatrix}\textbf{pron-lxm}\end{bmatrix}$: that is the single-node feature structure with the node having type **pron-lxm** (though obviously the process of making this well-formed expands the structure). Given the way the formalism is defined (following Carpenter), it is a category error to think of lexical entries as being like maximally-specific types, or even as 'instances' of types: lexical entries are typed feature structures and types label nodes in feature structures. However, the terminology in the literature is very confused, because *type* is often used to mean something more like the concept we refer to as the type constraint.

Note that the value of the feature ORTH in this definition is a string. Strings are a method of allowing a feature structure to contain a value without an explicit declaration of that value as a type being necessary. Formally, all strings can be treated as being a daughter of a specific atomic type, usually called **string** (the name can be specified as a parameter to the system). String types are all atomic, have no parent other than **string** and have no daughters.

The BNF for lexical entries is as follows:

Lexentry $\rightarrow$ *LexID* *Avm-def* **.**
LexID $\rightarrow$ *identifier*

Note that, although it is legal syntax to define a lexical entry with multiple types on a node, this will not be valid unless the types have an existing type as their greatest lower bound. Thus it is normal to specify this type directly in lexical entries.

In order for lexical entries to be handled correctly by the morphology system and parser, they must have a specified orthography, and the path to access that orthography must be specified as a system parameter.

5.3.4 Rules

Grammar and lexical rules in the LKB system are typed feature structures, which represent relationships between two or more signs. The BNF is essentially identical to that for lexical entries:

Ruleentry $\rightarrow$ *RuleID* *Avm-def* **.**
RuleID $\rightarrow$ *identifier*

Rules must expand out into feature structures which have identifiable paths for the mother and daughters of the rule. For example, a possible type constraint for binary rules might specify:

$$\begin{bmatrix} \textbf{binary-rule} \\ \text{ARGS} \begin{bmatrix} \text{FIRST } \textbf{sign} \\ \text{REST } \begin{bmatrix} \text{FIRST } \textbf{sign} \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

Here the mother is given by the empty path, one daughter by the path ARGS.FIRST and another by the path ARGS.REST.FIRST. The mother path and a function which gives the daughters in the correct linear order must be specified as system parameters.

Rules can be regarded statically, as expressing a dependency relationship between signs. For example, given the assumption about paths made above, we can say that a rule R applies to a mother, M and daughters D1 and D2, iff the following is well formed:

$$R \sqcap M \sqcap \begin{bmatrix} \text{ARGS} \begin{bmatrix} \text{FIRST } D1 \\ \text{REST} \begin{bmatrix} \text{FIRST } D2 \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

If the linear order is specified so that ARGS.FIRST precedes ARGS.REST.FIRST then D1 must precede D2.

Rules can alternatively be regarded as a means of constructing new signs. For instance, in bottom-up processing, if a series of signs, $F_1, F_2 \ldots F_n$ can be unified with the feature structures at the end of the paths $P_1, P_2 \ldots P_n$ in a rule R, where P_1 corresponds to the path associated with the first daughter, P_2 the second, etc, then the feature structure at the end of the mother path in R is a new sign. Rule application is order-independent, so parsers and generators following different strategies will achieve the same result.

Rules must have a definite number of daughters: there is no direct way of defining a rule using Kleene star, or of encoding optionality directly. A weakly-equivalent alternative formulation is always possible, using extra rules to get the required effect.

Lexical rules are treated as unary grammar rules: they are special only in that they may apply before affixation. In principle they may also be applied to phrases — all conditions on lexical rule application must be explicitly encoded, e.g., by stipulating that lexical rules may only apply to **word**s rather than **phrase**s. Normally this will be done by defining a type for lexical rules.

5.3.5 Morphological rules

In the terminology we will use here, morphological rules are a special case of lexical rules which involve affixation. The current form of orthographemics in the LKB system assumes that affixes are associated with specific rules. The LKB system uses a simple string unification approach for encoding orthographemics.[3] Affixation and any associated spelling changes is indicated by means of information which augments the standard lexical rules. This affixation information is specified after the identifier, but before the remainder of the rule description.

For example, in the following rule, the information introduced by % describes the spelling changes — the rest of the rule is just described in the standard TDL syntax.

```
past_verb_infl_rule :=
%suffix (* ed) (!ty !tied) (e ed) (!t!v!c !t!v!c!ced)
lex_rule_infl_affixed &
[ NEEDS-AFFIX +,
  ARGS [ FIRST [ AFFIX past_verb ]]].
```

The spelling rule has two parts — the first is simply `prefix` or `suffix` and the second contain a set of subrules in the form of matched simple partial regular expressions. The first of each pair of expressions must match letters in the word stem, either at the beginning of the stem (for prefixes) or at the end (for suffixes, as illustrated here). For example, the subrule `(e ed)` will match the

[3]This was implemented by Bernie Jones and the following description is adapted from text written by him.

stem *like*. The second expression in the subrule describes the set of letters which replace the letters matching the input in the affixed form of the word. Thus the stem *like* corresponds to the affixed *liked*.

The asterisk `*` and the symbols introduced by `!` are special characters. The asterisk represents a null character, and is interpreted so that the first sub-rule is the default (*ed* is added at the word-final position). Subrules without asterisks are treated as exceptions to the default. For instance, none of the explicit subrules match the stem *match*. This therefore corresponds to the first subrule and the affixed form is *matched*. The *!* structure is used to denote special macro symbols which correspond to sets of letters. These sets are defined at the beginning of the file with the morphological rules, for example:

```
%(letter-set (!c bdfglmnprstz))
%(letter-set (!s abcdefghijklmnopqrtuvwxyz))
%(letter-set (!t bcdfghjklmnpqrstvwxz))
%(letter-set (!v aeiou))
```

The interpretation of these symbols is that they match any one of the characters in the set, but the matching character must be the same throughout the subrule. For instance, (`!t!v!c !t!v!c!ced`) will match (*pot potted*), but would not match (*pot podded*).

As with the rest of the system, morphology is reversible, and can thus be used for parsing and generation. Irregular forms can be specified in the rule, or in a separate file.

The BNF for the letter sets is as follows:

Letterset → `%(`**letter-set** `(`*Macro letters*`))`
Macro → `!`*letter*

where *letter* corresponds to any character, *letters* to one or more characters and **letter-set** is a literal: i.e., ‘letter-set’ must appear in the file.

The rules themselves have the following BNF:

Mruleentry → *RuleID Mgraph-spec-list Avm-def*`.`
Mgraph-spec-list → *Mgraph-spec* | *Mgraph-spec Mgraph-spec-list*
Mgraph-spec → **%prefix** *SPair-list* | **%suffix** *SPair-list*
SPair-list → *SPair* | *SPair SPair-list*
SPair → `( * ` *Char-list* `)` | `(` *Char-list Char-list* `)`
`Char-list ->` *letter* | *Macro* | *letter Char-list* | *Macro Char-list*

If a separate file is used for irregular forms, it consists of a string containing a list of irregular entries, one per line, where each entry has the following form:

Irregentry → *base Rulespec inflected*

where both *base* and *inflected* are words. For example:

```
"
fell PAST-VERB fall
felt PAST-VERB feel
"
```

For compatibility with PAGE, the rule name can be constructed from the rule specification found in the file by concatenating a suffix. The suffix is specified as a parameter, `*lex-rule-suffix*` (see §C.2.3). Details of the treatment of irregular forms are given in §6.6.

5.3.6 Lists and difference lists

Lists and difference lists are very frequently used constructs in typed feature structure grammars. Because of this, the syntax provides a notation for them directly, which expands out into the feature structure representation. In the LKB, the names of features and types involved are controlled by system parameters. For example, suppose lists are defined as follows:

```
list :< *top*.
e-list :< list.
ne-list := list &
            [ HD *top*,
              TL *top* ].
```

Then the full representation of a list of elements a,b,c would be:

```
[ HD a,
  TL [ HD b,
       TL [ HD c,
            TL e-list ]]]
```

Using the abbreviatory notation, we could simplify this to:

```
< a, b, c >
```

Here and below, the a, b, c can be arbitrarily complex conjunctions of terms, which themselves contain lists etc. It is often necessary to specify potentially non-terminated lists, for example:

```
[ HD a,
  TL [ HD b,
       TL [ HD c,
            TL list ]]]
```

which allows the possibility of additional elements after c. This is represented as

```
< a, b, c ...>
```

Finally, the syntax allows for *dotted-pairs*. For instance, the pair a.b could be represented as:

```
[ HD a,
  TL b ]
```

which is abbreviated as

```
< a . b >
```

Difference lists can also be abbreviated. For example, assume the following type definition:

```
diff-list := *top*
            [ LIST list,
              LAST list ].
```

The full notation for the difference list containing a,b,c would be:

```
[ LIST [ HD a,
         TL [ HD b,
              TL [ HD c,
                   TL #last ]]],
  LAST #last ]
```

This can be abbreviated as:

```
<! a, b, c !>
```

Note that the list component of the difference list is not terminated. It is not possible to stipulate a difference list which has an arbitrary number of elements, since the coindexation of LIST and LAST requires a determinate path.

The following amends the BNF given earlier to allow for lists and difference lists:

Term → *Type* | *string* | *Feature-term* | *Coreference* | *List* | *Diff-list*
Diff-list → `<! !>` | `<!` *Conjunction-list* `!>`
Conjunction-list → *Conjunction* | *Conjunction* `,` *Conjunction-list*
List → `<>` | `<` *Conjunction-list* `>` | `<` *Conjunction-list* `, ... >` |
`<` *Conjunction-list* `.` *Conjunction* `>`

5.3.7 Parameterized templates

The PAGE system allows templates with parameters to occur in descriptions. These are an abbreviatory notation: they always expand out into typed feature structures. The LKB currently supports a limited use of parameterized templates, for compatibility with PAGE. For completeness the augmentation to the description language syntax is given here, although since this facility is likely to disappear, new templates should not be constructed.

Term → *Type* | *string* | *Feature-term* | *Coreference* | *List* | *Diff-list* | *Templ-call*
Templ-call → `@`*Templ-name* `( )` | `@`*Templ-name* `(`*Templ-par-list*`)`
Templ-name → *identifier*
Templ-par-list → *Templ-par* | *Templ-par* `,` *Templ-par-list*
Templ-par → `$`*Templ-var* | `$`*Templ-var* `=` *Conjunction*
Templ-var → *identifier*

5.3.8 Semantics of typed feature structure descriptions

The descriptions can be taken as formulas which must be satisfied by the feature structures they describe, as was done in Pereira and Shieber (1984). The logic of the description language used here is identical to that described by Carpenter (1992:52f) with the exception that we do not allow disjunctive descriptions (and thus the algorithm for deciding the satisfiability of a formula has the same order of complexity as unification). Thus, as Carpenter shows we have the usual results for the satisfaction relation, $\models$:

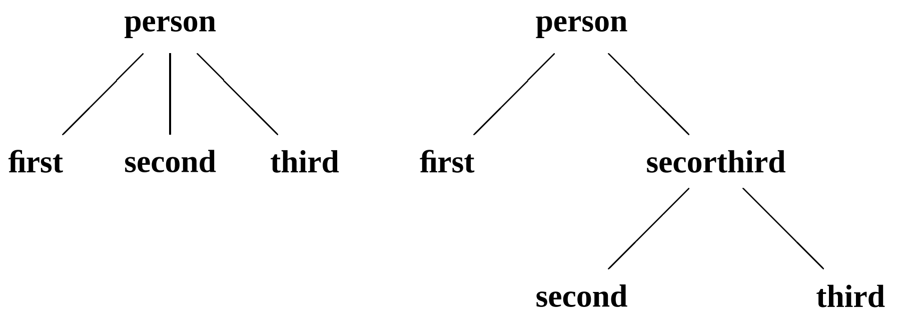


Figure 5.2: Adding types to the hierarchy

Monotonicity If ϕ is a formula then if $F_1 \models \phi$ and $F_2 \sqsubseteq F_1$ then $F_2 \models \phi$.

Most general satisfier For every satisfiable formula ϕ, there is a unique most general feature structure $MGSat(\phi)$ that satisfies it.

Description For any feature structure in $\mathcal{F}$ there is a description $\mathsf{Desc}(F)$ such that

$$F \sim MGSat(\mathsf{Desc}(F))$$

Note that this differs from some other typed feature structure formalisms in which the satisfier of a description is taken to be a set of maximally specific feature structures. The practical consequences of this distinction are not great, however.

5.4 A note about disjunction and negation

Although many feature structure based languages allow disjunctive feature structures and negation, this is avoided in the LKB system. Arbitrary disjunction can result in a computationally intractable system. Furthermore, support for disjunction and negation causes computational overheads in feature structure representation and operations such as unification, even if the particular grammar contains no disjunctions or negations.

We do not believe that disjunction within feature structures is necessary, given that the type system can be set up in a way which allows degrees of underspecification.[4] Note that the lowest common supertype (join) of two types might be more general than their disjunction. In this case, a new type may have to be created to get the required level of specification. For example if the type **person** was defined to have the subtypes **first**, **second**, **third**, a new type could be inserted in the hierarchy in order to express the equivalent of the disjunction **second** or **third** (see Figure 5.2).

The effect of the non-equivalence of disjunction and join may in fact be exploited to allow a more precise specification of a language. For example, Pollard and Sag (1994) give a description of the inflection of German adjectives such as *klein*, in which the following values for case are given as possibilities: **nom**, **acc**, **gen**, **dat**, **nom** $\vee$ **acc**, **gen** $\vee$ **dat**, *unspecified*. Encoding this in the type system, as shown in Figure 5.3, rather than making use of disjunction, would directly express the

[4]This is not to say there is no disjunction in the system: lexical ambiguity, for instance, can be regarded as a form of disjunction. However, this is a case where two feature structures are regarded as alternatives, rather than there being disjunctive information within a single structure.

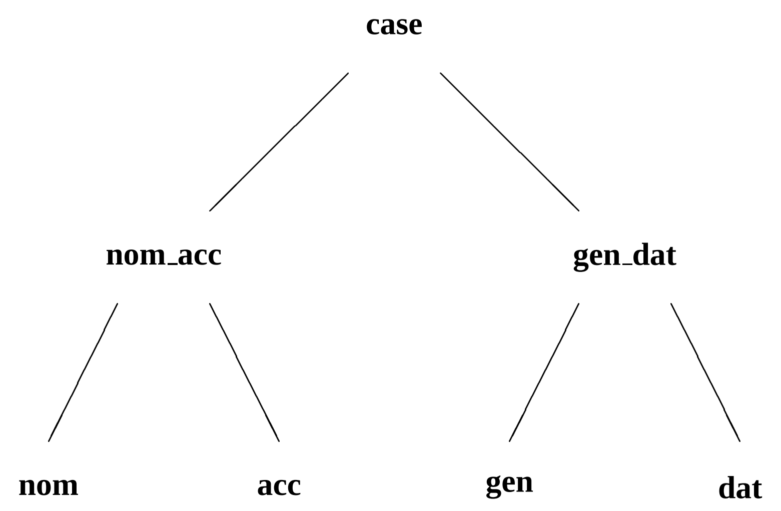


Figure 5.3: Restricting the possibilities for case specification

restriction that only these values were available and that the following were not: **nom** $\vee$ **gen**, **acc** $\vee$ **dat**, **nom** $\vee$ **acc** $\vee$ **gen**, **nom** $\vee$ **acc** $\vee$ **dat**, **nom** $\vee$ **gen** $\vee$ **dat**, **acc** $\vee$ **gen** $\vee$ **dat**.

Negation is not allowed in the LKB system: the interpretation of negation in a feature structure language is far from intuitive and the logic we have used to define typed feature structures does not in fact allow for any straightforward form of negation. We do not believe this is a disadvantage in developing practical grammars.

Chapter 6

LKB source files

The previous two chapters described the formalism used by the LKB. This chapter goes into the details of how the system evaluates grammar source files expressed in that formalism. We expect it will be mostly useful as a reference manual, for use especially when there is an error message that is not self-explanatory. Most of this chapter should be equally relevant to people using the graphical or tty versions of the system.

The source file organization in the LKB is based on the assumption that a single file contains one class of object. The user may however choose to split the descriptions in a particular class over multiple files, for example to have different type files for the types used in rules as opposed to those used in lexical entries, or have multiple files for the lexicon. This often enhances modularity.

The main classes of object within the LKB system are:

Types and constraints

Lexical entries

Grammar rules

Lexical and morphological rules

Apart from types and their constraints, all the rest of the objects are generically referred to as *entries*. They are all typed feature structures which are associated with an identifier.[1] They are distinguished because of their function within the system, with respect to parsing, for example. Two further categories of entry are also used in the sample grammars:

Start symbol descriptions

Parse node descriptions

If you have worked through Chapter 3, you have seen examples of types, type constraints, lexical entries and grammar rules. Lexical and morphological rules were not used in the 'toy' grammar, but are introduced in a slightly more complex grammar 'rattle', so where necessary we

[1]By *entry* we mean roughly what was meant by *psort* in the old LKB documentation, and what is sometime referred to as an *instance*. We've changed the terminology because *psort* was just confusing and *instance* is somewhat inaccurate.

will use examples from that.[2] This chapter contains full details for all the different types of source file in the ‘rattle’ grammar. It does not, however, cover all the capabilities of the LKB system for dealing with larger grammars or ones which have a different approach to syntax — the details of the advanced features are left to Chapter 8.

6.1 The script file

The following is the script file for ‘rattle’, which illustrates how the files of the different sorts of object are loaded into the LKB system:

```
(lkb-load-lisp (parent-directory) "globals.lsp")
(lkb-load-lisp (parent-directory) "user-fns.lsp")
(load-lkb-preferences (parent-directory) "user-prefs.lsp")
(read-tdl-type-files-aux
     (list (lkb-pathname (this-directory) "types.tdl")))
(read-tdl-lex-file-aux
     (lkb-pathname (this-directory) "lexicon.tdl"))
(read-tdl-grammar-file-aux
     (lkb-pathname (this-directory) "grules.tdl"))
(read-morph-file-aux
     (lkb-pathname (this-directory) "infl-rules.tdl"))
(load-irregular-spellings
     (lkb-pathname (this-directory) "irregs.txt"))
(read-tdl-psort-file-aux
          (lkb-pathname (this-directory) "roots.tdl"))
(read-tdl-parse-node-file-aux
          (lkb-pathname (this-directory) "parse-nodes.tdl"))
```

The script file is written in Lisp, although for convenience a number of functions have been defined to make writing a script file easier. These are discussed in detail in §8.2.

The first three lines read in some Lisp files which parameterize the system in various ways, as briefly discussed in §6.10. The following lines read in the types with their local constraint descriptions and the entries of the various classes listed above. Note there is also a file for morphologically irregular words, as discussed in §6.6. All these files are read in by functions which take as an argument the pathname for the file.

6.2 Types, constraints and type files

The type system is defined in one or more type files. It is necessary to have a valid type system before anything else will work. The system loads the type files and then carries out a series of checks and expands the type constraint descriptions. With an error-free type hierarchy, you will see messages such as the following while the system loads the files and does this computation.

[2]There are further ways to use entries in the LKB which are not described in this document. These include translation equivalences (sometimes referred to a bilexical entries) and rules for semantic conversion.

```
Reading in type file /home/aac/toy/types.tdl
Checking type hierarchy
Checking for unique greatest lower bounds
Expanding constraints
Making constraints well formed
Type file checked successfully
Computing display ordering
```

Once a type file is loaded successfully, a window showing the type hierarchy is displayed. This is described in detail in §7.2, below.

The formal conditions on the type hierarchy and the syntax of the language are detailed in Chapter 5. Here we will go through those conditions informally, and discuss what happens when you try and load a file in which they are violated. If you do not understand the terminology, please refer back to Chapter 4. This section is lengthy compared to the sections on lexical rules and so on, because the type hierarchy conditions are relatively complex.

Many examples of errors are given below: these all assume that we have made the minimal change to the 'toy' grammar to make it match the structures shown. The errors are not supposed to be particularly realistic!

IMPORTANT NOTE: always look at the first error message first! Error messages may scroll off the screen, so you may need to scroll up in order to do this. Sometimes errors propagate, causing other errors, so it's often a good idea to reload the grammar after you have fixed the first error.

6.2.1 Syntactic well-formedness

If the syntax of the constraint specifications in the type file is not correct, according to the definition in §5.3.2, then error messages will be generated. The system tries to make a partial recovery from syntactic errors, either by skipping to the end of a definition or inserting the character it expected, and then continuing to read the file. This recovery does not always work: sometimes the inserted character is not the intended one and sometimes an error recovery affects a subsequent definition. Thus you may get multiple error messages from a single error. The system will not try to do any further well-formedness checking on files with any syntactic errors. In the examples below, an incorrect definition is shown followed by the error message that is generated when the correct form of the corresponding definition in `toy/types.tdl` is replaced by the incorrect form.

```
feat-struc : *top*.

    Syntax error at position 273:
    Syntax error following type name FEAT-STRUC
    Ignoring (part of) entry for FEAT-STRUC
    Error:  Syntax error(s) in type file
```

The error is caused by the missing `=` following the `:`. The error message indicates the position of the error (using emacs you can use the command goto-char to go to this position in the file). The number given will not always indicate the exact position of the problem, since the description reader may not be able to detect the problem immediately, but is likely to be quite close. The system then says what it is doing to try and recover from the error (in this case, ignore the rest of the entry) and finally stops processing with the error message `Syntax error(s) in type file` (we will omit this in the rest of the examples).

```
agr-cat := feat-struc &
 [ PER per,
   NUM num,
   GEND gend .
```

```
    Syntax error:  ]  expected and not found in AGR-CAT at po-
    sition 343
    Inserting ]
```

In this example, the system tries to recover by inserting the character it thinks is missing, correctly here.

```
agr-cat := feat-struc &
 [ PER per,
   NUM num
   GEND gend ].
```

```
    Syntax error:  ]  expected and not found in AGR-CAT at po-
    sition 332
    Inserting ] Syntax error:  .  expected and not found in AGR-
    CAT at position 332
    Inserting .  Syntax error at position 337
    Incorrect syntax following type name GEND
    Ignoring (part of) entry for GEND
```

Here the system diagnosed the error incorrectly, since in fact a comma was missing rather than a ‘]’. The system’s recovery attempt doesn’t work, and the error propagates. This illustrates why you should reload the grammar after fixing the first error unless you are reasonably sure the error messages are independent.

```
head-feature-principle := hd-grule &
 [ SYN [ HEAD #head ],
   H [ SYN [ HEAD #headd ] ] ].
```

```
    Syntax error at position 3802:  Coreference (HEADD) only used
    once Syntax error at position 3802:  Coreference (HEAD) only
    used once
```

In this example, the system warns that the coreference was only used once: it is assumed that this would only be due to an error on the part of the user.

You may also get syntax errors such as the following:

```
    Unexpected eof when reading X
```

eof stands for end of file — this sort of message is usually caused by a missing character.

6.2.2 Conditions on the type hierarchy

After a syntactically valid type file (or series of type files) is read in, the hierarchy of types is constructed and checked to ensure it meets the conditions specified in §4.2/§5.2.1.

All types must be defined If a type is specified to have a parent which is not defined anywhere in the loaded files, an error message such as the following is generated:

```
    FEAT-STRUC specified to have non-existent parent *TOP-
    TYPE*
```

Although it is conventional to define parent types before their daughters in the file, this is not required, and order of type definition in general has no significance for the system. Note however that it is possible to redefine types, and if this is done, the actual definition will be the last one the system reads. If two definitions for types of the same name occur, a warning message will be generated, e.g.,:

```
    Type FEAT-STRUC redefined
```

Connectedness / unique top type There must be a single hierarchy containing all the types. Thus it is an error for a type to be defined without any parents, for example:

```
agr-cat :=
 [ PER per,
   NUM num,
   GEND gend ].
```

Omitting the parent(s) of a type will cause an error message such as the following:

```
    Error:  Two top types *TOP* and AGR-CAT have been defined
```

To fix this, define a parent for the type which is not intended to be the top type (i.e., **agr-cat** in this example).

If a type is defined with a single parent which is also specified to be its descendant, the connectedness check will give error messages such as the following for every descendant of the type:

```
    GRULE not connected to top
```

(This situation is also invalid because cycles are not allowed in the hierarchy, but because of the way cycles are checked for, the error will be found by the connectedness check rather than the cyclicity check).

No cycles It is an error for a descendant of a type to be one of that type's ancestors. This causes an error message to be generated such as:

```
    Cycle involving TV_PRED
```

The actual type specified in the messages may not be the one that needs to be changed, because the system cannot determine which link in the cycle is incorrect.

Redundant links This is the situation where a type is specified to be both an immediate and a non-immediate descendant of another type.

```
Redundancy involving TV_PRED
```

The assumption is that this would only happen because of a user error. The condition is checked for because it could cause problems with the greatest lower bound code (see §6.2.3). After finding this error, the system checks for any other redundancies and reports them all.

6.2.3 Uniqueness of greatest lower bound

The system requires that every set of types has a unique greatest lower bound (*glb*) as described in §4.2 and §5.2.1. This is necessary so that unification of typed feature structures can give a single result, with one type per node in the feature structure. Unlike the conditions listed in the previous section, however, the system can fix this problem without user intervention by introducing new types. These types are given names such as **glbtype1** etc. They never have their own local constraint descriptions.

For example, the toy-glb grammar is almost exactly the same as the toy grammar, but the type **hd-grule** is omitted and the types which would inherit from it instead inherit from its parents. This type **hd-grule** was actually included in the toy grammar purely to avoid a glb problem. To illustrate what happens if the type hierarchy does not meet the glb condition, load the script file `toy-glb/script`, which should give the following messages:

```
Reading in type file /home/aac/toy/types.tdl
Checking type hierarchy
Checking for unique greatest lower bounds
Fixing glb problem
Partition size 15
Elements in *interesting-types* 10
Checked
Expanding constraints
Making constraints well formed
Type file checked successfully
Computing display ordering
```

The messages

```
Partition size 15
Elements in *interesting-types* 10
Checked
```

are a side effect of the glb checking. They are displayed as a way of giving the user some feedback on what the system is doing: fixing glbs can be time-consuming in a large type system with complex multiple inheritance.

In this particular case, just one glbtype is introduced. By default, the type hierarchy is displayed without glbtypes, but a hierarchy with glb types can be shown by choosing View Type Hierarchy and setting the `Show all types` checkbox. If you view the type definition of a type which has a glb type as a parent, it will show the glb type, but show the 'real' parents after it in parentheses. Apart from their user-interface properties, glbtypes behave exactly like user-defined types.

6.2.4 Constraints

Once the type hierarchy is successfully computed, the constraint descriptions associated with types are checked, and inheritance and typing are performed to give expanded constraints on types (see §4.5 or §5.2.3).

Valid constraint description The check for syntactic well-formedness of the constraint description is performed as the files are loaded, but errors such as missing types which prevent a valid feature structure being constructed are detected when the constraint description is expanded. For example, suppose the following was in the 'toy' type file, but the type **foobar** was not defined.

```
agr-cat := feat-struc &
 [ PER foobar,
   NUM num,
   GEND gend ].
```

The error messages would be as follows:

```
Invalid types (FOOBAR)
Unifications specified are invalid or do not unify
Type AGR-CAT has an invalid constraint specification
Type NON-3SING's constraint specification clashes with
its parents'
Type 3SING's constraint specification clashes with its
parents'
```

Note that the error propagates because the descendants' constraints cannot be constructed either.

Another similar error is to declare two nodes to be reentrant which have incompatible values. For example:

```
agr-cat := feat-struc &
 [ PER #1 & per,
   NUM #1 & num,
   GEND gend ].
```

The error messages would be very similar to the case above:

```
Unifications specified are invalid or do not unify
Type AGR-CAT has an invalid constraint specification
Type NON-3SING’s constraint specification clashes with
its parents’
Type 3SING’s constraint specification clashes with its
parents’
```

No Cycles Feature structures are required to be acyclic in the LKB system (see §4.3 or §5.1 and §5.2.2): if a cycle is constructed during unification, then unification fails. In the case of construction of constraints, this sort of failure is indicated explicitly. For example, suppose the following is a type definition

```
birule-headfirst := binary-headed-rule &
 [ H #1,
   NH1 #2,
   ARGS < #1 & [ H #1 ], #2 > ] .
```

The following error is generated:

```
Cyclic check found cycle at < H >
Unification failed - cyclic result
Unification failed:  unifier found cycle at < >
Type BIRULE-HEADFIRST has an invalid constraint speci-
fication
```

Consistent inheritance Constraints are constructed by monotonic inheritance from the parents’. If the parental constraints do not unify with the constraint specification, or, in the case of multiple parents, if the parents’ feature structures are not mutually compatible, then the following error message is generated:

```
Type X’s constraint specification clashes with its par-
ents’
```

Maximal introduction of features As described in §4.5 and §5.2.3, there is a condition on the type system that any feature must be introduced at a single point in the hierarchy. That is, if a feature, F, is mentioned at the top level of a constraint on a type, t, and not on any of the constraints of ancestors of t, then all constraints where F is used must be constraints on descendants of t. For example, the following would be an error because PER is a top level feature on both the constraint for **agr-cat** and **pos** but not on the constraints of any of their ancestors:

```
feat-struc :< *top*.

agr-cat := feat-struc &
 [ PER per,
   NUM num,
   GEND gend ].

pos := feat-struc &
 [ PER per,
   FORM form-cat ].
```

The error message is as follows:

```
Feature PER is introduced at multiple types (POS AGR-CAT)
```

To fix this, it is necessary to introduce another type on which to locate the feature. For example:

```
feat-struc :< *top*.

per-intro := feat-struc &
 [ PER *top* ].

agr-cat := per-intro &
 [ PER per,
   NUM num,
   GEND gend ].

pos := per-intro &
 [ PER per,
   FORM form-cat ].
```

The reason for this condition is to allow deterministic typing of feature structures.

No infinite structures Because strong typing is used, it is an error for a constraint on a type to mention that type inside the constraint (see Carpenter, 1992). For example, the following is invalid.

```
ne-list := *list* &
 [ FIRST *top*,
   REST ne-list ].
```

The reason for this is that expansion of the constraint description would create an infinite structure (as discussed in §4.5.4 and §5.2.3):

```
 [ ne-list
   FIRST *top*,
   REST [ ne-list
          FIRST *top*,
          REST [ ne-list
                 FIRST *top*,
                 REST .....
```

The following error message is produced:

```
    Error in NE-LIST: Type NE-LIST occurs in constraint for
    type NE-LIST at (REST)
```

Similarly it is an error to mention a daughter of a type in its constraint. It is also an error to make two types mutually recursive:

```
foo := *top* &
[ F bar ].

bar := *top* &
[ G foo ].
```

The error message in this case is:

```
    FOO is used in expanding its own constraint expansion se-
    quence:  (BAR FOO)
```

Note that it *is* possible to define recursive constraints on types as long as they specify an ancestor of their type. For example, a correct definition of **list** is:

```
*list* :< *top*.

ne-list := *list* &
 [ FIRST *top*,
   REST *list* ].

elist :< *list*.
```

With this definition, the previously impossible feature structure can be strongly typed without causing an infinite structure:

```
[ ne-list
  FIRST *top*,
  REST ne-list ].
```

is expanded to:

```
[ ne-list
  FIRST *top*,
  REST  [ ne-list
          FIRST *top*,
          REST *list* ] ]
```

Type inference — features There are two cases where typing may fail due to the feature introduction condition. The first is illustrated by the following example:

```
noun-lxm := lexeme &
 [ SYN [ HEAD noun,
         INDEX *top* ],
   SEM [ INDEX ref-index ] ].
```

Here, the feature INDEX is only defined for structures of type **sem-struc**. This type clashes with **gram-cat** which is the value of SYN specified higher in the hierarchy. This example generates the following error messages:

```
Error in NOUN-LXM:
   No possible type for features (INDEX HEAD) at
   path (SYN)
Error in PN-LXM:
   No possible type for features (COMPS SPR HEAD INDEX) at
   path (SYN)
```

A slightly different error message is generated when a type is specified at a node which is incompatible with the node's features. For instance:

```
synsem-struc := feat-struc &
 [ ORTH list-of-orths,
   SYN gram-cat &
       [ MODE mode-cat ],
   SEM sem-struc ].
```

```
Error in SYNSEM-STRUC: Type of fs GRAM-CAT at path (SYN)
is incompatible with features (MODE) which have maximal
type SEM-STRUC
```

Note that, because the system attempts to expand other type constraint descriptions after detecting this error, there are a lot of similar error messages from the types for which **synsem-struc** is an ancestor.

Type inference — type constraints The final class of error is caused when type inference causes a type to be determined for a node which then clashes with an existing specification on a path from that node.

```
Unification with constraint of GRAM-CAT failed at path
(SYN)
```

6.3 Lexical entries

When lexicon files are loaded, they are only checked for syntactic correctness (as defined in §5.3.3) — entries are only fully expanded when they are needed during parsing or generation or because of a user request to view an entry. Thus when loading the lexicon, you may get syntactic errors similar to those discussed in 6.2.1 above, but not content errors since the feature structures are not expanded at load time. The lexicon is stored in a temporary file (called by default `templex`) when it is read in, not in main memory.

Incorrect lexical entries will therefore only be detected when you view a lexical entry or try to parse with it. The error messages that are obtained are very similar to some of those discussed for the type loading above, specifically:

Valid constraint description

No Cycles

Consistent inheritance

All types must be defined

Strong typing — features

Strong typing — type constraints

There is a menu option to do a complete check on a loaded lexicon for correctness: Check lexicon under Debug. See 7.1.7, below.

6.4 Grammar rules

Unlike lexical entries, grammar and lexical rules are expanded at load time. Therefore you may get error messages similar to those listed above for lexical entries when the rules are loaded. Rules must expand out into feature structures which have identifiable paths for the mother and daughters of the rule (§5.3.4). For the ‘toy’ grammar, the mother path is the empty path and the daughter paths are defined in terms of the ARGS feature. For example:

$$\begin{bmatrix} \textbf{binary-rule} & \\ \text{ARGS} & \begin{bmatrix} \text{FIRST } \textbf{sign} \\ \text{REST } \begin{bmatrix} \text{FIRST } \textbf{sign} \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

Here the mother is given by the empty path, one daughter by the path ARGS.FIRST and another by the path ARGS.REST.FIRST. The mother path and a function which gives the daughters in the correct linear order must be specified as system parameters in the globals and user-fns files respectively (see §C.2.3 and §C.3).

6.5 Lexical and morphological rules

Lexical rules are defined very similarly to grammar rules, but unlike grammar rules can have associated affixation information, in which case we refer to them as morphological rules. Lexical rules in general can be applied in any order that is licensed by the affixation: thus lexical rules that don’t affect spelling can be interleaved with morphological rules. The syntax for lexical rules without associated affixation is identical to that for grammar rules. In principle lexical rules which do not affect affixation may also be applied to phrases — all conditions on lexical rule application must be explicitly encoded, e.g., by stipulating that lexical rules may only apply to **word**s rather than **phrase**s. Normally this is done by defining type(s) for lexical rules.

For example, if you look at the `esslli/rattle` grammar, you will see that there is a three-way distinction between the types **lexeme**, **word** and **phrase** (the latter two being subtypes of **gram-cat**). All the inflectional lexical rules are either of type **lrule-infl** or **lrule-no-aff**. In either case they are defined to convert between a **lexeme** and a **word**. In contrast, all the grammar rules are defined so that their daughters are of type **gram-cat**, so that they cannot apply to lexemes. However, note that in the `esslli/enddayfour` grammar, two other classes of lexical rule are defined, one which converts **lexeme**s to **lexeme**s (dative shift) and one which converts **word**s to **word**s.

Morphological rules are lexical rules with added orthographic information describing affixation. The morphology system expects that the orthographic specification comes immediately after the `:=` or `:<` in the rule. For example:[3]

```
plur-noun_infl_rule :=
%suffix (!s !ss) (!ss !ssses) (ss sses)
(!ty !ties) (ch ches) (sh shes) (x xes) (z zes)
lex_rule_infl_affixed &
[ NEEDS-AFFIX true,
  ARGS [ FIRST [ AFFIX  plur-noun] ] ].
```

Note that the file is read in in two passes, with information beginning with % being interpreted as part of the orthographemics specification, and everything else being treated as feature structure descriptions, just like ordinary lexical rules. Lexical rules which don't affect affixation may be in a file with morphological rules: the former are simply ignored by the orthographemic reader. A description of the operation of the orthographemic component is given in §5.3.5.

For discussion of how the rules are treated during parsing, see §6.7.

6.6 Irregular morphology

Irregular morphology may be specified in association with a particular lexical rule, but it is often more convenient to have a separate file for irregular morphemes. For compatibility with the PAGE system, this file should take the form of a string containing irregular form entries, one per line, each consisting of a triplet:

1. inflected form
2. rule
3. stem

For example:

[3]Note: the linebreak in the orthographemic specification below is just for readability, it is not allowed in the actual file.

```
"
fell PAST-VERB fall
felt PAST-VERB feel
"
```

The interpretation of irregular forms is similar to the operation of the regular morphology: that is, the irregular form is assumed to correspond to the spelling obtained when the specified rule is applied to a lexical entry with an orthography corresponding to the stem. If the value of `*lex-rule-suffix*` (see §C.2.3) is specified, the actual rule name is constructed by concatenating this suffix onto the supplied name (e.g. if `*lex-rule-suffix*` is `"-lex-rule"` then `past-verb` will be interpreted as the rule `past-verb-lex-rule`).

The default operation of the irregular morphology system is one of the very few cases where there may be an asymmetry in system behaviour between parsing and generation: when parsing, a regularly derived form will be accepted even if there is also an irregular form if the value of `*irregular-forms-only-p*` (see §C.2.3) is `nil`.[4] Thus, for example, *gived* will be accepted as well as *gave*, and *dreamed* as well as *dreamt*. If the value is `t`, an irregular form will block acceptance of a regular form. Generation will always produce the irregular form if there is one: currently it will simply produce the first form for a particular rule even if there are alternative spellings. So assume the following is included in the irregulars file:

```
dreamed PAST-VERB dream
dreamt PAST-VERB dream
```

Including both forms would be desirable for parsing if `*irregular-forms-only-p*` is true, because it would allow both variants to be accepted, but for generation, only *dreamed* would be produced.

6.7 Rule application during parsing

At this point, it is useful to bring together a few details about how rules are applied during parsing. It's important to notice that there is considerable flexibility in the way rules are applied, since as far as possible we try not to build in any unnecessary assumptions about processing. As far as the parser is concerned, the primary distinction is between rules that affect spelling changes (i.e., morphological rules) and those that don't. The system makes the assumption that all morphological processing happens at the level of an individual word (although see §8.4). Thus, when parsing, all affixation operations apply before grammar rules.[5] This means that it is the grammar writer's responsibility to stop rules applying in unwanted ways. On the whole, this is done via the type system, as was discussed above in §6.5. However there are two situations for which this mechanism is insufficient, or undesirably clunky. The first case is the marking of rules which have associated

[4]Note that throughout the LKB, Lisp conventions are used for the specification of boolean parameters, so `t` indicates true and `nil` indicates false.

[5]There are some examples in English morphology which arguably make this assumption problematic. For example, there is a suffix *-ed*, which forms adjectives such as *broken-hearted*, and which could be described as applying to an adjective noun phrase to form an adjective. Note that the adjective is obligatory (**a hearted lover*), the result is sometimes but not always hyphenated, and that the process is productive (e.g., *rattan chaired terrace*). We leave this problem as an exercise for the advanced reader.

spelling effects. This is necessary to prevent these rules being applied when they are not licensed by the spelling. This is done by means of a user-definable function, `spelling-change-rule-p`, which specifies whether or not a rule affects spelling (see §C.3). In the version of the file `userfns` supplied with the toy grammar, this checks the rule to see if its type is **lrule-infl**, or a subtype of that. The other case in which a rule should not be applied by the parser is when it is a redundancy rule which is not intended to be applied productively, but we leave discussion of redundancy rules to §C.3, since they are not used in any of the grammars supplied.

The other complication in parsing is the notion of an *initial structure* (also known as *root*) that corresponds to a *start symbol* discussed in the next section.

6.8 Start symbol file

A valid parse is defined as a well-formed phrase that spans the entire input string and which also satisfies any *initial structure* conditions that the grammar writer may impose. For instance, *Kim sleep*, with non-finite *sleep*, might be a valid phrase (because of sentences such as *Sandy prefers that Kim sleep*), but blocked from being a sentence because of an initial condition that requires a finite main verb.

Initial conditions are implemented in the LKB via a parameter `*start-symbol*` which points to feature structure specifications which must be compatible with all parses. If the value of `*start-symbol*` is `nil`, then any phrase which spans the input is accepted. Otherwise, the value of `*start-symbol*` may be a single identifier or a list of identifiers of feature structures: the feature structure associated with a phrase must unify with at least one of the start symbol feature structures in order to be accepted as a valid parse. The identifiers may be types, in which case the associated feature structure is the constraint on the type. Start symbol types are treated like any other type with respect to loading, viewing etc.

The value of `*start-symbol*` may be altered interactively, via the Options / Set options menu command: if the right initial condition structures are defined this allows the user to switch easily between allowing only full sentences and allowing fragments.

In the sample `esslli/toy` grammar, the start symbols are entries. For convenience, such entries can be stored in a separate file. Start symbol entries may be viewed via View Lex Entry.

6.9 Parse tree node labels

The parse node file allows feature structures which control the labelling of the nodes in the parse tree to be defined (for parse tree display, see 7.5). We will refer to these structures as templates, but this use shouldn't be confused with any other use of the term. In very general terms, a node will be labelled with a template, iff the feature structure associated with the node is matched by the feature structure(s) associated with that template. The format for parse node descriptions is identical to that of lexical entries. Parse nodes may be viewed via Lex Entry on the View menu.

The precise behaviour of the node labelling depends on the value of `*lkb-system-version*`.

6.9.1 Original version

If `*lkb-system-version*` is not set to `:page`, then the templates consist of identifiers associated with single feature structures. If the template feature structure subsumes the structure constructed for a node in a parse, the node is labelled with the identifier of the template. The first matching template is used, and if no template matches, then the node is labelled with the type of its own feature structure.

6.9.2 PAGE emulation version

If `*lkb-system-version*` is set to `:page`, the parse tree labelling is more complex. There are two classes of templates: *label* and *meta* structures (see §C.1.3 for the parameters). Each label template feature structure specifies a single string at a fixed path in its feature structure (LABEL-NAME in the sample grammars). For instance, the following is a label from the 'textbook' grammar.

```
np :=  label &
 [ SYN [ HEAD noun,
         SPR < > ],
   LABEL-NAME "NP" ].
```

Meta templates are used for things such as `/` (e.g. to produce the label `S/NP`). If meta templates are specified, each meta template feature structure must specify a prefix string and a suffix string (by default, at the paths META-PREFIX and META-SUFFIX). For instance, the following is specified as a meta template in the textbook grammar:

```
slash := meta &
  [ SYN [ GAP [ LIST ne-list ] ],
    META-PREFIX "/",
    META-SUFFIX "" ].
```

To calculate the label for a node, the label templates are first checked to find a match. Matching is tested by unification of the template feature structure, excluding the label path, with the feature structure on the parse tree node. For instance, if a parse tree node had the following feature structure:

```
[ SYN [ HEAD *top*,
        SPR < > ]].
```

it would unify with

```
 [ SYN [ HEAD noun,
         SPR < > ]].
```

and could thus be labelled `NP`, given the structure above. There is a parameter, `*label-fs-path*`, which allows templates to be checked on only the substructure of the node feature structure which follows that path, but this is parameter is set to the empty path in the textbook grammar.

If meta templates are specified, the feature structure at the end of the path specified by the parameter `*recursive-path*` ((SYN GAP LIST FIRST) in the textbook grammar) is checked to see whether it matches a meta template. If it does, the meta structure is checked against the label templates (the parameter `*local-path*` allows them to be checked against a substructure of the meta structure). The final node label is constructed as the concatenation of the first label name, the meta prefix, the label of the meta structure, and the meta suffix.

6.10 Ancillary files

The following are grammar specific files which parameterize the behaviour of the system. These should not be relevant to users who are working on an existing grammar, so details are left to Chapter 8 and the appendices.

6.10.1 Globals

Default file name `globals.lsp`. Contains parameters that may be changed by the user. Details are given in Appendix C.

6.10.2 User preferences

Default file name `user-prefs.lsp`. Some of the parameter settings can be controlled interactively via Set options on the Options menu (see §7.1.9). Specifying this file in the script means that any preferences which are set in one session will be saved for a subsequent session. The user should not need to look at this file and should not edit it, since any changes may be overwritten. Details of the individual parameters are given in Appendix C.

6.10.3 User defined functions

Default file name `user-fns.lsp`. There are a few functions which control parameters such as rule ordering which may differ in different grammars. These are in the user-fns file (written in Lisp). Details are given in Appendix C.

Chapter 7

LKB user interface

In this chapter, we explain the details of the menu commands and other aspects of the graphical user interface. Note that most of this is not relevant for people using the tty version of the system.

Apart from the LKB top window in the ACL/CLIM interface, there are a number of other types of LKB window which are described in this chapter, which display the following classes of object:

1. Type hierarchy
2. Feature structure
3. Parser and generator output results
4. Individual parse trees
5. Parse chart

Note that in the ACL/CLIM version, all windows for these structures have three buttons: Close, Close all and Print. Close will close the individual window, Close all will close all windows of that class — e.g., all type hierarchy windows etc. Print produces a dialog that allows one to write a Postscript file which can then be printed. Printing directly to a printer is not implemented yet.

7.1 Top level commands

The top level command window is displayed when the LKB is loaded in the ACL/CLIM interface. Note that, in the ACL version, it is possible for the interaction window to be closed inadvertently. It may be reopened by evaluating (clim-user::restart-lkb-window) in Lisp (i.e., the `*common-lisp*` buffer in emacs). In both versions it is possible to end up in a state where most of the commands are unavailable because the system does not think a grammar has been loaded: to fix this, evaluate (enable-type-interactions).

In the MCL interface, the LKB menu is added to the top menu.

In this section the LKB menu commands will be briefly described in the order in which they appear in the ‘mini’ interface. Commands which are only in the ‘advanced’ version are indicated by an asterisk. To switch between versions, use the Shrink menu or Expand menu commands under Options.

7.1.1 Quit

ACL/CLIM only. Prompts the user to check if they really do want to quit. If so, it shuts down Lisp.

7.1.2 Load

The basic commands allow the loading of a script file and the reloading of the same file (normally this would be done after some editing). The advanced commands allow the user to reload various types of file using the menu interface. A script is used initially to load a set of files, and then individual files can be reloaded as necessary after editing. Reloading files is not as safe as reloading the script, since there are various circumstances which may cause an individually reloaded file to cause a grammar to behave differently from the expected behaviour (some of which are mentioned below). The reload options are therefore only on the 'advanced' menu.

Complete grammar This prompts for a script file to load, and then loads the grammar as discussed above.

Reload grammar This reloads the last loaded script file.

Reload constraints*

Reload leaf types*

Reload lexicon*

Reload grammar rules*

Reload lexical rules* includes morphological rules

Reload tree nodes* There is an infelicity which causes this to give refinition warnings for each tree node.

Reload other entries* There is an infelicity which causes this to give refinition warnings for each entry.

7.1.3 View

These commands all concern the display of various entities in the grammar. Many of these commands prompt for the name of a type or entry. For the ACL/CLIM version, if there are a relatively small number of possibilities, these will be displayed in a menu.

Type hierarchy Displays a type hierarchy window.

Prompts for the highest node to be displayed. If the type hierarchy under this node is very large, it will double-check that the user wants to continue (generally, large hierarchies won't be very readable, so it's probably not worth the wait). The check box allows 'invisible' types, such as glbtypes, to be displayed if set. Details of the type hierarchy window are in §7.2.

Type definition Shows the definition of a type constraint plus the type's parents.

Prompts for the name of a type. If the type hierarchy window is displayed, scrolls the type hierarchy window so that the chosen type is centered and highlighted. Displays the type's parents and the constraint specification in a feature structure window: details of feature structure windows are in §7.3.

Expanded type Shows the fully expanded constraint of a type.

Prompts for the name of a type. If the type hierarchy window is displayed, scrolls the type hierarchy window so that the chosen type is centered and highlighted. Displays the type's parents and the full constraint on the type.

Lex entry The expanded feature structure associated with a lexical entry (or parse node label or root structure etc).

Prompts for the identifier of a lexical entry (or a parse node label or root structure). Displays the associated feature structure.

Word entries All the expanded feature structures associated with a particular orthographic form.

Prompts for a word stem. Displays the feature structures corresponding to lexical entries which have this stem.

Grammar rule Displays a grammar rule.

Prompts for the name of a grammar rule, displays it in a feature structure window.

Lexical rule Displays a lexical or morphological rule.

Prompts for the name of a lexical rule, displays its feature structure in a window.

7.1.4 Parse

Parse input This command prompts the user for a sentence (or any string), and calls the parser (possibly modifying the input according to the user-defined function `preprocess-sentence-string`, see C.3). A valid parse is defined as a structure which spans the entire input and which will unify with the feature structure(s) identified by the value of the parameter `*start-symbol*`, if specified (i.e., the initial structure(s), see §6.8 and §6.7). (Note that `*start-symbol*` may be set interactively.) If there is a valid parse, the parse tree(s) are displayed. Currently, in the Mac version, all the parse trees are displayed in separate windows, while in the ACL/CLIM version a single window with very small parse trees is displayed (see §7.4).

Note that it is sometimes more useful to run the parser from the Lisp command line interface, since this means that any results generated by post-processing will appear in an editor buffer and can be searched, edited and so on. It may also be useful to do this if you have to use emacs to enter diacritics. The command `do-parse-tty` is therefore available in non-tty mode as well as tty-mode — it takes a string as an argument. For example:

```
(do-parse-tty "Kim sleeps")
```

In the tty version of the system, this outputs a bracketed structure — otherwise the normal graphical parse output is produced.

Redisplay parse Shows the tree(s) from the last parse again.

Show parse chart Shows the parse chart (see §7.6).

Batch parse This prompts for the name of a file which contains sentences on which you wish to check the operation of the parser, one sentence per line (see the file `test.items` in the `esslli/toy` grammar). It then prompts for the name of a new file to which the results will be output. The output simply tells you the number of parses found (if any) for each sentence in the input file and the number of edges, and gives a time for the whole set at the end. This is a very simple form of test suite: vastly more functionality is available from the [incr tsdb()] machinery which can be run in conjunction with the LKB (see 8.13).

Compare* (ACL/CLIM only) This displays the results of the last parse, together with a dialog that allows selection / rejection of rule applications which differ between the parses. It thus allows comparison of parses according to the rules applied. It is intended for collection of data on preferences but can also be useful for distinguishing between a large set of parse results. Specifying that a particular phrase is in/out will cause the relevant parse trees to be indicated as possible/impossible and the other phrases to be marked in/out, to the extent that this can be determined.

The parameter `*discriminant-path*` can be set to identify a useful discriminating position in a structure: the default value corresponds to the location of the key relation in the semantic structure used by the LinGO ERG.

7.1.5 MRS*

MRS commands are only available if the MRS system has been loaded (i.e., (load-system ”mrs”) rather than (load-system ”lkb”)) — see Chapter 2. The MRS commands are loaded into the distributed images.

The MRS commands relate to semantic representation, but they assume a particular style of semantic encoding, as is used in the LinGO ERG. The textbook grammars use a simplified version of MRS. MRS is briefly discussed in §8.11. MRS output can be displayed in various ways by clicking on the result of a parse in the compact parse tree representation (ACL/CLIM only, see §7.4), or displayed in the main editor window (*common-lisp* buffer or Listener), as controlled by the Output level command below. The parameterisation for MRS is controlled by various MRS-specific files, discussed in §8.11.

Load munger The term *munger* refers to a set of rules which manipulate the MRS in application-specific ways. Loading a new set of rules will overwrite the previously loaded set. Most users can ignore this.

Clear munger Deletes the munger rules.

Output level Allows the user to control the output to the editor window.

None

Base An underspecified MRS, generally quite similar to the feature structure representation.

Scoped The scoped forms corresponding to the underspecified structure produced by the grammar. If no scoped forms can be produced, warning messages are output. If there are a large number of scoped forms, only a limited number are shown, by default. Because scoping can be computationally expensive, there is a limit on the search space for scopes: this is controlled by `mrs::*scoping-call-limit*`.

VIT VIT stands for Verbmobil interchange term. This is not available for most users. (Note for CSLI users: the VIT output attempts to invoke a Prolog process to check the VIT — this can cause noticeable delays.)

The default output level is **none**, but this may be changed by the grammar-specific MRS globals files.

7.1.6 Generate*

The generator is only available if the MRS system has been loaded (i.e., (load-system ”mrs”) rather than (load-system ”lkb”)) — see Chapter 2. The MRS commands are loaded into the distributed images.

The generator is described in more detail in §8.12, but is currently in a fairly early stage of development. It operates in a very similar manner to the parser but relies on the use of an MRS style semantics, thus it will only work with grammars that produce such semantics: currently just the LinGO ERG and the textbook grammar (though the latter has several problems at the time of writing). Before the generator can be used, the command Index must be run from this menu. At the moment, there is no interactive way of entering an MRS input other than by parsing a sentence which produces that MRS and then choosing Generate from the appropriate parse window.

Redisplay realisation Redisplays the results from the last sentence generated.

Show gen chart Displays a chart from the generation process (see §7.6). Note that the ordering of items on the chart is controlled by their semantic indices.

Load heuristics Prompts for a file which should contain a set of heuristics for determining null semantics lexical items (see §8.12).

Clear heuristics Clears a set of heuristics, loaded as above.

Index Indexes the lexicon and the rules for the generator. This has to be run before anything can be generated.

7.1.7 Debug

Check lexicon Expands all entries in the lexicon, notifying the user of any entries which fail to expand. This will take a few minutes for a large lexicon.

Find features' type* Used to find the maximal type (if any) for a list of features (see §4.5.4 and/or §5.2.3 for a discussion of maximal types). Warns if feature is not known.

Prompts for a list of features.

Print parser chart Displays the chart (crudely) in the LKB interaction window. This can be useful as an alternative display to the parse chart window, especially with very large charts.

Print generator chart* As above, but for generator.

7.1.8 Advanced*

Tidy up This command clears expanded lexical entries which are cached. If accessed again they will be read from file and expanded again.

Expansion of a large number of word senses will tend to fill up memory with a large number of feature structures. Most commands which are likely to do this to excess, such as the batch parser, actually clear the cached feature structures themselves, but if a lot of sentences have been parsed interactively and memory is becoming restricted this option can be used. However often more memory will be reclaimed by closing any open feature structure windows, and especially the Type Hierarchy window.

Create quick check file The check path mechanism constructs a filter which improves efficiency by processing a set of example sentences. It is discussed in more detail in §8.3.1.

The command prompts for a file of test sentences and an output file to which the resulting paths should be written. This file should subsequently be read in by the script. Note that constructing the check paths is fairly time-consuming, but it is not necessary to use a very large set of sentences. The mechanism is mildly grammar-specific in that it assumes the style of enconding where the daughters of a rule are given by an ARGS list — see §8.3.1 for details.

7.1.9 Options

Expand/Shrink menu Changes the LKB top menu so that the asterisked commands are added/removed.

Set options Allows interactive setting of some system parameters. Note that the values of the boolean parameters are specified in the standard way for Common Lisp: that is, `t` indicates true and `nil` indicates false. We will not go through the parameters here: Appendix C gives full details of all parameters, including those that cannot be altered interactively.

If a parameter file has been read in by the script (using `load-lkb-preferences`) the parameter settings are saved in the same file. Otherwise the user is prompted for the name of a file to save any preference changes to.

Usually the preferences file is loaded by the script so that any preferences which are set in one session will be saved for a subsequent session with that grammar. (In the cases of 'families' of grammars, such as the ESSLLI grammars supplied with the LKB, the user-prefs file may be shared by all the grammars in the family.) The user should not need to look at this file and should not edit it, since any changes may be overwritten.

Save display settings Save shrunkenness of feature structures (see the description of Shrink/Expand in §7.3).

Load display settings Load pre-saved display setting file.

7.2 Type hierarchy display

By default, a type hierarchy is displayed automatically after a grammar is loaded (though this default must be turned off for grammars that use very large numbers of types, see §C.1.1)). The type hierarchy can also be accessed via the top level command Type hierarchy in the View menu, as discussed above in 7.1.3.

The top of the hierarchy, that is the most general type, is displayed at the left of the window. The window is scrollable by the user and is automatically scrolled by various View options. Nodes in the window are active; clicking on a type node will give a menu with the following options:

Shrink/Expand Shrinking a type node results in the type hierarchy being redisplayed without the part of the hierarchy which appears under that type being shown. The shrunk type is indicated by an outline box. Any subtypes of a shrunk type which are also subtypes of an unshrunk type will still be displayed. Selecting this option on a shrunk type reverses the process.

Type definition Display the definition for the constraint on that type (see Section 7.1.3, above).

Expanded type Display the expanded constraint for that type (see Section 7.1.3, above).

New hierarchy Displays the type hierarchy under the clicked-on node in a new window, via the same dialog as the top-level menu command. This is useful for complex hierarchies.

7.3 Feature structure display

Most of the view options display feature structures in a window. Our usual orthographic conventions for drawing feature structures are followed; types are lowercased bold, features are uppercased. Feature structure windows are active - currently the following operations are supported:

1. Clicking on the window identifier (i.e. the first item in the window) will display a menu of options which apply to the whole window.

   Output TeX Outputs the FS as LaTeX macros to a file selected by the user. The LaTeX macros are defined in `avmmacros` in the data directory.

   Apply lex rule Only available if the identifier points to something that might be a lexical entry. It prompts for a lexical or morphological rule and applies the rule to the entry. The result is displayed if application succeeds.

   Apply all lex rules Only available if the identifier points to something that might be a lexical entry. This tries to apply all the defined lexical and morphological rules to the entry, and to any results of the application and so on. (To prevent infinite recursion on inappropriately specified rules the number of applications is limited.) The results are displayed in summary form, for instance:

   ```
   consultant_n1 + SING_NOUN_INFL_RULE

   consultant_n1 + PLUR_NOUN_INFL_RULE
   ```

   Clicking on one of these summaries will display the resulting feature structure.

   Show source Shows the source code for this structure if ACL/CLIM is being used with emacs — see §8.9 This is not available with all structures: it is not available for any entries which have been read in from a cached file.

2. Clicking on a reentrancy marker gives the following sub-menu:

   Find value Shows the value of this node, scrolling as necessary.

   Find next Shows the next place in the display where there is a pointer to the node, scrolling as necessary.

3. Clicking on a type (either a parent, or a type in the feature structure itself) will give a submenu with the following options:

   Hierarchy Scroll the type hierarchy window so that the type is centered. If the type hierarchy window is not visible, use View Type Hierarchy to redisplay it in order to make this command available.

   Shrink/Expand Shrinking means that the feature structure will be redisplayed without the feature structure which follows the type being shown. The existence of further undisplayed structure is indicated by a box round the type. Atomic feature structures may not be shrunk. Shrinking persists, so that if the window is closed, and subsequently a new window opened onto that feature structure, the shrunken status will be retained.

Furthermore, if the shrunken structure is a type constraint, any feature structures which inherit from this constraint will also be displayed with equivalent parts hidden. For instance, if the constraint on a type has parts shrunk, any lexical entry which involves that type will also be displayed with parts hidden.

If this option is chosen on an already shrunken feature structure then the feature structure will be expanded. Again this can affect the display of other structures.

The shrunkenness state may be saved via and loaded via the Save/Load display settings commands on the Options menu (see §7.1.9).

Show source Shows the source code for this structure if ACL/CLIM is being used with emacs — see §8.9 (not available with all structures)

Type definition Display the definition for that type.

Expanded type Display the expanded definition for that type.

Select Selects the feature structure rooted at the clicked node in order to test unification.

Unify Attempts to unify the previously selected feature structure with the selected node. Success or (detailed) failure messages are shown in the LKB Top window. See 7.3.1 for further details.

Clicking on a type which is in fact a string, and thus has no definition etc, will result in the warning beep, and no display.

The order in which features are displayed is determined according to their order when introduced in the type specification file. For example, assume we have the following fragment of a type file:

```
sign := feat-struc &
 [ SYN *top*,
   SEM *top* ].

word := sign &
 [ ORTH string ].
```

then when a feature structure of type **sign** is displayed, the features will be displayed in the order SYN, SEM; when a **word** is displayed the order will be SYN, SEM, ORTH. This ordering can be changed or further specified by means of the parameter `*feature-ordering*`, which consists of a list of features in the desired order (see §C.1.2).

ACL/CLIM only — the bar at the bottom of the window shows the path to the node the cursor is currently at.

7.3.1 Unification checks

The unification check mechanism operates on feature structures that are displayed in windows. One can temporarily select any feature structure or part of a feature structure by clicking on the relevant node in a displayed window and choosing Select from the menu. Then to check whether this structure unifies with another, and to get detailed messages if unification fails, find the node corresponding to the second structure, click on that, and choose Unify. If the unification fails, failure messages will be shown in the top level LKB window. If it succeeds, a new feature structure window will be displayed. This can in turn be used to check further unifications.

For example, consider why "Kim sleep" does not parse in the `eslli/buggy` grammar. In fact, the parse is blocked by the initial (root) structure condition because we will want to license the phrase "Kim sleep" in some contexts, e.g., *Sandy prefers that Kim sleep*. By looking at the parse chart for the sentence, one can determine that the hd-spec-rule will apply to combine the VP for the infinitival form of *sleep* and the NP for *Kim*. However this is not a valid parse, because the result is not unifiable with the feature structure named by `root`.

You can verify this by the following procedure:

1. Load the `buggy` grammar.
2. Parse input on "Kim sleep". The parse will fail.
3. Do Show chart. A chart window will appear.
4. Click on the node in the chart that says hd-spec-rule and select Feature structure. A feature structure window will appear.
5. Click on the root node of the feature structure (i.e., the one that says **birule-hdfinal** in the new feature structure window and choose Select.
6. Display the feature structure for `root` by choosing Lex entry from the View menu (`root` is not actually a lexical entry, but it is structurally similar, and we wanted to avoid putting too many items on the View menu.)
7. Click on the root node of `root` (i.e., the node with the type **phrase**) and choose Unify from the pop-up menu.
8. Look at the Lkb Top window. You should see:

```
Unification of (INF) and (FIN) failed at path
< SYN : HEAD : FORM >
```

To check why a rule does not work, a more complex procedure is sometimes necessary, because of the need to see whether three (or more) feature structures can be unified. Suppose we want to check to see why the head-specifier-rule does not apply to "the book sleep" using the the finite form of *sleep*. This is complex, since both the feature structures for the NP for "the book" and the VP for 3pl *sleep* will individually unify with the daughter slots of the hd-spec-rule feature structure. So we need to use the intermediate results from the unification test mechanism.

The following description details one way to do this.

1. Parse "the book sleep". The parse will fail.
2. Select Show chart to show the edges produced during the failed parse.
3. Bring up the feature structure window for the uninstantiated hd-spec-rule (either via the View Rule command in the top window menu or from the chart).

4. Find the node in the hd-spec-rule window corresponding to the specifier (i.e. the node labelled **gram-cat** at the end of the path `(ARGS FIRST)`). Because this is coindexed with `(NH1)` you may have to follow the coindexations to get to the node itself. Click on it and choose Select.

5. Find the node for `the book` in the parse chart window and choose Unify. (Note that this is a shortcut which is equivalent to displaying the feature structure for the phrase via the Feature Structure option in the chart menu and then selecting Unify from the menu on the top node of the feature structure displayed.) Unification should succeed and a new feature structure window (titled Unification Result) will be displayed.

6. Find the node in the new Unification Result window corresponding to the head in the rule, i.e. the node at the end of the path `(ARGS REST FIRST)`, click on it and choose Select.

7. Click on the node in the parse chart for the finite form of `sleep` (i.e., the one labelled `non3sg-v_irule`) and choose Unify.

8. This time unification should fail, with the following message in the LKB Top window:

```
Unification of 3SING and NON-3SING failed at path
< SYN : SPR : FIRST : SYN : HEAD : AGR >
```

Note that it is important to Select the node in the rule and Unify the daughter nodes because the result shown always corresponds to the initially selected feature structure. We want this to be the rule so we can try unifying the other daughter into the partially instantiated result.

7.4 Parse output display

ACL/CLIM version only.

The parse output display is intended to give an easily readable overview of the results of a parse, even if there are several analyses. The display shows a parse tree for each separate parse, using a very small font to get as many trees as possible on the screen. Clicking on a tree gives several options:

Show enlarged tree produces a full size parse tree window, as in §7.5, with clickable nodes etc.

Highlight chart nodes will highlight the nodes on the parse chart corresponding to this tree. If the parse chart is not currently displayed, this option will bring up a new window (see §7.6 for details of the chart display).

If the MRS system has been loaded, the following commands are also available:

Generate Tries to generate from the MRS for this parse. Note that in order to run the generator, the Generate / Index command must have been run.

MRS Displays an MRS in the feature structure style representation.

Indexed MRS Displays an MRS using the alternative linear notation.

Scoped MRS Displays all the scopes that can be constructed from the MRS: warning messages will be output if the MRS does not scope.

Besides the standard Close and Close all buttons, the window has a button for Show chart for convenience. It has the same effect as the top-level menu command.

7.5 Parse tree display

Parse trees are convenient abbreviations for feature structures representing phrases and their daughters. When a sentence is successfully parsed, the trees which display valid parses are shown, but parse trees may also be displayed for any edge in a parse chart (see §7.6). The nodes in the parse tree are labelled with the name of the (first) parse node label which has a feature structure which matches the feature structure associated with the node, if such a label is present. The matching criteria are detailed in 6.9.

Clicking on a node in the parse tree will give the following options:

Feature structure - Edge X (where X is the edge number in the parse chart) displays the feature structure associated with a node. Note that if the parameter `*deleted-daughter-features*` is set, the tree will still display the full structure (it is reconstructed after parsing). See §8.3.3.

Show edge in chart Highlights the node in the chart corresponding to the edge. The chart will be redisplayed if necessary. Currently not available for a tree produced by the generator.

Rule X (where X is the name of the rule used to form the node) displays the feature structure associated with the rule.

Generate from edge Only available if the MRS system is loaded, this attempts to generate a string from the MRS associated with this node. Can give strange results if the node is not the uppermost one in the tree. Currently not available with a tree produced by the generator. Note that in order to run the generator, the Generate / Index command must have been run.

Lex ids This isn't a selectable option - it's just here as a way of listing the identifiers of the lexical entries under the node.

The input words are indicated in bold below the terminal parse tree nodes — if any morphological rules have been applied, these are indicated by nodes beneath the words if the parameter `*show-morphology*` is t, but not shown otherwise. Similarly the parameter `*show-lex-rules*` controls whether or not the lexical rule applications are displayed. Both these parameters may be set interactively, via the Options / Set options menu command.

7.6 Chart display

The chart is a record of the structures that the LKB system has built in the course of attempting to find a valid parse or parses.[1] The parser works bottom-up: that is, it does not use any information

[1]Chart parsing is a technique described in many introductory NLP and AI texts. We don't assume any detailed knowledge of it here.

about the global goal of constructing a sentence (or whatever the initial structures are) in order to constrain the structures that it builds. A structure built by the parser and put on the chart is called an *edge*: edges are identified by an integer (*edge number*). By default, all edges that are displayed on the chart represent complete rule applications.

The chart window shows the words of the sentence to the left, with lines indicating how the structures corresponding to these words are combined to form phrases. Each node in the chart display proper corresponds to an edge in the chart. Its label shows the following information:

1. The nodes of the input that this edge covers (where the first node is notionally to the left of the first word and is numbered 0, just to show we're doing real computer science here).

2. The edge number (in square brackets)

3. The name of the rule used to construct the edge (or the type of the lexical item)

For instance, in the chart for the sentence *Kim does like Sandy*, the nodes for the input are numbered

$\cdot_0$ *Kim* $\cdot_1$ *does* $\cdot_2$ *like* $\cdot_3$ *Sandy* $\cdot_4$

In the chart display resulting from parsing this sentence in the textbook grammar, one edge is specified as:

```
2-4 [25] HEAD-COMPLEMENT-RULE
```

Thus this edge is edge number 25, it covers *like Sandy*, and was formed by applying the `head-complement-rule`.

Clicking on an edge node results in the following menu:

Highlight nodes Highlights all the nodes in the chart for which the chosen node is an ancestor or a descendant. In ACL/CLIM, this option also selects the node so that it can be compared with another node (see **Compare**, below).

Feature structure Shows the feature structure for the edge. Unlike the parse tree display, this represents the feature structure which is actually used by the parser: that is it is not reconstructed if `*deleted-daughter-features*` is used. See §8.3.3.

Rule X Shows the feature structure for the rule that was used to create this edge

New chart Displays a new chart which only contains nodes for which the chosen node is an ancestor or a descendant (i.e. those that would be highlighted). This is useful for isolating structures when the chart contains hundreds of edges.

Tree Shows the tree headed by the phrase corresponding to this edge

Compare ACL/CLIM only. This option is only available if another node has been previously selected (using Highlight Nodes). The two nodes are compared using the parse tree comparison tool described in §7.1.4.

Unify This is only shown if a feature structure is currently Selected for the unification test — see §7.3.1.

The chart display is sensitive to the parameters `*show-morphology*` and `*show-lex-rules*` in the same way as the tree display.

In ACL/CLIM only, moving the cursor over an edge in the chart displays the yield of the edge at the bottom of the window. Clicking on a word node (i.e., one of the nodes at the leftmost side of the chart which just show orthography) will select it. When at least one word is selected, all the edges that cover all the selected words are highlighted. Clicking on a word node again deselects it.

Chapter 8

Advanced features

The previous chapters have described the main features of the LKB system which are utilized in the distributed grammars. There are a range of other features which are in some sense advanced: for instance because they concern facilities for using the LKB with grammars in frameworks other than the variety of HPSG assumed here, or because they cover functionality which is less well tested (in particular defaults and generation), or because the features are primarily used for efficiency (some of these are rather specific to the LinGO ERG). These features are described in this chapter. It should probably not be read by anyone who hasn't worked through the earlier material in some detail. On the whole, this chapter assumes rather more knowledge of NLP and of Lisp programming than we have in the earlier chapters.

The chapter starts with a section which gives some hints on starting to write an entirely new grammar.

8.1 Defining a new grammar

If possible, it is best to start from one of the sample grammars rather than to build a new grammar completely from scratch. However, when building a grammar in a framework other than HPSG, the existing source may not be of much use. These notes are primarily intended for someone trying to build a grammar almost from scratch.

The first step is to try and decide whether the LKB system is going to be adequate for your needs. The system is not designed for building full NLP applications (though it could form part of such a system for teaching or research purposes, and might have some utility for prototyping). For research, there are some limitations imposed by the typed-feature structure formalism.[1] There's no way of describing any form of transformation or movement directly, though, as is well known, feature structure formalisms have alternative ways of achieving the same effect.

Even with respect to other typed feature structure formalisms, the LKB has some self-imposed limitations. There is no way of writing a disjunctive or negated feature structure (see 5.4). In many cases, grammars can be reformulated to eliminate disjunction in favour of the use of types

[1]The system can be used to build grammars which are Turing equivalent, so these comments aren't about formal power. There is a useful contrast between whether a language *supports* a technique, which means it supplies the right primitives etc, or merely *enables* its use, which means that one can implement the technique if one is sufficiently devious. What's of interest here is the techniques the LKB supports or doesn't support.

which express generalisations. Occasionally it may be better to have multiple lexical entries or grammar rules. The LKB does not support negation, although we do intend to release a version which incorporates inequalities (Carpenter, 1992) at some point. More fundamentally for HPSG, the system does not support set operations. Alternative formalisations are possible for most of the standard uses of sets. For example, operations which are described as set union in Pollard and Sag (1994) can be reformulated as a list append. We think we have good reasons for adopting these limitations, and that the LinGO ERG shows that an HPSG grammar can be built without these devices, so the system is unlikely to change.

There are other limitations which are less fundamental, though they might require considerable reimplementation. In these cases, it may be worth considering using the LKB system if you have some programming experience, or can persuade someone else to do some programming for you. For instance, the current system for encoding orthographemics is very restricted. However, the interface to the rest of the system is fairly well-defined, so it should be relatively easy to replace.

If you've decided you want to use the LKB system, then you should start by defining a very simple grammar. It will make life simpler if you copy the definitions for basic types like lists and difference lists from the existing grammars, so you do not have to redefine the global parameters unnecessarily. Similarly, if you are happy to use a list feature ARGS to indicate the order of daughters in a grammar rule, you will not have to change the parameters which specify daughters or the ordering function. There are some basic architectural decisions which have to be taken early on. For instance, if you decide on a **lexeme**, **word**, **phrase** distinction, this will affect how you write lexical and grammar rules.

As described at the beginning of Chapter 6, you need to have distinct files for each class of object. You will have to write a script file to load your grammar files — the full details of how to do this are given below, but the easiest technique is to copy an existing script and to change the file names, then to look at the documentation if you find the behaviour surprising. To start off with, aim at a grammar which is comparable in scope to the `esslli/toy` grammar supplied with the system: i.e., use fully inflected forms, one or two grammar rules, a very small number of lexical entries and just enough types to make the structures well-formed (the `esslli/toy` grammar actually has many more types than are strictly speaking needed, because it was defined to make it relatively straightforward to extend using a predefined feature structure architecture).

There are many practical aspects to grammar engineering, many of which are similar to good practise in other forms of programming. One aspect which is to some extent peculiar to grammar writing is the use of test suites (see e.g., Oepen and Flickinger, 1998). The LKB system is compatible with the [incr tsdb()] system, as discussed in §8.13. You should use a test-suite of sentences as soon as you have got anything to parse, to help you tell quickly when something breaks. You should also adopt a convention with respect to format of description files right from the start: e.g., with respect to upper/lower case distinctions, indentation etc. Needless to say, comments and documentation are very important. You may find the strong typing annoying at first, but we have found that it catches a large number of bugs quickly which can otherwise go undetected or be very hard to track down.

At some point, if you develop a moderate size grammar, or have a slow machine, you will probably start to worry about processing efficiency. Although this is partly a matter of the implementation of the LKB system, it is very heavily dependent on the grammar. For instance, the textbook grammar is not a particularly good model for anyone concerned with efficient processing, partly because it makes use of large numbers of non-branching rules. The LKB system code has been optimized with respect to the LinGO ERG, so it may well have considerable inefficiencies for other styles of grammar. For instance, the ERG has about 40 rules (constructions) — grammars with hundreds of rules might benefit from an improvement in the rule lookup mechanism. We have put a lot of effort in making processing efficient with type hierarchies like the ERG's which contains thousands of types, with a reasonably high degree of multiple inheritance. However, there are cases of multiple inheritance which the algorithm for determining greatest lower bounds will not handle gracefully.

8.2 Script files

Here is an example of a complex script file, as used for the CSLI LinGO ERG:

```
(lkb-load-lisp (parent-directory) "Version.lisp" t)
(setf *grammar-directory* (parent-directory)) ; needed for MRS
(lkb-load-lisp (this-directory) "globals.lsp")
(lkb-load-lisp (this-directory) "user-fns.lsp")
(load-lkb-preferences (this-directory) "user-prefs.lsp")
(lkb-load-lisp (this-directory) "lkb-code-patches.lsp" t)
(lkb-load-lisp (this-directory) "templates.lsp")
(lkb-load-lisp (this-directory) "checkpaths.lsp" t)
(lkb-load-lisp (this-directory) "comlex.lsp" t)
(load-irregular-spellings (lkb-pathname (parent-directory) "irregs.tab"))
(read-tdl-type-files-aux
     (list (lkb-pathname (this-directory) "extra.tdl")
           (lkb-pathname (parent-directory) "fundamentals.tdl")
           (lkb-pathname (parent-directory) "lextypes.tdl")
           (lkb-pathname (parent-directory) "syntax.tdl")
           (lkb-pathname (parent-directory) "lexrules.tdl")
           (lkb-pathname (parent-directory) "auxverbs.tdl")
   (lkb-pathname (parent-directory) "multiletypes.tdl")
           (lkb-pathname (this-directory) "lkbpatches.tdl")
           (lkb-pathname (this-directory) "mrsmunge.tdl"))
     (lkb-pathname (this-directory) "settings.lsp"))
(read-cached-leaf-types-if-available
 (list (lkb-pathname (parent-directory) "letypes.tdl")
       (lkb-pathname (parent-directory) "semrels.tdl")))
(read-cached-lex-if-available
          (lkb-pathname (parent-directory) "lexicon.tdl"))
(read-tdl-grammar-file-aux
          (lkb-pathname (parent-directory) "constructions.tdl"))
(read-morph-file-aux (lkb-pathname (this-directory) "inflr.tdl"))
(read-tdl-psort-file-aux
          (lkb-pathname (parent-directory) "roots.tdl"))
(read-tdl-lex-rule-file-aux
          (lkb-pathname (parent-directory) "lexrinst.tdl"))
(read-tdl-parse-node-file-aux
          (lkb-pathname (parent-directory) "parse-nodes.tdl"))
(lkb-load-lisp (this-directory) "mrs-initialization.lsp" t)
```

We won't go through this in detail, but note the following:

1. The command to read in the script file is specified to carry out all the necessary initializations of grammar parameters etc. So although it might look as though a script file can be read in via `load` like a standard Lisp file, this will cause various things to go wrong.

2. The first load statement looks for a file called `Version.lsp` in the directory above the one where the script file itself is located. (As before, all paths are given relative to the location of the script file, so the same script will work with different systems, provided the directory structure is maintained.) The file `Version.lsp` sets a variable `*grammar-version*` recording the grammar version. This is used for record-keeping purposes and also to give names to the cache files (see §8.8).

3. The userprefs file is loaded automatically. Here we assume it's kept in the same directory as the other globals file, which allows a user to set up different preferences for different grammars.

4. The `templates.lsp` file contains a list of parameterized templates as used in TDL, but here defined in Lisp to avoid the necessity to reimplement the TDL reader. Parameterized templates are only supported for PAGE compatibility, and should not be used when developing a new grammar, because this facility will eventually be removed.

5. The `checkpaths` file is loaded to improve efficiency, as discussed in §8.3.1. The third argument to `lkb-load-lisp` is `t`, to indicate that the file is optional.

6. The `comlex.lsp` file contains code which provides an interface to a lexicon constructed automatically from the COMLEX lexicon which is distributed by the Linguistic Data Consortium. This acts as a secondary lexicon when the specially built lexicon is missing a word entry.

7. There is a list of type files read in by `read-tdl-type-files-aux` — the second argument to this function is a file for display settings (see §7.1.9).

8. Two type files are specified as leaf types (see §8.7). The leaf types are cached so that they can be read in quickly if the files are unaltered.

9. The lexicon is cached so that it can be read in quickly if it is unaltered: see §8.8.

10. The final file `mrs-initialization.lsp` contains code to initialize the behaviour of the MRS code (if present). It is responsible for loading the grammar-specific MRS parameters file.

8.2.1 Loading functions

The following is a full list of available functions for loading in LKB source files written using the TDL syntax. All files are specified as full pathnames. Unless otherwise specified, details of file format etc are specified in Chapter 5 and error messages etc are in Chapter 6.

load-lkb-preferences *directory file-name*

Loads a preferences file and sets `*user-params-file*` to the name of that file, so that any preferences the user changes interactively will be reloaded next session.

read-tdl-type-files-aux *file-names* &optional *settings-file*

Reads in a list of type files and processes them. An optional settings file controls shrunkenness (see §7.1.9). If you wish to split types into more than one file, they must all be specified in the file name list, since processing assumes it has all the types (apart from leaf types).

read-tdl-leaf-type-file-aux *file-name*

Reads in a leaf type file. There may be more than one such command in a script. See §8.7.

read-cached-leaf-types-if-available *file-name(s)*

Takes a file or a list of files. Reads in a leaf type cache if available (WARNING, there is no guarantee that it will correspond to the file(s) specified). If there is no existing leaf type cache, or it is out of date, reads in the specified files using `read-tdl-leaf-type-file-aux`. See §8.8.

read-tdl-lex-file-aux *file-name*

Reads in a lexicon file. There may be more than one such command in a script.

read-cached-lex-if-available *file-name(s)*

Takes a file or a list of files. Reads in a cached lexicon if available (WARNING, there is no guarantee that it will correspond to the file(s) specified). If there is no existing cached lexicon, or it is out of date, reads in the specified files using `read-tdl-lex-file-aux`. See §8.8.

read-tdl-grammar-file-aux *file-name*

Reads in a grammar file. There may be more than one such command in a script.

read-morph-file-aux *file-name*

Reads in a lexical rule file with associated orthographemic information. Note that the orthographemic system assumes there will only be one such file in a grammar, so this command may not occur more than once in a script, even though it takes a single file as argument.

read-tdl-lex-rule-file-aux *file-name*

Reads in a lexical rule file where the rules do not have associated orthographemic information. There may be more than one such command in a script.

load-irregular-spellings *file-name*

Reads in a file of irregular forms. It is assumed there is only one such file in a grammar.

read-tdl-parse-node-file-aux *file-name*

Reads in a file containing entries which define parse nodes.

read-tdl-psort-file-aux *file-name*

Reads in a file containing any other sort of entry. This file simply defines the entries, without giving them any particular functionality. This command is used in the example grammars for the roots file, but note that this is possible only because start symbols are enumerated in the globals file.

8.2.2 Utility functions

The following functions are defined as utilities for people who want to write script files and don't know much lisp (the definitions are in the source file `io-general/utils`).

this-directory

Returns the directory which contains the script file (only usable inside the script file).

parent-directory

Returns the directory which is contains the directory containing the script file (only usable inside the script file).

lkb-pathname *directory name*

Takes a directory as specified by the commands above, and combines it with a file name to produce a valid full name for the other commands.

lkb-load-lisp *directory name* &optional *boolean*

Constructs a file name as with `lkb-pathname` and loads it as a lisp file. If optional is `t` (i.e., true), ignore the file if it is missing, otherwise signals a (continuable) error.

8.3 Parsing and generation efficiency techniques

8.3.1 Check paths

The check paths mechanism greatly increases the efficiency of parsing and generation with large grammars like the LinGO ERG. It relies on the fact that unification failure during rule application is normally caused by type incompatibility on one of a relatively small set of paths. These paths can be checked very efficiently before full unification is attempted, thus providing a filtering mechanism which considerably improves performance. The paths are constructed automatically by batch parsing a representative range of sentences.

To construct a set of check-paths, the macro `with-check-path-list-collection` is used. It takes two arguments: the first is a file to which the set of paths will be written, the second is a call to a batch parsing function. For example:

```
(with-check-path-list-collection "~aac/checkpaths.lsp"
  (parse-sentences "~aac/grammar/lkb/test-sentences"
    "~aac/grammar/lkb/results"))
```

The menu command Create quick check file, described in 7.1.8, allows this process to be run from the graphical interface on a set of test sentences.

The file of checkpaths created in this way is then read in as part of the script. For instance:

```
(lkb-load-lisp (this-directory) "checkpaths.lsp" t)
```

To maintain filtering efficiency, the checkpaths should be recomputed when there is a major change to the architecture of the feature structures used in the grammar.

Note that there is currently a function which converts the output of the macro into a form suitable for the style of rules used in the textbook and LinGO grammars, i.e. with the daughters given by an ARGS list. This is at the end of `main/check-unif.lsp`. It would have to be rewritten for grammars that use a different mother/daughter encoding.

The checkpaths will never affect the result of parsing or generation.

8.3.2 Key-driven processing

When the parser or generator attempts to apply a grammar-rule to two or more daughters, it is often the case that it is more efficient to check the daughters in a particular order, so that unification can fail as quickly as possible. This mechanism allows the grammar developer to specify a daughter as the *key*: the key daughter can be checked first. The value of the path `*key-daughter-path*` in the daughter structure of the grammar rule should be set to the value of `*key-daughter-type*` when that daughter is the key. By default, the value of `*key-daughter-path*` is (KEY-ARG) and the value of `*key-daughter-type*` is `+`. So, for instance, if the daughters in the rule are described as a list which is the value of the feature ARGS and the first daughter is the key, the value of (ARGS FIRST KEY-ARG) should be `+`. A rule is not required to have a specified key and the `*key-daughter-path*` need not be present in this case. Specifying a key will never affect the result of parsing or generation.

8.3.3 Avoiding copying and tree reconstruction

The HPSG framework is usually described in such a way that phrases are complete trees: that is, a phrase feature structure contains substructures which are also phrases. This leads to very large structures and computational inefficiency. However, HPSG also has a locality principle, which means that it is not possible for a phrase to access substructures under its immediate daughters. Any such information has to be carried up explicitly.

The locality principle guarantees that it is possible to remove the daughters of a rule after constructing the mother. The LKB system allows the grammar writer to supply a list of features which will not be passed from daughter to mother when parsing: `*deleted-daughter-features*`.

8.4 Multiword lexemes

The LKB system allows lexical items to be specified which have a value for their orthography which is a list of more than one string. These items are treated as multiword lexemes and the parser checks that all the strings are present before putting the lexical entry on the chart.

Multiword lexemes may have at most one affixation site. This is specified on a per-entry basis, via the user-definable function `find-infl-pos` (see §C.3). By default, this allows affixation on the rightmost element: e.g. *ice creams*. It can be defined in a more complex way, to allow for e.g., *attorneys general*.

8.5 Parse ordering

The parser supports a simple mechanism for ordering parses and for returning the first parse only. The application of this mechanism is controlled by the variable `*first-only-p*` which may be set interactively, Options / Set options menu command. The weighting is controlled by two functions `rule-priority` and `lex-priority` which may be defined in the grammar-specific `user-fns.lsp` file, if desired. Since the mechanism is likely to change, we don't propose to document it in detail here, but we suggest that anyone who wishes to experiment with this capability looks at the definitions of `rule-priority` and `lex-priority` in the user-fns file for the LinGO ERG.

8.6 Character sets

Because the LKB is implemented in Common Lisp, its ability to handle characters which are not part of the basic ASCII character set is determined by the version of Common Lisp used. The following notes are very preliminary — we would welcome more information.

8.6.1 MCL

Old versions of MCL supported 8-bit characters, newer versions support Apple's double-byte character encoding. On the basis of rather limited testing, this means support for non-English alphabets is reasonable — if you can enter the characters on your keyboard (via the standard Apple sequences), they appear to behave correctly in the LKB. Note however that there will be portability issues when using files constructed on a Mac in other environments.

8.6.2 ACL/CLIM on Unix

The situation with ACL on Unix is more complicated. Standard ACL supports 8-bit characters, which means that you can use the LKB for development for most European languages, provided you have the necessary fonts etc installed. Note that emacs has an iso-accents-mode, which allows one to enter accented characters from a US keyboard. This allows one to enter lexical entries etc, but it doesn't help when interacting with the LKB dialogues. Doing this requires that the keyboard and X keyboard mappings are set up appropriately for the desired character set. It is possible to avoid using dialogues by using the alternative Lisp commands instead: in particular, `do-parse-tty` (see §7.1.4). Correct display depends on the fonts available in the Xresources file: ACL 4.3 doesn't check to ensure the font is using the given encoding, so e.g., bold font display (as used for types) may be wrong when normal face font display is correct. ACL 5.0 apparently fixes this problem.

To support double-byte encoding, needed for Japanese, it is necessary to have International ACL. This uses a version of EUC. See the ACL documentation for more information. We have not tested the LKB in International ACL, though in principle it should work.

8.7 Leaf types

The notion of a leaf type is defined for efficiency. A leaf type is a type which is not required for the valid definition or expansion of any other type or type constraint. Specifically this means that a leaf type must meet the following criteria:

1. A leaf type has no daughters.
2. A leaf type may not introduce any new features on its constraint.
3. A leaf type may not be used in the constraint of another type.

4. A leaf type only has one ‘real’ parent type — it may have one or more template parents (see C.2.1).

Under these conditions, much more efficient type checking is possible, and the type constraint description can be expanded on demand rather than being expanded when the type file is read in.

In the LinGO ERG, most of the terminal lexical types (i.e. those from which lexical entries inherit directly) are leaf types, as are most of the relation types. The latter class is particularly important, since it means that a lexicon can be of indefinite size and expanded on demand, while still using distinct types to represent semantic relations.

Various checks are performed on leaf types to ensure they do meet the above criteria. However the tests cannot be completely comprehensive if the efficiency benefits of leaf types are to be maintained. If a type is treated as a leaf type when it does not fulfill the criteria above, unexpected results will occur. Thus the leaf type facility has the potential for causing problems which are difficult to diagnose and it should therefore be used with caution.

8.8 Caches

The cache functionality is provided to speed up reloading a grammar when leaf types or the lexicon have not changed.

Lexicon cache Whenever a lexicon is read into the LKB, it is stored in an external file rather than in memory. Lexical entries are pulled in from this file as required. The caching facility saves this file and an associated index file so that they do not need to be recreated when the grammar is read in again if the lexicon has not changed. The location of these files is set by the `user-fns.lsp` function `set-temporary-lexicon-filenames`. The file names are stored in the parameters `*psorts-temp-file*` and `*psorts-temp-index-file*` (see §C.3.1). The default function uses the function `lkb-tmp-dir` to find a directory and names the files `templex` and `templex-index` respectively. A more complex version of `set-temporary-lexicon-filenames` is given in the LinGO ERG `user-fns.lsp` file: this uses a parameter `*grammar-version*` to name the files.

The script command `read-cached-lex-if-available` (see §8.2.1), takes a file or list of files as arguments. If a cached lexicon is available in the locations specified by `*psorts-temp-file*` and `*psorts-temp-index-file*`, and is more recent than the file(s) given as arguments to the function, then it will be used instead of reading in the specified files. The code does not check to see whether the cached lexicon was created from the specified files, and there are other ways in which the system can be fooled. Thus you should definitely not use this unless you have a sufficiently large lexicon that the reload time is annoying.

Leaf type cache A similar caching mechanism is provided for leaf types (§8.7). The parameter storing the name of the file is `*leaf-temp-file*` but like the lexicon cache files this is set by `set-temporary-lexicon-filenames`.

8.9 Emacs interface

The menu command Show source requires that emacs be used as the editor, and that a command is run which allows the linkage — see §2.4.1. The emacs interface also puts some LKB menu commands on the top menu bar of the emacs window, for convenience.

8.10 YADU

The structures used in the LKB system are not actually ordinary typed feature structures, but typed default feature structures (TDFSs). So far in this document we have assumed non-default structures and monotonic unification, but this is actually just a special case of typed default unification. The full description of TDFSs and default unification is given in Lascarides and Copestake (1999) (henceforth L+C). The following notes are intended to supplement that paper.

Default information is introduced into the description language by `/`, followed by an indication of the persistence of the default. In terms of the current implementation, the supported distinctions in persistence are between defaults which are fully persistent and those which become non-default when an entry feature structure is constructed (referred to as description persistence). The value of the description persistence indicator is given by the global `*description-persistence*` — the default is `l`.

The modification to the BNF given for the TDL syntax in §5.3.2 is as follows:

Conjunction → *DefTerm* | *DefTerm* `&` *Conjunction*
DefTerm → *Term* | *Term* `/`*identifier* *Term* | `/`*identifier* *Term*

It is not legal to have a default inside a default.

For example, the following definition of **verb** makes the features PAST, PASTP and PASSP indefeasibly coindexed, and PASTP and PASSP defeasibly coindexed. The definition for **regverb** makes the value of PAST be `ed`, by default.

```
verb := *top* &
[ PAST *top* /l #pp,
  PASTP #p /l #pp,
  PASSP #p /l #pp ].

regverb := verb &
[ PAST /l "ed" ] .
```

Any entry using these types will be completely indefeasible, since the defaults have description persistence. Further examples of the use of defaults, following the examples in L+C, are given in the files in `data/yadu_test`.

You should note that the description language specifies dual feature structures from which BasicTDFSs are constructed as defined in §3.5 of L+C. See also the discussion of the encoding of VALP in §4.2 of L+C.

If you view a feature structure which contains defaults, you will see three parts. The first is the indefeasible structure, the second the 'winning' defeasible structure, and the third the tail.

(Unfortunately this is very verbose: a more concise representation will be implemented at some point.)

Notice that the current implementation effectivly assumes that defaults are only relevant with respect to an inheritance hierarchy: default constraints which are specified on types other than the root node of a structure are ignored when expanding the feature structure. Warning messages are output if this happens.

8.11 MRS

MRS (minimal recursion semantics) is a framework for computational semantics which is intended to simplify the design of algorithms for generation and semantic transfer, and to allow the representation of underspecified scope while being fully integrated with a typed feature structure representation. It is decribed in detail in Copestake et al (1999). The LKB system supports MRS in providing various procedures for processing MRS structures (for printing, checking correctness, scoping, translation to other formalisms etc). The LKB generation component (described in §8.12) assumes an MRS style of representation. The LinGO grammar produces MRS structures, the textbook grammar produces a form of simplified MRS which is not adequate to support scope resolution, though it can be used for generation.

The MRS system is included in the distributed images. However, if working with source code, in order to load the MRS code, the system must be compiled with

```
(compile-system "mrs" :force t)
```

and loaded with

```
(load-system "mrs")
```

See the relevant sections on compiling and loading the LKB for more details (i.e., §2.3.1 or §2.3.2 and §2.4.1, §2.4.2 or §2.4.3).

The menu commands are described in §7.1.5 and §7.4 (ACL/CLIM only). No further documentation is available at this time.

8.12 Generation

The generator requires a grammar which is using MRS or a relatively similar formalism: currently just the LinGO ERG, though it will also work in a somewhat rudimentary way on the textbook grammar. The generator is described in Carroll et al (1999).

The following notes are VERY sketchy.

1. Instead of loading the lkb source, the mrs source must be loaded. This is done by replacing `"lkb"` with `"mrs"` as the argument to `load-system` and `compile-system`. The distributed images already contain the appropriate code. See §8.11.

2. The textbook grammar and the LinGO grammar each contain a file defining some necessary global parameters which is automatically loaded if the mrs code is available.

3. Before generating, the lexicon and lexical and grammar rules must be indexed. The function which does this, `index-for-generator`, can be run with the Index command from the Generate menu.

4. To generate, after indexing, first parse a sentence. Then choose Generate from the pop-up menu associated with the parse tree you are interested in (in the mini-parse-tree display), or the relevant node on a full-size parse tree (though in this case you may get unintuitive results if you choose anything other than the uppermost node).

5. If the grammar uses lexical entries which do not have any relations, warning messages will be issued by the indexing process. A set of grammar-specific heuristics can be defined which will determine which such lexical entries might be required for a given semantics. These are loaded via the Load Heuristics command on the Generate menu. If no such heuristics are loaded, and the generator is run on the results of a parse, and the parameter `*null-semantics-hack-p*` is set to t, the system cheats and just licenses the null semantics items that were used in the parse. Otherwise it attempts to use all null semantics items, which can be very slow.

8.13 Testing and Diagnosis

The batch parsing support which is distributed with the LKB is very simple. For extensive grammar development, more sophisticated tools are available through the [incr tsdb()] package that was recently integrated with the LKB. The following description is by Stephan Oepen (to whom all comments should be directed: `oe@coli.uni-sb.de`).

The [incr tsdb()] package combines the following components and modules:

- test and reference data stored with annotations in a structured database; annotations can range from minimal information (unique test item identifier, item origin, length et al.) to fine-grained linguistic classifications (e.g., regarding grammaticality and linguistic phenomena presented in an item) as represented by the TSNLP test suites (Oepen et al, 1997).

- tools to browse the available data, identify suitable subsets and feed them through the analysis component of a processing system like the LKB or PAGE;

- the ability to gather a multitude of precise and fine-grained system performance measures (like the number of readings obtained per test item, various time and memory usage metrics, ambiguity and non-determinism parameters, and salient properties of the result structures) and store them as a *competence and performance profile* into the database;

- graphical facilities to inspect the resulting profiles, analyze system competence (i.e., grammatical coverage and overgeneration) and performance at highly variable granularities, aggregate, correlate, and visualize the data, and compare profiles obtained from previous grammar or system versions or other platforms.

- a universal pronounciation rule: *tee ess dee bee plus plus* is the name of the game.

While [incr tsdb()] is not yet available for public download, the author will happily make it available to tolerant testers and provide consolation to users as required. Please send email to ‘`oe@coli.uni-sb.de`’ or visit the [incr tsdb()] web site (under construction) at

```
    http://www.coli.uni-sb.de/itsdb/
```

to learn more about the [incr tsdb()] package.

Appendix A

The tty interface

A.1 What is the tty mode?

The LKB tty mode is provided to allow people to use the LKB system even if they do not have access to a machine configuration which we currently support, as long as they have some version of Common Lisp.[1] tty mode is also useful if you are accessing a machine over a slow network where the graphical display would take too long. In this mode, commands are entered by typing rather than menu selection, and display commands result in ASCII output. Some commands have no tty equivalent.

tty mode allows you to read in grammars, parse sentences and generate sentences. It is less convenient than the graphical mode for grammar development and debugging because it is more difficult to view feature structures, type hierarchies, charts and so on. In this appendix, we describe the commands which are available in tty mode. All commands are entered as Lisp commands at the Lisp prompt. For example:

```
USER(3): (read-script-file-aux "~aac/grammar/lkb/script")
```

Here `USER(3):` is the system provided prompt (it may not look like this on your system) and the user has typed the rest of the line followed by the return or enter key. `read-script-file-aux` is the LKB command, `"~aac/grammar/lkb/script"` is the argument to the command (in this case a filename). In what follows, we show the generic command and its arguments in the style used in Steele.

A.2 Loading the LKB in tty mode

We do not provide a tty only image, so at least initially the tty version of the LKB must be loaded from the source files. The procedure is essentially the same as that described in §2.3.1. If you are using a version of Common Lisp which does not have supported graphics (i.e., a version other than ACL with CLIM or MCL), the tty version of the system will be loaded automatically. If you want a tty version for some reason in a platform where the graphics is supported, evaluate the following command before the load-system:

[1] We believe that tty mode only uses generic Common Lisp commands (assuming CLTL II) but we haven't tested it on an extensive range of Lisps. If it doesn't work with your system, please let us know.

```
(pushnew :tty *features*)
```

You will see a lot of warning messages about undefined functions when loading the system in tty mode, but these can be ignored.

A.3 Loading grammars

See also §8.2.
read-script-file-aux *filename*
  Loads the given file as a script file. For example:

```
(read-script-file-aux "~aac/grammar/lkb/script")
```

Note that the file has to be expressed as a string (i.e., starting and ending with "). For MCL, pathnames are expressed differently, for example:

```
(read-script-file-aux "Macintosh HD:grammar:lkb:script")
```

See Load / Complete grammar (§7.1.2)
reload-script-file
  Reloads the previously loaded script file. See Load / Reload grammar (§7.1.2)
read-type-patch-files
  Reloads the type constraints. See Load / Reload constraints (§7.1.2)
reload-leaf-files
  Reloads the leaf type files. See Load / Reload leaf types (§7.1.2)
reload-lex-files See Load / Reload lexicon (§7.1.2)
reload-grammar-rules See Load / Reload grammar rules (§7.1.2)
reload-lexical-rules See Load / Reload lexical rules (§7.1.2) As with the menu command, this also loads morphological rules.
reload-template-files See Load / Reload tree nodes (§7.1.2)
reload-psort-files See Load / Reload other entries (§7.1.2)

A.4 View commands

All the view commands print out an ASCII version of the feature structures etc in a way analogous to the graphical display described in the main body of the manual.
show-type-spec-tty *type*
  Displays a type's parents and the specification of its constraint (if any). For example,

```
(show-type-spec-tty 'synsem-struc)
```

Note that the type name has to be preceded by a quote. See View / Type definition (§7.1.3).

The following is an example of the output. This shows the feature structure followed by the parents.

```
 [SYNSEM-STRUC
  ORTH:  (*DIFF-LIST*)
  SYN:   (GRAM-CAT)
  SEM:   (SEM-STRUC)
  KEY-ARG:  (BOOLNUM)]
(FEAT-STRUC)
```

show-type-tty *type*
Displays the expanded type constraint. For example,

```
(show-type-tty 'synsem-struc)
```

See View / Expanded type (§7.1.3)
show-lex-tty *lexidentifier*
Displays the expanded lexical entry corresponding to the identifier. For example,

```
(show-lex-tty 'Kim_1)
```

See View / Lex entry (§7.1.3)
show-words-tty *string*
Displays the expanded lexical entries corresponding to the orthography given by the string. For example,

```
(show-words-tty "Kim")
```

The argument has to be a Lisp string but the command is not case-sensitive. See View / Word entries (§7.1.3)
show-grammar-rule-tty *gruleidentifier*
Displays the grammar rule corresponding to the identifier. For example,

```
(show-grammar-rule-tty 'hd_spec_rule)
```

See View / Grammar rule (§7.1.3)
show-lex-rule-tty *lruleidentifier*
Displays the lexical or morphological rule corresponding to the identifier. For example,

```
(show-lex-rule-tty 'plur_noun)
```

See View / Lexical rule (§7.1.3)

A.5 Parsing

do-parse-tty *string*
Takes a string and runs the parser, returning a bracketed structure or structures corresponding to the parses. For example, with the textbook grammar:

```
(do-parse-tty "Kim sleeps")
Edge 9 P:
("S" ("NP" ("NP" ("NP" ("Kim" "Kim"))))
 ("VP" ("VP" ("sleeps" 3RD-SING-VERB_INFL_RULE))))
```

Note that the edge number for the parse is given so that it can be identified in the ASCII chart (see below) or used as input to generation.

See Parse / Parse input (§7.1.4)

show-parse Displays the results of the parse again. See Parse / Show parse (§7.1.4)

print-chart

This shows the results of the parse in an ASCII format. Each line represents an edge: the first field shows the vertices that the edge spans (starting at 0). The second field gives the edge number: the edge numbers given for the parse results will correspond with one of the edge numbers shown in the chart. The third field shows the type of the feature structure corresponding to the edge. The fourth field shows the words in the input string that the edge covers, and the final field shows the daughter edges. For example:

```
 > chart dump:

0-1 [1] WORD => (Kim)  []

0-2 [4] PHRASE => (Kim dies)  [1 2]
1-2 [2] WORD => (dies)  []
```

See §7.1.4.

parse-sentences *input-file output-file*

Similar to the menu command Parse / Batch parse (§7.1.4) but requires an input file of test sentences and an output file for the results. For example:

```
(parse-sentences "~aac/grammar/lkb/test-sentences"
    "~aac/grammar/lkb/results")
```

A.6 Lexical rules

apply-lex-tty *lexidentifier lruleidentifier*

Similar to Apply lexical rule (see §7.3), but requires a lexical identifier and a rule identifier to be specified. For example:

```
(apply-lex-tty ’sleep_1 ’3RD-SING-VERB_INFL_RULE)
```

A feature structure is printed corresponding to the result of the rule application (if it succeeds).

apply-lex-rules-tty *lexidentifier*

Similar to Apply all lex rules (see §7.3), but requires a lexical identifier to be specified. For example:

```
(apply-lex-rules-tty ’sleep_1)
```

All the resulting structures will be printed. Note - this can be tediously long.

A.7 Generation

do-generate-tty &optional *edge-number*
show-gen-result
print-gen-chart

A.8 Miscellaneous

clear-non-parents

Appendix B

Path syntax

Earlier versions of the LKB used a syntax for descriptions which was based on the path value syntax used in PATR. This syntax is still supported, although the extensions to it described in Copestake (1993) are currently not. The BNFs for the path syntax are given here.

B.1 Type descriptions

The following BNF description gives the syntax of the type specification language using the path syntax:

```
Type specification ->
        typename Parents [Comment][Constraint].
Comment -> " string "
Parents -> ( typename* )
Constraint -> Path_spec_list | Enumeration
Path_spec_list -> Path_spec*
Path_spec -> EPath = Typevalue | Path = Path
Typevalue -> typename
Epath -> Path | <>
Path -> < Type_F_pair_list >
Type_F_pair_list -> Type_Feature_pair
        | Type_Feature_pair :  Type_F_pair_list
Type_Feature_pair -> [typename] feature
Enumeration -> ( OR typename+ )
```

Enumeration is syntactic sugar for enumerated atomic types. For example:

> **boolean** (**top**) (OR **true** **false**).

expands out into the equivalent of:

> **boolean** (**top**).
> **true** (**boolean**).
> **false** (**boolean**).

B.2 Entry descriptions

The syntactic description for lexical entries is as follows:

```
Lexentry -> LexID PPath_spec+ .
LexID -> orth sense-id
PPath_spec -> Path_spec | typename
```

`orth`, `sense-id`, `typename` and `feature` are terminal symbols.

Grammar and morphological rule files and template files are identical to this, except that the identifier is a single element.

```
Rule/template -> id PPath_spec+ .
```

where `id` is a terminal symbol.

Morphological rule files may have one or more letter sets at the beginning of the file:

```
Letterset -> %(letter-set (Macro letter+))
Macro -> !letter
```

where `letter` is a terminal symbol corresponding to any character.

The rules themselves have the following form:

```
Mrule -> id morph-rule Mgraph_spec+ Path_spec+ .
Mgraph_spec -> %prefix | suffix SPair+
SPair -> ( Mstring Char+ )
Mstring -> * | Char+
Char -> letter | Macro
```

All files may have comments in between elements introduced by `;`.

Appendix C

Details of system parameters

Various parameters control the operation of the LKB and some feature and type names are regarded as special in various ways. The system provides default settings but typically, each grammar will have its own files which set these parameters, redefining some of the default settings, though obviously a set of closely related grammars can share parameter files. Each script must load the grammar-specific parameter files before loading any of the other grammar files. Other parameters control aspects of the system which are not grammar specific, but which concern things such as font size, which are more a matter of an individual user's preferences. This class of parameters can mostly be set via the Options menu (described in §7.1.9). Changing parameters in the Options menu results in a file being automatically generated with the preferences: this shouldn't be manually edited, since any changes may be overridden. There's nothing to prevent global variables which affect user preferences being specified in the grammar-specific globals files, but it is better to avoid doing this, since it could be confusing.

There are also some functions which can be (re)defined by the grammar writer to control some aspects of system behavior.

This appendix describes all the parameters and functions that the LKB system allows the user/grammar writer to set, including both grammar specific and user preference parameters. We sometimes refer to the parameters as *globals*, since they correspond to Common Lisp global variables. Note that the parameters in the grammar-specific globals files are all specified as

```
(defparameter global-variable value comment)
```

where the comment is optional. Thus only a very basic knowledge of Common Lisp is required to edit a globals file: the main thing to remember is that symbols have to be preceded by a quote, for instance:

```
(defparameter *string-type* ’string)
```

The descriptions below gives the default values for the variables and functions (as they are set in the source file `main/globals` and `main/userfns`). The description of the global variables is divided into sections based on the function of the variables: these distinctions do not correspond to any difference in the implementation with the exception that the globals which can be set via the Options/ Set options menu are nearly all ones that are specified as being grammar independent. (Not all grammar independent variables are available under Options, since some are complex to set interactively, or rarely used.)

C.1 Grammar independent global variables

C.1.1 System behaviour

***lkb-system-version*, :page** This parameter controls the behaviour of the system with respect to such things as the expected syntax (TDL or path style). The default setting is intended to make the system as compatible as possible with the PAGE system. Currently this has the following main effects:

1. TDL syntax assumed by default for grammar files
2. Tree nodes labels are constructed according to the dual label/meta system (see §6.9) rather than by simple matching with category feature structures.

For behaviour which is more similar to earlier versions of the LKB, this variable can be set to :lkb4.

***gc-before-reload*, nil** This boolean parameter controls whether or not a full garbage collection is triggered before a grammar is reloaded. It is best set to t for large grammars, to avoid image size increasing, but it is nil by default, since it slows down reloading.

***sense-unif-fn*, nil** If set, this must correspond to a function. See make-sense-unifications in §C.3, below.

***maximum-number-of-edges*, 500** A limit on the number of edges that can be created in a chart, to avoid runaway grammars taking over multi-user machines. If this limit is exceeded, the following error message is generated:

```
Error:  Probable runaway rule:  parse/generate aborted
(see documentation of *maximum-number-of-edges*)
```

When parsing a short sentence with a small grammar, this message is likely to indicate a rule which is applying circularly (that is, applying to its own output in a way that will not terminate). But this value must be increased to at least 2000 for large scale grammars with a lot of ambiguity. May be set interactively.

***maximum-number-of-tasks*, 50000** A limit on the number of tasks that can be put on the agenda. This limit is only likely to be exceeded because of an error such as a circularly applicable rule.

***chart-limit*, 100** The limit on the number of words in a sentence which can be parsed. Whether the system can actually parse sentences of this length depends on the grammar . . .

***maximal-lex-rule-applications*, 7** The number of lexical rule applications which may be made before it is assumed that some rules are applying circularly and the system signals an error.

***display-type-hierarchy-on-load*, t** A boolean variable, which controls whether the type hierarchy is displayed on loading or not. This must be set to nil for grammars with large numbers of types, because the type hierarchy display becomes too slow (and if the type hierarchy involves much multiple inheritance, the results are not very readable anyway). May be changed interactively.

C.1.2 Display parameters

***feature-ordering*, nil** A list which is interpreted as a partial order of features for fixing or resolving the default display ordering when feature structures are displayed or printed (see §5.2).

***show-morphology*, t** A boolean variable. If set, the morphological derivations are shown in parse trees (see §7.5). May be set interactively.

***show-lex-rules*, t** A boolean variable. If set, applications of lexical rules are shown in parse trees (see §7.5). May be set interactively.

***simple-tree-display*, nil** A boolean variable which can be set in order to use the simple node labelling scheme in parse trees when in PAGE compatability mode.

***substantive-roots-p*, nil** A boolean variable which can be set to allow the structures constructed when checking the initial (root) conditions to be regarded as real edges for the purposes of chart display (see §6.8).

***display-type-hierarchy-on-load*, t** see §C.1.1 above. May be set interactively.

***parse-tree-font-size*, 12** The font size for parse tree nodes. May be set interactively.

***fs-type-font-size*, 12** The font size for nodes in AVM windows. May be set interactively.

***fs-title-font-size*, 12** The font size for titles in AVM windows. May be set interactively.

***type-tree-font-size*, 12** The font size for the nodes in the type hierarchy. May be set interactively.

***dialog-font-size*, 12** The font size used in dialogue windows. May be set interactively.

***maximum-list-pane-items*, 50** ACL/CLIM only: the maximum number of rules, lexical entries etc that will be offered as choices in menus that allow selection of such entities.

C.1.3 Parse tree node labels

These parameters are only used when in PAGE compatibility mode. For details of how this operates, see §6.9.

***label-path*, (LABEL-NAME)** The path where the name string is stored.

***prefix-path*, (META-PREFIX)** The path for the meta prefix symbol.

***suffix-path*, (META-SUFFIX)** The path for the meta suffix symbol.

***recursive-path* (NON-LOCAL SLASH LIST FIRST)** The path for the recursive category.

***local-path*, (LOCAL)** The path inside the node to be unified with the recursive node.

***label-fs-path*, (SYNSEM)** The path inside the node to be unified with the label node.

***label-template-type*, label**

C.1.4 Defaults

See §8.10.

***description-persistence*, l** The symbol used to indicate that a default should be made hard (if possible) when an entry is expanded into a complete feature structure.

C.2 Grammar specific parameters

C.2.1 Type hierarchy

***templates*, nil** A list of types which may be treated as templates, where by template in this context we mean simply a named feature structure used to abbreviate a description of another structure (they are not parameterizable). This is used in the LinGO ERG to reduce multiple inheritance and to allow the bottommost lexical types to be treated as leaf types (§8.7). This facility has only been included to allow compatibility with an existing grammar, in a context where multiple type inheritance was being used for implementation-specific purposes rather than for any linguistically motivated reason. It should not be used when developing a new grammar.

***toptype*, top** This gives *toptype* a value before a type file is read in, which is necessary for the TDL syntax or in the path syntax if the definition of $\top$ does not appear before all type descriptions which contain constraint specifications.

***string-type*, string** The name of the type which is special, in that all Lisp strings are recognised as valid subtypes of it.

C.2.2 Orthography and lists

***orth-path*, (orth lst)** The path into a sign, specified as a list of features, which leads to the orthographic specification. See also the functions `make-sense-unifications` and `make-orth-tdfs` in §C.3.

***list-head*, (hd)** The path for the first element of a list.

***list-tail*, (tl)** The path for the rest of a list.

list-type*, *list The type of a list.

empty-list-type*, *null The type of an empty list — it must be a subtype of ***list-type***.

diff-list-type*, *diff-list The type of a difference list (see §5.3.6).

***diff-list-list*, list** The feature for the list portion of a difference list.

***diff-list-last* last** The feature for the last element of a difference list.

C.2.3 Morphology and parsing

***lex-rule-suffix*, nil** If set, this is appended to the string associated with an irregular form in the irregs file in order to construct the appropriate inflectional rule name. Required for PAGE compatibility in the LinGO ERG.

***mother-feature*, 0** The feature specifying the mother in a rule. May be NIL.

***start-symbol*, sign** A type which specifies the type of any valid parse. Can be used to allow relatively complex initial (root) conditions. See §6.8. Unlike most grammar specific parameters, this can be set interactively to allow a switch between parsing fragments and only allowing full sentences, for instance.

***deleted-daughter-features*, nil** A list of features which will not be passed from daughter to mother when parsing. This should be set if efficiency is a consideration in order to avoid copying parts of the feature structure that can never be (directly) referenced from rules pertaining to higher nodes in the parse tree. This will include daughter features in HPSG, since it is never the case that a structure can be directly selected on the basis of its daughters.

***key-daughter-path*, (key-arg)** A path into a daughter in a rule which should have its value set to `*key-daughter-type*` if that daughter is to be treated as the key. See §8.3.2.

***key-daughter-type*,** `+` . See above.

***check-paths*, nil** An alist in which the keys are feature paths that often fail — these are checked first before attempting unification to improve efficiency. See §8.3.1. The value of this parameter could be set in the globals file, but since the list of paths is automatically generated, it is normally kept in a distinct file. The parameter should ideally be set to `nil` in the globals file for grammars which do not use check paths, in case the grammar is read in after a previous grammar which does set the paths.

***irregular-forms-only-p*, nil** If set, the parser will not invoke the morphological analyzer on a form which has an irregular spelling. This prevents the system analyzing words such as *mouses*. Note that this means that if the grammar writer wants to be able to analyze *dreamed* as well as *dreamt*, both entries have to be in the irregular morphology file. Also note that we currently assume (incorrectly) that spelling is not affected by sense. For instance, the system cannot handle the usage where the plural of *mouse* is *mouses* when referring to computers. Note that this flag does not affect generation, which always treats an irregular form as blocking a regular spelling.

first-only-p If set, only one parse will be returned, where any preferences must be defined as specified in §8.5. May be set interactively.

C.2.4 Generator parameters

***semantics-index-path*, (synsem local cont index)** The path used by the generator to index the chart.

***intersective-rule-names*, (adjh_i nadj_i hadj_i_uns)** The names of rules that introduce intersective modifiers. Used by the generator to improve efficiency. Default value is appropriate for the LinGO grammar. It should be set to NIL for grammars where the intersective modifier rules do not meet the necessary conditions for adjunction. See also the function `intersective-modifier-dag-p` in §C.3.

***duplicate-lex-ids*, (an)** Used in grammars which do not have any way of representing alternative spellings, this is a list of lexical identifiers that should be ignored by the generator. (The *a/an* alternatives are chosen by a post-generation spelling realization step.)

C.2.5 MRS parameters

We will not go through most of the MRS parameters here. They are stored in a separate file from the other globals (called `mrsglobals-eng.lisp` for the LinGO grammar).

mrs::*scoping-call-limit*, 10000 Controls the search space for scoping. May be set interactively.

mrs::*null-semantics-hack-p*, nil If set, allows the generator to cheat by using only the null semantic lexical entries that were found from the last parse. Requires that the generator is run only on the output of the last sentence parsed.

C.3 User definable functions

make-sense-unifications If this function is defined, it takes three arguments so that the orthographic form of a lexical entry, its id and the language are recorded in an appropriate place in the feature structure. The value of *sense-unif-fn* must be set to this function, if it is defined. The function is not defined by default.

The idea is that this function can be used to specify paths (such as `< ORTH : LST : HD >`) which will have their values set to the orthographic form of a lexical entry.[1] This allows the lexicon files to be shorter. It is assumed to be exactly equivalent to specifying that the paths take particular atomic values in the lexical entry. For example, instead of writing:

```
teacher 1
<> = common-noun
< ORTH : LST : HD > = "teacher"
< SEM : KEY > = teacher1_rel .
```

the function could be defined so it was only necessary to write:

[1]Note that this description is in the alternative path notation defined in §B.

```
teacher 1
<> = common-noun.
```

since the value of the orthography string and the semantic relation name are predictable from the identifying material.

make-orth-tdfs A function used by the parser which takes a string and returns a feature structure which corresponds to the orthographic part of a sign corresponding to that string. The default version assumes that the string may have spaces, and that the feature structure will contain a list representation with each element corresponding to one word (i.e. sequence of characters separated by a space). For instance, the string `"ice cream"` would give rise to the structure

```
[ ORTH [ LST [ HD ice
               TL [ HD cream ]]]]
```

establish-linear-precedence A function which takes a rule feature structure and returns the top level features in a list structures so that the ordering corresponds to mother, daughter 1, daughter 2 ... daughter n. The default version assumes that the daughters of a rule are indicated by the features 1 through n.

spelling-change-rule-p A function which takes a rule structure and checks whether the rule has an effect on spelling. It is used to prevent the parser trying to apply a rule which affects spelling and which ought therefore only be applied by the morphology The current value of this function checks for `< NEEDS-AFFIX > = true`. If this matches a rule, the parser will not attempt to apply this rule. (Note that the function will return false if the value of NEEDS-AFFIX is anything other than **true**, since the test is equality, not unifiability.) See §5.3.5.

redundancy-rule-p Takes a rule as input and checks whether it is a redundancy rule, defined as one which is only used in descriptions and is not intended to be applied productively. For instance, the prefix *step-*, as in *stepfather*, has a regular meaning, but only applies to a small, fixed set of words. A redundancy rule for *step-* prefixation can be specified to capture the regularity and avoid redundancy, but it can only be used in the lexical descriptions of *stepfather* etc, and not applied productively. (There is nothing to prevent productive lexical rules being used in descriptions.)

The default value of this function checks for `< PRODUCTIVE > = false`. If this matches a rule, the parser will not attempt to apply that rule. (Note that the function will return false if the value of PRODUCTIVE is anything other than **false**, since the test is equality, not unifiability.)

preprocess-sentence-string The function takes an input string and preprocesses it for the parser. The result of this function should be a single string which is passed to a simple word identifier which splits the string into words (defined as things with a space between them). So minimally this function could be simply return its input string. However, by default some more complex processing is carried out here, in order to strip punctuation and separate *'s*.

find-infl-poss This function is called when a lexical item is read in, but only for lexical items which have more than one item in their orth value (i.e., multiword lexemes). It must be defined to take three arguments: a set of unifications (in the internal data structures), an orthography value (a list of strings) and a sense identifier. It should return an integer, indicating which element in a multi-word lexeme may be inflected (counting left to right, leftmost is 1) or `nil`, which indicates that no item may be inflected. The default value for the function allows inflection on the rightmost element. See §8.4.

hide-in-type-hierarchy-p Can be defined so that certain types are not shown when a hierarchy is displayed (useful for hierarchies where there are a very large number of similar leaf types, for instance representing semantic relations).

rule-priority See §8.5. The default function assigns a priority of 1 to all rules.

lex-priority See §8.5. The default function assigns a priority of 1 to all lexical items.

intersective-modifier-dag-p Used by the generator to test whether a structure is an intersective modifier. Default value is applicable for the LinGO grammar. It should be set to NIL in grammars where intersective modifiers do not meet the conditions the generator requires for adjunction. See also the parameter `*intersective-rule-names*` in §C.2.4.

C.3.1 System files

There are two user definable functions which control two system files. The file names are associated with two global variables — these are initally set to `nil` and are then instantiated by the functions. The global variables are described below, but should not be changed by the user. The functions which instantiate them may need to be changed for different systems.

lkb-tmp-dir This function attempts to find a sensible directory for the temporary files needed by the LKB. The default value for this on Unix is a directory `tmp` in the user's home directory: on a Macintosh it is `Macintosh HD:tmp`. The function should be redefined as necessary to give a valid path. It is currently only called by `set-temporary-lexicon-filenames` (below).

set-temporary-lexicon-filenames This function is called in order to set the temporary files. It uses lkb-tmp-dir, as defined above. It is useful to change the file names in this function if one is working with multiple grammars and using cacheing to ensure that the lexicon file associated with a grammar has a unique name which avoids overriding another lexicon (see §8.8).

psorts-temp-file This file is constructed by the system and used to store the unexpanded lexical entries, in order to save memory. Once a lexical entry is used, it will be cached until either a new lexicon is read in, or until the Tidy up command is used (§7.1.8). If the temporary lexicon file is deleted or modified while the LKB is running, it will not be possible to correctly access lexical entries. The file is retained after the LKB is exited so that it may be reused if the lexicon has not been modified (see §8.8, §8.2.1 and the description of `*psorts-temp-index-file*`, below).

The pathname is actually specified as:

```
  (make-pathname :name "templex"
                 :directory (lkb-tmp-dir))
```

psorts-temp-index-file This file is used to store an index for the temporary lexicon file. If the option is taken to read in a cached lexicon (see §8.8 and §8.2.1), then the lexicon index is reconstructed from this file. If this file has been deleted, or is apparently outdated, the lexicon will be reconstructed from the source file.

leaf-temp-file This file is used to store cached leaf types.

References

Aho, A. V., J.E. Hopcroft and J.D. Ullman (1982) *Data Structures and Algorithms,* Addison Wesley, Reading, MA.

Briscoe, E.J., A. Copestake and V. de Paiva (1993) *Inheritance, defaults and the lexicon,* Cambridge University Press.

Carpenter, B. (1992) *The logic of typed feature structures,* (Tracts in Theoretical Computer Science), Cambridge University Press, Cambridge, England.

Carpenter, B. (1993) 'Skeptical And Credulous Default Unification With Application To Templates And Inheritance' in E.J. Briscoe, A. Copestake and V. de Paiva (ed.), *Inheritance, Defaults and the Lexicon,* Cambridge University Press, Cambridge, England, pp. 13–37.

Carroll, J. A. Copestake, D. Flickinger and V. Poznanski (1999) 'An Efficient Chart Generator for (Semi-)Lexicalist Grammars', *Proceedings of the 7th European Workshop on Natural Language Generation (EWNLG'99),* Toulouse, pp. 86–95.

Copestake, A. (1992) 'The ACQUILEX LKB: representation issues in semi-automatic acquisition of large lexicons', *Proceedings of the 3rd Conference on Applied Natural Language Processing (ANLP-92),* Trento, Italy, pp. 88–96.

Copestake, A. (1993) 'The Compleat LKB', Technical report 316, University of Cambridge Computer Laboratory.

Copestake, A., D. Flickinger, I.A. Sag and C. Pollard (1999) 'Minimal Recursion Semantics: An introduction', ms. CSLI, Stanford.

Kasper, R. T. and W. C. Rounds (1986) 'A logical semantics for feature structures', *Proceedings of the 24th Annual Conference of the Association for Computational Linguistics (ACL-86),* Columbia University, pp. 235–242.

Kasper, R. T. and W. C. Rounds (1990) 'The logic of unification in grammar', *Linguistics and Philosophy,* **13 (1)**, 35–58.

Lascarides, A. and A. Copestake (1999) 'Default representation in constraint-based frameworks', *Computational Linguistics,* **25 (1)**, 55–106.

Moens, M., J. Calder, E. Klein, M. Reape, and H. Zeevat (1989) 'Expressing generalizations in unification-based grammar formalisms', *Proceedings of the 4th Conference of the European Chapter of the Association for Computational Linguistics (EACL-89),* Manchester, England, pp. 66–71.

Oepen, Stephan, Klaus Netter and Judith Klein (1997) 'TSNLP — Test Suites for Natural Language Processing' in John Nerbonne (ed.), *Linguistic Databases,* CSLI Lecture Notes 77, CSLI Publications, Stanford CA, pp. 13 – 36.

Oepen, Stephan and Daniel P. Flickinger (1998) 'Towards Systematic Grammar Profiling. Test Suite Technology Ten Years After', *Journal of Computer Speech and Language: Special Issue* *on Evaluation,* **12 (4)**, 411-437.

Pereira, F. C. N. and S. M. Shieber (1984) 'The semantics of grammar formalisms seen as computer languages', *Proceedings of the 10th International Conference on Computational Linguistics (COLING-84),* Stanford, California, pp. 123–129.

Pollard, C. and I.A. Sag (1987) *An information-based approach to syntax and semantics: Volume 1 fundamentals,* CSLI Lecture Notes 13, CSLI Publications, Stanford CA.

Pollard, C. and I.A. Sag (1994) *Head-driven phrase structure grammar,* Chicago University Press, Chicago.

Sag, I.A. and T. Wasow (1999) *Syntactic Theory — a formal introduction,* CSLI Publications, Stanford CA (also distributed by Cambridge University Press).

Shieber, S. M. (1986) *An introduction to unification-based approaches to grammar,* CSLI Lecture Notes 4, Stanford CA.

Uszkoreit, Hans, Rolf Backofen, Stephan Busemann, Abdel Kader Diagne, Elizabeth A. Hinkelman, Walter Kasper, Bernd Kiefer, Hans-Ulrich Krieger, Klaus Netter, Günter Neumann, Stephan Oepen and Stephen P. Spackman (1994) 'DISCO — An HPSG-based NLP System and its Application for Appointment Scheduling', *Proceedings of the 15th International Conference on Computational Linguistics (COLING-94),* Kyoto, Japan.