The XSB System
Version 3.3.x
Volume 1: Programmer's Manual

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Credits

Day-to-day care and feeding of XSB including bug fixes, ports, and configuration management is currently done by David Warren and Terrance Swift with the help of Michael Kifer. In the past Kostis Sagonas, Prasad Rao, Steve Dawson, Juliana Freire, Ernie Johnson, Baoqiu Cui, Bart Demoen and Luis F. Castro have provided tremendous help.

In Version 3.3, the core engine development of the SLG-WAM has been mainly implemented by Terrance Swift, Kostis Sagonas, Prasad Rao, Juliana Freire, Ernie Johnson, Luis Castro and Rui Marques. The breakdown, very roughly, was that Terrance Swift wrote the initial tabling engine, the SLG-WAM, and its built-ins; and leads the current development of the tabling subsystem. Prasad Rao reimplemented the engine's tabling subsystem to use tries for variant-based table access and Ernie Johnson extended and refactored these routines in a number of ways, including adding call subsumption. Kostis Sagonas implemented most of tabled negation. Juliana Freire revised the table scheduling mechanism starting from Version 1.5.0 to create the batched and local scheduling that is currently used. Baoqiu Cui revised the data structures used to maintain delay lists, and added attributed variables to the engine. Luis Castro rewrote the emulator to use jump tables and wrote a heap-garbage collector for the SLG-WAM. Rui Marques was responsible for the concurrency control algorithms used for shared tables, and mainly responsible for making the XSB engine multi-threaded. The incremental table maintenance subsystem was designed and implemented by Diptikalyan Saha.

Other engine work includes the following. Memory expansion code for WAM stacks was written by Ernie Johnson, Bart Demoen and David S. Warren. Heap garbage collection was written by Luis de Castro, Kostis Sagonas and Bart Demoen. Atom space garbage collection was written by David Warren; table garbage collection was written by Terrance Swift based in part on space reclamation code written by Prasad Rao. Rui Marques rewrote much of the engine to make it compliant with 64-bit architectures. Assert and retract code was based on code written by Jiyang Xu; it significantly revised by David S. Warren, who added alternative, multiple, and star indexing and by Terrance Swift who implemented dynamic clause garbage collection. Trie assert/retract code, and trie interning code was written by Prasad Rao, as was most code for reclaiming table space. The current version of `findall/3` was re-written from scratch by Bart Demoen, as was XSB's throw and catch mechanism. 64-bit floats were added by Charles Rojo. Walter Wilson has written several of XSB's builtin predicates.

In terms of core system Prolog code, Kostis Sagonas was responsible for HiLog compilation and associated built-ins as well as coding or revising many standard predicates. Steve Dawson implemented Unification Factoring. The revision of

XSB's I/O into ISO-compatible streams was done by Michael Kifer and Terrance Swift. The `auto_table` and `suppl_table` directives were written by Kostis Sagonas. The DCG expansion module was written by Kostis Sagonas for non-tabled code and by Baoqiu Cui, Terrance Swift and David Warren for tabled code. The handling of the `multifile` directive was written by Baoqiu Cui. C.R. Ramakrishnan wrote the mode analyzer for XSB. Michael Kifer implemented the `storage` module. The multi-threaded API was written by Terrance Swift and Rui Marques.

Michael Kifer has been in charge of XSB's installation procedures, rewriting parts of the XSB code to make XSB configurable with GNU's Autoconf, implementing XSB's package system, and integrated GPP with XSB's compiler. GPP, the source code preprocessor used by XSB, was written by Denis Auroux, who also wrote the GPP manual reproduced in Appendix A.

The starting point of XSB (in 1990) was PSB-Prolog 2.0 by Jiyang Xu. PSB-Prolog in its turn was based on SB-Prolog, primarily designed and written by Saumya Debray, David S. Warren, and Jiyang Xu. Thanks are also due to Weidong Chen for his work on Prolog clause indexing for SB-Prolog, to Richard O'Keefe, who contributed the Prolog code for the Prolog reader and the C code for the tokenizer, and to Ciao Prolog whose `write_term/[2,3]` we use.

... Now what did I forget this time ?

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Chapter 1

Introduction

XSB is a research-oriented, commercial-grade Logic Programming system for Unix and Windows-based platforms. In addition to providing nearly all functionality of ISO-Prolog, XSB includes the following features:

- Evaluation of queries according to the Well-Founded Semantics [78] through full SLG resolution (tabling with negation). XSB's tabling implementation supports incremental tabling, as well as call and answer subsumption.
- A fully multi-threaded engine with thread-shared static code, and that allows dynamic code and tables to be thread-shared or thread-private. This engine fully supports the draft ISO standard for multi-threading [35].
- Constraint handling for tabled programs based on an engine-level implementation of annotated variables and various costraint packages, including `clpqr` for handling real constraints, and `bounds` a simple finite domain constraint library.
- A package for Constraint Handling Rules [30] which can be used to implement user-written constraint libraries.
- A variety of indexing techniques for asserted code including variable-depth indexing on several alternate arguments, fixed-depth indexing on combined arguments, trie-indexing.
- A set of mature packages, to extend XSB to evaluate F-logic [39] through the *FLORA-2* package (distributed separately from XSB), to model check concurrent systems through the *XMC* system, to manage ontologies through the *Cold Dead Fish* package, to support literate programming through the `xsbdoc` package, and to support answer set programming through the `XASP` package among other features.
- A number of interfaces to other software systems, such a C, Java, Perl, ODBC, SModels [53], and Oracle.

- Fast loading of large files by the `load_dync` predicate, and by other means.
- A compiled HiLog implementation;
- Backtrackable updates through XSB's `storage` module that support the semantics of transaction logic [6].
- Extensive pattern matching packages, and interfaces to `libwww` routines, all of which are especially useful for Web applications.
- A novel transformation technique called *unification factoring* that can improve program speed and indexing for compiled code;
- Macro substitution for Prolog files via the `xpp` preprocessor (included with the XSB distribution).
- Preprocessors and Interpreters so that XSB can be used to evaluate programs that are based on advanced formalisms, such as extended logic programs (according to the Well-Founded Semantics [2]); Generalized Annotated Programs [40].
- Source code availability for portability and extensibility under the GNU General Public Library License.

Though XSB can be used as a Prolog system, we avoid referring to XSB as such, because of the availability of SLG resolution and the handling of HiLog terms. These facilities, while seemingly simple, significantly extend its capabilities beyond those of a typical Prolog system. We feel that these capabilities justify viewing XSB as a new paradigm for Logic Programming. We briefly discuss some of these features; others are discussed in Volumes 1 and 2 of the XSB manual, as well as the manuals for various XSB packages such as FLORA, XMC, Cold Dead Fish, xsbdoc, and XASP.

Well-Founded Semantics To understand the implications of SLG resolution [15], recall that Prolog is based on a depth-first search through trees that are built using program clause resolution (SLD). As such, Prolog is susceptible to getting lost in an infinite branch of a search tree, where it may loop infinitely. SLG evaluation, available in XSB, can correctly evaluate many such logic programs. To take the simplest of examples, any query to the program:

```
:- table ancestor/2.

ancestor(X,Y) :- ancestor(X,Z), parent(Z,Y).
ancestor(X,Y) :- parent(X,Y).
```

will terminate in XSB, since `ancestor/2` is compiled as a tabled predicate; Prolog systems, however, would go into an infinite loop. The user can declare that SLG resolution is to

be used for a predicate by using `table` declarations, as here. Alternately, an `auto_table` compiler directive can be used to direct the system to invoke a simple static analysis to decide what predicates to table (see Section 3.10.4). This power to solve recursive queries has proven very useful in a number of areas, including deductive databases, language processing [41, 42], program analysis [21, 16, 7], model checking [56] and diagnosis [31]. For efficiency, we have implemented SLG at the abstract machine level so that tabled predicates will be executed with the speed of compiled Prolog. We finally note that for definite programs SLG resolution is similar to other tabling methods such as OLDT resolution [76] (see Chapter 5 for details).

Example 1.0.1 *The use of tabling also makes possible the evaluation of programs with non-stratified negation through its implementation of the* well-founded semantics *[78]. When logic programming rules have negation, paradoxes become possible. As an example consider one of Russell's paradoxes — the barber in a town shaves every person who does not shave himself — written as a logic program.*

```
:- table shaves/2.

shaves(barber,Person):- person(Person), tnot(shaves(Person,Person)).
person(barber).
person(mayor).
```

Logically speaking, the meaning of this program should be that the barber shaves the mayor, but the case of the barber is trickier. If we conclude that the barber does not shave himself our meaning does not reflect the first rule in the program. If we conclude that the barber does shave himself, we have reached that conclusion using information beyond what is provided in the program. The well-founded semantics, does not treat `shaves(barber,barber)` *as either true or false, but as* undefined. *Prolog, of course, would enter an infinite loop. XSB's treatment of negation is discussed further in Chapter 5.*

Multi-threading From Version 3.0 onward, XSB has been thoroughly revised to support multi-threading using POSIX or Windows threads. Detached XSB threads can be created to execute specific tasks, and these threads will exit when the query succeeds (or fails, or throws an exception) and all thread memory reclaimed. While a thread's execution state is, of course, private, it shares many resources with other threads, such as static code and I/O streams. Dynamic code and tables can be either thread-shared or thread-provate by default or by explicit declaration.

Constraint Support XSB supports logic-based constraint handling at a low level through attributed variables and associated packages (e.g. `setarg/3`. In addition, constraints may

be handled through Constraint Handling Rules. Constraint logic programs that use attributed variables may be tabled; those that use Constraint Handling Rules may be efficiently tabled if the `CHRd` package is used. Constraint programming in XSB is mainly covered in Volume 2.

Indexing Methods Data oriented applications may require indices other than Prolog's first argument indexing. XSB offers a variety of indexing techniques for asserted code. Clauses can be indexed on a group of arguments or on alternative arguments. For instance, the executable directive `index(p/4,[3,2+1])` specifies indexes on the (outer functor symbol of) the third argument *or* on a combination of (the outer function symbol of) the second and first arguments. If data is expected to be structured within function symbols and is in unit clauses, the directive `i ndex(p/4,trie)` constructs an indexing trie of the `p/4` clauses using a depth-first, left-to-right traversal through each clause. Representing data in this way allows discrimination of information nested arbitrarily deep within clauses. Advantages of both kinds of indexing can be combined via *star-indexing*. Star-indexing indicates that up to the first 5 fields in an argument will be used for indexing (the ordering of the fields is via a depth-first traversal). For instance, `index(p/4,[*(4),3,2+1])` acts as above, but looks within 4th argument of `p/4` before examining the outer functor of argument 3 (and finally examining the outer functors of arguments 2 and 1 together. Using such indexing, XSB routinely performs efficiently intensive analyses of in-memory knowledge bases with millions of highly structured facts. Indexing techniques for asserted code are covered in Section 6.14.

Interfaces A number of interfaces are available to link XSB to other systems. In UNIX systems XSB can be directly linked into C programs; in Windows-based system XSB can be linked into C programs through a DLL interface. On either class of operating system, C functions can be made callable from XSB either directly within a process, or using a socket library. XSB can also inter-communicate with Java through the InterProlog interface [1] or using YJXSB. Within Interprolog, XSB and Java can be linked either through Java's JNI interface, or through sockets. XSB can access external data in a variety of ways: through an ODBC interface, through an Oracle interface, or through a variety of mechanisms to read data from flat files. These interfaces are all described in Volume 2 of this manual.

Fast Loading of Code A further goal of XSB is to provide in implementation engine for both logic programming and for data-oriented applications such as in-memory deductive database queries and data mining [61]. One prerequisite for this functionality is the ability to load a large amount of data very quickly. We have taken care to code in C a compiler for asserted clauses. The result is that the speed of asserting and retracting code is faster in XSB than in any other Prolog system of which we are aware, even when some of the sophisticated

[1] InterProlog is available at `www.declarativa.com/InterProlog/default.htm`.

indexing mechanisms described above are employed. At the same time, because asserted code is compiled into SLG-WAM code, the speed of executing asserted code in XSB is faster than that of many other Prologs as well. We note however, that XSB does not follow the ISO-semantics of assert [45].

HiLog XSB also supports HiLog programming [13, 64]. HiLog allows a form of higher-order programming, in which predicate "symbols" can be variable or structured. For example, definition and execution of *generic predicates* like this generic transitive closure relation are allowed:

```
closure(R)(X,Y) :- R(X,Y).
closure(R)(X,Y) :- R(X,Z), closure(R)(Z,Y).
```

where `closure(R)/2` is (syntactically) a second-order predicate which, given any relation `R`, returns its transitive closure relation `closure(R)`. XSB supports reading and writing of HiLog terms, converting them to or from internal format as necessary (see Section 4.2). Special meta-logical standard predicates (see Section 6.7) are also provided for inspection and handling of HiLog terms. Unlike earlier versions of XSB (prior to version 1.3.1) the current version automatically provides *full compilation of HiLog predicates*. As a result, most uses of HiLog execute at essentially the speed of compiled Prolog. For more information about the compilation scheme for HiLog employed in XSB see [64].

HiLog can also be used with tabling, so that the program above can also be written as:

```
:- hilog closure.
:- table apply/3.

closure(R)(X,Y) :- R(X,Y).
closure(R)(X,Y) :- closure(R)(X,Z), R(Z,Y).
```

as long as the underlying relations (the predicate symbols to which R will be unified) are also declared as Hilog. For example, if `a/2` were a binary relation to which the `closure` predicate would be applied, then the declaration `:- hilog a.` would also need to be included.

Unification Factoring For compiled code, XSB offers *unification factoring*, which extends clause indexing methods found in functional programming into the logic programming framework. Briefly, unification factoring can offer not only complete indexing through non-deterministic indexing automata, but can also *factor* elementary unification operations. The general technique is described in [20], and the XSB directives needed to use it are covered in Section 3.10.

XSB Packages Based on these features, a number of sophisticated packages have been implemented using XSB. For instance, XSB supports a sophisticated object-oriented interface called *Flora*. *Flora* (`http://flora.sourceforge.net`) is available as an XSB package

and is described in its own manual, available from the same site from which XSB was downloaded. Another package, XMC http://www.cs.sunnysb.edu/~lmc depends on XSB to perform sophisticated model-checking of concurrent systems. Within the XSB project, the Cold Dead Fish package supports maintenance of, and reasoning over ontologies; xsbdoc supports literate programming in XSB, and XASP provides an interface to Smodels to support Answer Set programming. XSB packages also support Perl-style pattern matching and POSIX-style pattern matching. In addition, experimental preprocessing libraries currently supported are Extended logic programs (under the well-founded semantics), and Annotated Logic Programs. These latter libraries are described in Volume 2 of this manual.

1.1 Using This Manual

We adopt some standard notational conventions, such as the name/arity convention for describing predicates and functors, `+` to denote input arguments, `-` to denote output arguments, `?` for arguments that may be either input or output and `#` for arguments that are both input and output (can be changed by the procedure). See Section 3.10.4 for more details. . Also, the manual uses UNIX syntax for files and directories except when it specifically addresses other operating systems such as Windows.

Finally, we note that XSB is under continuous development, and this document — intended to be the user manual— reflects the current status (Version 3.3) of our system. While we have taken great effort to create a robust and efficient system, we would like to emphasize that XSB is also a research system and is to some degree experimental. When the research features of XSB — tabling, HiLog, and Indexing Techniques — are discussed in this manual, we also cite documents where they are fully explained. All of these documents can be found without difficulty on the web.

While some of Version 3.3 is subject to change in future releases, we will try to be as upward-compatible as possible. We would also like to hear from experienced users of our system about features they would like us to include. We do try to accommodate serious users of XSB whenever we can. Finally, we must mention that the use of undocumented features is not supported, and at the user's own risk.

Chapter 2

Getting Started with XSB

This section describes the steps needed to install XSB under UNIX and under Windows.

2.1 Installing XSB under UNIX

If you are installing on a UNIX platform, the version of XSB that you received may not include all the object code files so that an installation will be necessary. The easiest way to install XSB is to use the following procedure.

1. Decide in which directory in your file system you want to install XSB and copy or move XSB there.
2. Make sure that after you have obtained XSB, you have uncompressed it by following the instructions found in the file `README`.
3. Note that after you uncompress and untar the XSB tar file, a subdirectory `XSB` will be created in the current directory. All XSB files will be located in that subdirectory. In the rest of this manual, we use `$XSB_DIR` to refer to this subdirectory. Note the original directory structure of XSB must be maintained, namely, the directory `$XSB_DIR` should contain all the subdirectories and files that came with the distribution. In particular, the following directories are required for XSB to work: `emu`, `syslib`, `cmplib`, `lib`, `packages`, `build`, and `etc`.
4. Change directory to `$XSB_DIR/build` and then run these commands:

   ```
   configure
   makexsb
   ```

   This is it!

In addition, it is now possible to install XSB in a shared directory (*e.g.*, `/usr/local`) for everyone to use. In this situation, you should use the following sequence of commands:

```
configure -prefix=$SHARED_XSB
makexsb
makexsb install
```

where `$SHARED_XSB` denotes the shared directory where XSB is installed. In all cases, XSB can be run using the script

```
$XSB_DIR/bin/xsb
```

However, if XSB is installed in a central location, the script for general use is:

```
<central-installation-directory>/<xsb-version>/bin/xsb
```

Important: The XSB executable determines the location of the libraries it needs based on the full path name by which it was invoked. The "smart script" `bin/xsb` also uses its full path name to determine the location of the various scripts that it needs in order to figure out the configuration of your machine. Therefore, there are certain limitations on how XSB can be invoked.

Here are some legal ways to invoke XSB:

1. invoking the smart script `bin/xsb` or the XSB executable using their absolute or relative path name.
2. using an alias for `bin/xsb` or the executable.
3. creating a new shell script that invokes either `bin/xsb` or the XSB executable using their *full* path names.

Here are some ways that are guaranteed to not work in some or all cases:

1. creating a hard link to either `bin/xsb` or the executable and using *it* to invoke XSB. (Symbolic links should be ok.)
2. changing the relative position of either `bin/xsb` or the XSB executable with respect to the rest of the XSB directory tree.

The configuration script allows many different options to be specified. A full listing can be obtained by typing `$XSB_DIR/build/configure -help`.

Type of Machine. The configuration script automatically detects your machine and OS type, and builds XSB accordingly. On 64-bit platforms, the default compilation of XSB will reflect the default for the C compiler (e.g. gcc) on that platform. Moreover, you can build XSB for different architectures while using the same tree and the same installation directory provided, of course, that these machines are sharing this directory, say using NFS or Samba. All you will have to do is to login to a different machine with a different architecture or OS type, and repeat the above sequence of commands – or configure with different parameters.

The configuration files for different architectures reside in different directories, and there is no danger of an architecture conflict. In fact, you can keep using the same `./bin/xsb` script regardless of the architecture. It will detect your configuration and will use the right files for the right architecture!

If XSB is being built on a machine running Windows in which Cygwin is installed, Cygwin and Windows are treated as separate operating systems, as their APIs are completely different. If no previous configuration has been made, the configure script will attempt to use `gcc` and other Unix facilities, and therefore will compile the system under Cygwin. If this behavior is not desired, the option `-with-wind` (equivalently, `-with-os=wind`) uses a Window compiler and API. If a user wants to ensure the Cygwin compiler is used (say after a previous configuration for Windows), the option `-without-wind` can be used. See Section 2.2.2 for more details.

Choice of the C Compiler and compiler-related options On Unix systems, XSB is developed and tested mainly using gcc. Accordingly, the `configure` script will attempt to use `gcc`, if it is available. Otherwise, it will revert to `cc` or `acc`. Some versions of `gcc` are broken for particular platforms or `gcc` may not have been installed; in which case you would have to give `configure` an additional directive `-with-cc` (or `-with-acc`). If you must use some special compiler, use `-with-cc=your-own-compiler`. You can also use the `-with-optimization` option to change the default C compiler optimization level. (or `-disable-optimization` to disable all compiler optimizations). `-enable-debug` is mainly a devlopment option that allows XSB to be debugged using gdb – there are many other compiler-based options options. Type `configure -help` to see them all. Also see the file `$XSB_DIR/INSTALL` for more details.

Word Size XSB's configuration script checks whether the default compilation mode of a platform is 32- or 64-bits, and will build a version of XSB accoringly. Some platforms, however, support both 32-bit and 64-bit compilation. On such a platform, a user can explicitly specify the type of compilation using the options `with-bits32` and `with-bits64`.

XSB and Site-specific Information Using the option `-prefix=PREFIX` installs architecture-independent files in the directory `PREFIX`, e.g. `/usr/local`, which can be useful if XSB is to be shared at a site. Using the option `-site-prefix=DIR` installs site-specific libraries in `DIR/site`. Other options indicate directories in which to search

for site-specific static and dynamic libraries, and for include files.

Multi-threading Version 3.0 of XSB was the first version that supports multi-threading. On some platforms, the multi-threaded engine is slightly slower than the single-threaded engine, mostly due to its need for concurrency control. To obtain the benefits of multiple threads on a platform that supports either POSIX or Windows threads (i.e. nearly all platforms) users must configure XSB with the directive `enable-mt` (see Section 7.8 for instructions specific to Windows. The multi-threaded engine works with other configuration options, multi-threading can be compiled with batched or local scheduling, with the ODBC or Interprolog interfaces, and so on.

Interfaces Certain interfaces must be designated at configuration time, including those to Oracle, ODBC, Smodels, Tck/Tk, and Libwww. However, the XSB-calling-C interface interface does not need to be specified at configuration time. If you wish to use the InterProlog Java interface that is based on JNI, you must specify this at configuration time; otherwise if you wish to use the sockets-based Interprolog interface, it does not need to be specified at configuration time. See Volume 2 and the InterProlog site `www.declarativa.com` for details of specific interfaces

While the XSB configuration mechanism can detect most include and library paths, use of certain interfaces may require information about particular directories. In particular the `-with-static-libraries` option might be needed if compiling with support for statically linked packages (such as Oracle) or if your standard C libraries are in odd places. Alternately, dynamic libraries on odd places may need to be specified at configuration time using the `-with-dynamic-libraries` option. and finally, the `-with-includes` option might be needed if your standard header files (or your `jni.h` file) are in odd places, or if XSB is compiled with ODBC support. Type `configure -help` for more details.

Type of Scheduling Strategy. The ordering of operations within a tabled evaluation can drastically affect its performance. XSB provides two scheduling strategies: Batched Evaluation and Local Evaluation. Local Evaluation ensures that, whenever possible, subgoals are fully evaluated before there answers are returned, and provides superior behavior for programs in which tabled negation is used. Batched Evaluation evaluates queries to reduce the time to the first answer of a query. Both evaluation methods can be useful for different programs. Since Version 2.4, Local Evaluation has been the default evaluation method for XSB. Batched Evaluation can be chosen via the `-enable-batched-scheduling` configure option. Detailed explanations of the scheduling strategies can be found in [27], and further experimentation in [11].

Other options are of interest to advanced users who wish to experiment with XSB, or to use XSB for large-scale projects. In general, however users need not concern themselves with these options.

2.1.1 Possible Installation Problems

Lack of Space for Optimized Compilation of C Code When making the optimized version of the emulator, the temporary space available to the C compiler for intermediate files is sometimes not sufficient. For example on one of our SPARCstations that had very little `/tmp` space the `"-O4"` option could not be used for the compilation of files `emuloop.c`, and `tries.c`, without changing the default `tmp` directory and increasing the swap space. Depending on your C compiler, the amount and nature of `/tmp` and swap space of your machine you may or may not encounter problems. If you are using the SUN C compiler, and have disk space in one of your directories, say `dir`, add the following option to the entries of any files that cannot be compiled:

```
-temp=dir
```

If you are using the GNU C compiler, consult its manual pages to find out how you can change the default `tmp` directory or how you can use pipes to avoid the use of temporary space during compiling. Usually changing the default directory can be done by declaring/modifying the `TMPDIR` environment variable as follows:

```
setenv TMPDIR dir
```

Missing XSB Object Files When an object (*.xwam) file is missing from the `lib` directories you can normally run the `make` command in that directory to restore it (instructions for doing so are given in Chapter 2). However, to restore an object file in the directories `syslib` and `cmplib`, one needs to have a separate Prolog compiler accessible (such as a separate copy of XSB), because the XSB compiler uses most of the files in these two directories and hence will not function when some of them are missing. For this reason, distributed versions normally include all the object files in `syslib` and `cmplib`.

XSB on 64-bit platforms XSB has been fully tested on 64-bit Debian Linux, 64-bit and Mac OS X. However, the sockets library may have problems in Version 3.3. If this limitation prove a problem, please contact `xsb-development@lists.sourceforge.net` [1].

Typically, if the 64-bit system generates 32-bit code by default, XSB will run just as in 32-bit mode (including 64-bit floats). 64-bit compilation can be forced for XSB by configuring with the option `-with-bits64`, and in a similar manner 32-bit compilation can be forced with the option `-with-bits32`. Users who employ either option should be aware of issues that may arise when linking XSB to external C code.

- When XSB calls C code the C file must have been compiled with the same memory option as XSB. This is done automatically if the C file is compiled via a call from

[1] 64-bit XSB was broken in a recent releases prior to Version 3.1 because for a time the developers did not have access to a 64-bit machine.

XSB's compiler, but must be handled by the user otherwise. For instance, if XSB were configured `-with-bits32` on a 64-bit machine defaulting to 64-bits, then C files called by XSB require the `-m32` option in `gcc` (if not compiled by XSB).

- The appropriate memory option must be used when embedding XSB into a C or Java process. For instance, if a XSB is to be linked into a 32-bit application on a 64-bit platform defaulting to 64-bits, XSB must be configured `-with-bits32`, and the linking of `xsb.o/so` to the calling program must specify `-m32`.

2.2 Installing XSB under Windows

2.2.1 Using Cygnus Software's CygWin32

This is easy: just follow the Unix instructions. This is the preferred way to run XSB under Windows, because this ensures that all features of XSB are available.

2.2.2 Using Microsoft Visual C++

1. XSB will unpack into a subdirectory named `xsb`. Assuming that you have `XSB.ZIP` in the `$XSB_DIR` directory, you can issue the command

   ```
   unzip386 xsb.zip
   ```

   which will install XSB in the subdirectory `xsb`.

2. If you decide to move XSB to some other place, make sure that the entire directory tree is moved — XSB executable looks for the files it needs relatively to its current position in the file system.

You can compile XSB under Microsoft Visual C++ compiler by following these steps:

1. Download the free of charge Microsoft Visual C++ Express Edition from

   ```
   http://www.microsoft.com/express/vc/
   ```

   By default, this program is installed in `C:\Program Files\Microsoft Visual Studio 10.0`, and we shall assume this directory below (at the time of this writing, the latest version was 10.0, but the version number may change).

2. Go to Start Menu then Control Panel then System (depending on your version of Windows, the System panel might not be directly inside Control Panel, but one or two levels below. Then click "Change Settings," select the "Advanced" tab, and then

click the "Environment Variables" button. In the panel that is now selected, choose the PATH variable and click Edit. At the end of the string that represents the value of PATH, add

```
;C:\Program Files\Microsoft Visual Studio 10.0\VC\BIN
```

On a 64-bit machine, add both of these:

```
;C:\Program Files\Microsoft SDKs\Windows\v7.1\bin
;C:\Program Files (x86)\Microsoft Visual Studio 10.0\VC\BIN
```

Note: to compile XSB as 64 bit application you must install Microsoft Windows SDK found at http://msdn.microsoft.com/en-us/windows/bb980924.aspx. The version numbers, `v7.1` and `10.0`, may vary, of course.

Visual C++ has a command file called `vcvars32.bat`, which you should find and drag into the command window (and press Return). This will set all the necessary environment variables. On a 64 bit machine, this command file is called `vcvarsx86_amd64.bat` or `vcvarsx86_ia64.bat` — whichever is appropriate for your configuration. In Visual Studio Express 9.0, these files are in

```
C:\Program Files (x86)\Microsoft Visual Studio 9.0\VC\BIN\vcvars32.bat
C:\Program Files (x86)\Microsoft Visual Studio 9.0\VC\BIN\ia64\vcvarsx86_ia64.bat
C:\Program Files (x86)\Microsoft Visual Studio 9.0\VC\BIN\amd64\vcvarsx86_amd64.bat
```

At some point, Microsoft eliminated `vcvarsx86_*` in Visual Studio 10.0 and introduced `SetEnv.cmd` instead, requiring the users to download Microsoft Windows SDK. This command file is usually found in

```
C:\Program Files\Microsoft SDKs\Windows\v7.1\bin\SetEnv.cmd
```

As far as we know, `SetEnv.cmd` is the only file from the entire SDK that is necessary to build XSB as a 64-bit application. For 32 bit applications, the file

```
C:\Program Files (x86)\Microsoft Visual Studio 10.0\VC\BIN\vcvars32.bat
```

is still there and installation does not require the Windows SDK.

3. `cd $XSB_DIR\build`

4. On a 32 bit machine, type:
   `makexsb ["CFG=opt"] ["ORACLE=yes"] ["MY_LIBRARY_DIRS=libs"] ["MY_INCLUDE_DIRS=opts"]`

   - The items in square brackets are optional and usually are not necessary.

- The options for `CFG` are: *release* (default) or *debug*. The latter is used when you want to compile XSB with debugging enabled.
- The `ORACLE` parameter (default is "no") compiles XSB with native support for Oracle DBMS. If `ORACLE` is specified, you **must** also specify the necessary Oracle libraries using the parameter `SITE_LIBS`. Native Oracle support is rarely used and ODBC is the recommended way to connect to databases.
- `MY_LIBRARY_DIRS` is used to specify the external libraries and `libs` there has the form `/LIBPATH:"libdir1" /LIBPATH:"libdir2" ....`
- `MY_INCLUDE_DIRS` is used to specify additional directories for included files. Here `opts` has the form `/I"incdir1" /I"incdir2" ....`

Instead of specifying the options on command line, it might be more convenient, however, to create the file

```
XSB\build\windows\custom_settings.mak
```

and put the options there. For instance,

```
XSB_INTERPROLOG=yes
MY_INCLUDE_DIRS=/I"C:\Program Files\Java\jdk1.6.0_26\include" \
      /I"C:\Program Files\Java\jdk1.6.0_26\include\win32"
MY_LIBRARY_DIRS=/LIBPATH:"C:\pthreads\pthreadVC1.lib" /libpath:"C:\oracle"
ORACLE=yes
```

5. The above command will compile XSB as requested and will put the XSB executable and its DLL in:

```
$XSB_DIR\config\x86-pc-windows\bin\xsb.exe
$XSB_DIR\config\x86-pc-windows\bin\xsb.dll
```

6. On a 64 bit machine, use `makexsb64` instead of `makexsb`. The compiled code will be installed in

```
$XSB_DIR\config\x64-pc-windows\bin\xsb.exe
$XSB_DIR\config\x64-pc-windows\bin\xsb.dll
```

The `custom_settings.mak` file must be in

```
XSB\build\windows64\custom_settings.mak
```

Make sure you do not misspell the name of that file or else none of the specified options will take effect!

Note: if you compiled XSB with one set of parameters and then want to recompile with a different set, it is recommended that you run

```
makexsb  clean
```

in between the compilations (or `makexsb64 clean` in the 64-bit case). This also applies to recompilations for 32/64 bits.

2.3 Invoking XSB

Under Unix, XSB can be invoked by the command:

```
$XSB_DIR/bin/xsb
```

if you have installed XSB in your private directory. If XSB is installed in a shared directory (*e.g.*, `$SHARED_XSB` for the entire site (UNIX only), then you should use

```
$SHARED_XSB/bin/xsb
```

In both cases, you will find yourself in the top level interpreter. As mentioned above, this script automatically detects the system configuration you are running on and will use the right files and executables. (Of course, XSB should have been built for that architecture earlier.)

Under Windows, you should invoke XSB by typing:

```
$XSB_DIR\bin\xsb
```

This script tries to find the XSB executable and invoke it. If, for some reason, it fails to do so, the user should call the executable directly.

```
$XSB_DIR\config\x86-pc-windows\bin\xsb.exe
```

You may want to make an alias such as `xsb` to the above commands, for convenience, or you might want to put the directory where the XSB command is found in the `$PATH` environment variable. However, you should **not** make hard links to this script or to the XSB executable. If you invoke XSB via such a hard link, XSB will likely be confused and will not find its libraries. That said, you **can** create other scripts and call the above script from there.

ISO"standard" Prolog predicates are supported by XSB, in addition to many other predicates: so those of you who consider yourselves champion entomologists, can try to test them for bugs now. Details are in Chapter 6.

2.4 Compiling XSB programs

One way to compile a program from a file, such as `myfile.P` in the current directory and load it into memory, is to type the query:

```
[my_file].
```

where `my_file` is the name of the file. Chapter 3 contains a full discussion of the compiling and consulting.

If you are eccentric (or you don't know how to use an editor) you can also compile and load predicates input directly from the terminal by using the command:

```
[user].
```

A `CTRL-d` or the atom `end_of_file` followed by a period terminates the input stream.

2.5 Sample XSB Programs

There are several sample XSB source programs in the directory: `$XSB_DIR/examples` illustrating a number of standard features, as well as a number of non-standardized or XSB-specific features including plain tabling, incremental tabling, tabling with negation, attributed variables, annotated programs, constraint handling rules, XSB embedded in a C program, XSB calling C functions, sockets, and various semantic web appliation

Hence, a sample session might look like (the actual times shown below may vary and some extra information is given using comments after the % character):

```
my_favourite_prompt> cd $XSB_DIR/examples
my_favourite_prompt> $XSB_DIR/bin/xsb
XSB Version 3.1 (Incognito) of August 10, 2007
[i386-apple-darwin8.9.1; mode: optimal; engine: slg-wam; scheduling: local; word size: 32]
| ?- [queens].
[queens loaded]

yes
| ?- demo.

% ...... output from queens program .......

Time used: 0.4810 sec

yes
| ?- statistics.
```

```
memory (total)         1906488 bytes:       203452 in use,      1703036 free
  permanent space       202552 bytes
  glob/loc space        786432 bytes:          432 in use,       786000 free
    global                                     240 bytes
    local                                      192 bytes
  trail/cp space        786432 bytes:          468 in use,       785964 free
    trail                                      132 bytes
    choice point                               336 bytes
  SLG subgoal space          0 bytes:            0 in use,            0 free
  SLG unific. space      65536 bytes:            0 in use,        65536 free
  SLG completion         65536 bytes:            0 in use,        65536 free
  SLG trie space             0 bytes:            0 in use,            0 free
   (call+ret. trie           0 bytes,     trie hash tables            0 bytes)

      0 subgoals currently in tables
      0 subgoal check/insert attempts inserted     0 subgoals in the tables
      0 answer  check/insert attempts inserted     0 answers  in the tables

       Time: 0.610 sec. cputime,  18.048 sec. elapsetime

yes
| ?- halt.          % I had enough !!!

End XSB (cputime 1.19 secs, elapsetime 270.25 secs)
my_favourite_prompt>
```

2.6 Exiting XSB

If you want to exit XSB, issue the command `halt.` or simply type `CTRL-d` at the XSB prompt. To exit XSB while it is executing queries, strike `CTRL-c` a number of times.

Chapter 3

System Description

Throughout this chapter, we use `$XSB_DIR` to refer to the directory in which XSB was installed.

3.1 Entering and Exiting XSB from the Command Line

After the system has been installed, the emulator's executable code appears in the file:

```
$XSB_DIR/bin/xsb
```

If, after being built, XSB is later installed at a central location, `$SHARED_XSB`, the emulators executable code appears in

```
$SHARED_XSB/bin/xsb
```

Either of these commands invokes XSB's top-level interpreter, which is the most common way of using XSB.

XSB can also directly execute object code files from the command line interface. Suppose you have a top-level routine `go` in a file `foo.P` that you would like to run from the UNIX or Windows command line. As long as `foo.P` contains a directive, e.g. `:- go.`, and `foo.P` has been compiled to an object file (`foo.xwam`), then

```
$XSB_DIR/bin/xsb foo
```

will execute `go` (and any other directives), loading the appropriate files as needed [1]. In fact the command `$XSB_DIR/bin/xsb` is equivalent to the command:

```
$XSB_DIR/bin/xsb -B $XSB_DIR/syslib/loader.xwam
```

There is one other way to execute XSB from a command line. Using the `-e` command-line option any goal can be can be executed, up to 1024 characters. For instance

```
$XSB_DIR/bin/xsb -e "writeln('hello world'),halt."
```

writes "hello world" and exits XSB. Within the 1024 character limit, any query or command can be executed, including consulting files, so this method is actually quite general footnoteVarious options can suppress XSB's startup and end messages, as discussed below..

There are several ways to exit XSB. A user may issue the command `halt.` or `end_of_file.`, or simply type `CTRL-d` at the XSB prompt. To interrupt XSB while it is executing a query, strike `CTRL-c`.

3.2 The System and its Directories

When installed, the XSB system resides in a single directory that contains several subdirectories. For completeness, we review the information in all subdirectories. Normally, only the documentation and files in the Prolog subdirectories, particularly `examples`, `lib`, and `packages` will be of interest to users.

1. `bin` contains scripts that call XSB executables for various configurations.
2. `build` contains XSB configuration scripts. You may already be familiar with the `build` directory, which is used to build XSB.
3. `config` contains executables and other files specific to particular configurations.
4. `docs` contains the user manuals and other documentation, including the technical documentation manual for developers.
5. `emu` contains the C source code for the XSB emulator, for I/O and for various interfaces.
6. `etc` contains miscellaneous files used by XSB.

[1] In XSB, all extensions except '.pl' — (default '.P', '.H', '.xwam', '.D' (output by mode inferencing), and '.A' (assembly dump) — are defined in C and Prolog code using macros in `$XSB_DIR/emu/extensions_xsb.h` and can be changed by a user if desired. Of course, such a step should not be taken lightly, as it can cause severe compatibility problems.

7. `examples` contains some examples for Prolog, tabling, HiLog and various interfaces.
8. `cmplib` contains Prolog source and object code for the compiler.
9. `gpp` contains a copy of the Gnu pre-processor used to preprocess Prolog files.
10. `lib` contains Prolog source and object code for extended libraries.
11. `packages` The directory `packages` contains the various applications, such as FLORA, the XMC model checker and many others. These applications are written in XSB and can be quite useful, but are not part of the XSB system per se.
12. `Prolog_includes` contains include files for the Prolog libraries, which are preprocessed using GPP.
13. `syslib` contains Prolog source and object code for core XSB libraries.

All Prolog source programs are written in XSB, and all object (byte code) files contain SLG-WAM instructions that can be executed by the emulator. These byte-coded instructions are machine-independent, so usually no installation procedure is needed for the byte code files.

If you are distributing an application based on XSB and need to cut down space, the `packages`, `examples` and `docs` directories are not usually needed (unless of course you are using one of the packages in your application). `lib` may not be needed, (most core system files are in syslib) nor are Prolog source files necessary. Unless your application needs to rebuild XSB, the `emu` and `build` directories do not need to be distributed.

3.3 How XSB Finds Files: Source File Designators

Three files are associated with Prolog source code in XSB [2].

- A single *source* file, whose name is the *base file name* plus an optional extension suffix `.P` or `.pl`.
- An *object (byte-code)* file, whose name consists of the base file name plus the suffix `.xwam`.
- An optional *header* file, whose name is the base file name plus the suffix "`.H`". When used, the header file normally contains file-level declarations and directives while the source file usually contains the actual definitions of the predicates defined in that module. However, such information can be equivalently put into the `.P` (or `.pl` file.

[2] Other types of files may be associated with foreign code — see Volume 2.

Most of the XSB system predicates for compiling, consulting, and loading code, such as `consult/[1,2]`, `compile/[1,2]`, `load_dyn/1` and others are somewhat flexible in how they designate the file of interest. Each of these predicates take as input a *source file designator* which can be a base file name, a source file name; or the relative or absolute paths to a base or source file name. Unfortunately, the exact semantics of a file designator differs among system predicates in Version 3.3, as well as among platforms.

In general, however, when given a source file designator, system predicates perform *name resolution*. There are two steps to name resolution: determining the proper directory prefix and determining the proper file extension. When `FileName` is absolute (i.e. it contains a path from the file to the root of the file system) determining the proper directory prefix is straightforward. If `FileName` is relative, i.e. it contains a `'/'` in Unix or `'/'` in Windows, `FileName` is expanded to a directory prefix in an OS-dependent way, resolving symbols like `'.'`, `'..'` and `'~'` when applicable. However, the user may also enter a name without any directory prefix. In this case, XSB tries to determine the directory prefix using a set of diretories it knows about: those directories in the dynamic loader path (see Section 3.6). As it searches through directory prefixes, different forms of the file name may be checked. If the source file designator has no extension the loader first checks for a file in the directory with the `.P` extension, (or `.c` for foreign modules) before searching for a file without the extension, and finally for a file with a `.pl` extension. Note that since directories in the dynamic loader path are searched in a predetermined order (see Section 3.6), if the same file name appears in more than one of these directories, the first one encountered will be used.

3.4 The Module System of XSB

XSB has been designed as a module-oriented Prolog system. Modules provide a small step towards *logic programming "in the large"* that facilitates the construction of large programs or projects from components that are developed, compiled and tested separately. Also, module systems support the principle of information hiding and can provide a basis for data abstraction. The module system of XSB is *file based* – one module per file – and *flat* – modules cannot be nested. In addition, XSB's module system is to some extent *atom-based*, where any symbol in a module can be imported, exported or be a local symbol, as opposed to the predicate-based ones where this can be done only for predicate symbols [3]. As we will discuss, this leads to certain differences of XSB's module system from those of some other Prologs, and to certain incompatabilities with the ISO standard for modules (which is not supported by most Prologs). At the same time, XSB's module system has enough commonalities with those of other Prologs to be able to support Prolog commons libraries.

[3] Operator symbols can be exported as any other symbols, but their precedence must be redeclared in the importing module.

Module Syntax By default, files are not treated as modules. In order for a file to be treated as a module, it must contain one or more `module/2` or `export/1` declarations, which specify that a set of symbols appearing in that module is visible and therefore can be used by any other module. In XSB, the *module name* must be equal to the base file name in which the module is defined. Any file (either module or not) may also contain `use_module/2` or `import/1` declarations, which allow symbols defined in and exported by other modules to be used in the current module. In addition, a module can also contain *local declarations*, which specify that a set of symbols is *visible by this module only*, and therefore cannot be accessed by any other module. Module declarations can appear anywhere in the source or header files and have the following forms:

:- export sym_1, ..., sym_l.

:- import sym_1, ..., sym_n from *module*.

:- import *sym* from *module* as sym'.

:- local sym_1, ..., sym_m.

where sym_i has the form $functor/arity$, and *module* is a Prolog atom representing a module name.

In XSB, the declaration

:- module(*filename*,[sym_1, ..., sym_l.]).

can be seen as syntactic sugar for

:- export sym_1, ..., sym_l.

as long as the *filename* is the same as the name of the file in which it was contained. Similarly,

:- use_module(*module*,[sym_1, ..., sym_l.]).

is treated as semantically equivalent to

:- import sym_1, ..., sym_n from *module*.

Accordingly, `use_module/2` and `module/1` can be used interchangibly with `import/2` and `export/1`. However the declaration

:- use_module(*module*).

which is often used in other Prolog systems, is *not* equivalent to an XSB import statement, as each XSB import statement must explicitly declare a list of predicates that are used from each module. Such a declaration will raise a compilation error.

The declaration

:- import *sym* from *module* as sym'.

allows a predicate to be imported from a module, but renamed as sym' within the importing

module. Such a feature is useful when porting a library written for another Prolog (e.g. a constraint library) to XSB.

For modules, the base file name is stored in its byte code file, so that renaming a byte-code file for a mule may cause problems, as the renaming will not affect the information within the byte-code file. However, byte code files generated for non-modules can be safely renamed.

Module Semantics In XSB's atom-based module system, the name of each predicate and function symbol `p/n` is identified as if it were prefixed with its module name (i.e. base file name). Hence the occurrence of `p/n` in two different modules, `m1` and `m2` are distinct symbols that can be denoted as `m1:p/n` and `m2:p/n`.

Normally, only exported symbols can be imported; if a non-exported symbol `p/2` is imported from a module `m1` by module `m2` an environment conflict warning will be issued as soon as `m1` and `m2` are loaded in the same session – i.e. the conflict is detected at run-time. When a non-module file is loaded, its predicates and symbols are loaded into the module `usermod`, which is the working module of the XSB command-line interpreter and C-calling XSB interface. Dynamically asserted code is also loaded into `usermod` by default. Currently the following set of rules is used to determine the module prefix of a symbol:

- A predicate symbol `p/n` is *defined* in a module `m` if `m` contains a clause with head `p/n` or a dynamic declaration for `p/n`. Any predicate symbol `p/n` defined in a module `m`, whether exported or not, can be called by prepending the module prefix using the `:/2` functor, e.g. `m:p(A,...)`. For brevity, we call this an *explicit module call* to `p/n`. The following example illustrates these principles.

Exported and Non-Exported Predicates

```
m1

:- export p/2.

exported(a,b).

local(c,d).
```

```
| ?- exported(X,Y).

X = a
Y = b

yes
| ?- local(X,Y).
/* Existence Error */
| ?- m1:local(X,Y).

X = c
Y = d

yes
```

- Every predicate symbol defined in a module is assumed by default to be *local* to a module unless it is declared otherwise by an export or import declaration. Symbols that are local to a given module are not visible to other modules except through explicit module calls. The following example shows how different declarations for dynamic predicates within a module may be global (`usermod`) or local. Calls to statically defined predicates behave similarly.

Visibility of Dynamic Predicates

m1

```
:- export p1/2, p2/2, p3/2, p4/2.
:- dynamic d1/2.
:- import d2/2 from usermod.

p10:- a1.

p1(X,Y):- assert(d1(X,Y)).
p2(X,Y):- d1(X,Y).

p2(X,Y):- assert(d2(X,Y)).
p3(X,Y):- d2(X,Y).
```

m2

```
| ?- [m1].
[m1 loaded]

yes
| ?- p1(a,b).

yes
| ?- p2(X,Y).

X = a
Y = b

yes
| ?- d1(X,Y).
/* Existence Error */
| ?- m1:d1(X,Y).

X = a
Y = b

yes
| ?- p3(1,2).

yes
| ?- p4(X,Y).

X = 1
Y = 2

yes
| ?- d2(X,Y).

X = 1
Y = 2

yes
```

- Functors that occur as literals in the bodies of clauses, are treated as predicate symbols.

  - *Standard* predicates are taken to be a part of `usermod`, and are implicitly imported into user-defined modules. Standard predicates include ISO predicates along with many other XSB predicates for tabling, indexing and other functions. The current listing of standard predicates can be found in the index of this manual under *Standard predicates*.
  - Other predicates are taken to be local to the module in which they occur.

- Functors that do not occur as literals in the body of clauses in a module are taken to be structure symbols. These symbols are assumed to be global and do not require an explicit module call to be used, unless declared otherwise through a `local/1` declaration. In addition, terms that are dynamically created by standard predicates such as `read/1, functor/3, '=..'/2`, etc) are taken to be structure symbols and are contained in `usermod`.

- All atoms are assumed to be global and do not require an explicit module call to be used. This can occasionally lead to unexpected results if a token is used both as an atom and a 0-ary function symbol. In the following table, the query `?- p10` will call `a1/0`, while `?- p11.` will throw an existence error.

Atoms and 0-ary Predicates

m1	m2
`:- export p10/0, p11/0.` `:- import a1/0 from m2.`	`:- export a1/0.`
`p10:- a1.`	
`p11:- atom_chars(A1,[a,'1']),` `  call(A1).`	`a1:- writeln(found_a1).`

For clarity, we state a few consequences of these rules.

- In Version 3.3, a module *cannot* export predicate symbols that are imported from other modules. This happens because an `import` declaration is considered a request for permission to use a symbol from a module where its definition and an `export` declaration appear.

- The implicit module for a particular symbol appearing in a module must be uniquely determined. As a consequence, a symbol of a specific *functor/arity cannot* be declared as both exported and local, or (as just discussed) both exported and imported from another module, or declared to be imported from more than one module, etc. These types of environment conflicts are detected at compile-time and abort the compilation.

- If a module `m1` imports a predicate `p/n` from a module `m2`, but `m2` does not export `p/n`, nothing is detected at the time of compilation. As discussed above, if `p/n` is defined in `m2` a runtime warning about an environment conflict will be issued. However, if `p/n` is not defined in `m2`, a runtime existence error will be thrown [4].
- Only one definition of a symbol `p/n` can appear in a module, without being explicitly associated with a module using the `:/2` functor. Accordingly only one default definition of `p/n` can be loaded into the interpreter's module (`usermod`). An attempt to load a module that redefines `p/n` results in a warning to the user and the newly loaded symbol *redefines* the definition of the previously loaded one.

Usage inference and the module system The import and export statements of a module M are used by the compiler for inferring usage of predicates. At compilation time, if a predicate P/N occurs as callable in the body of a clause defined in M, but P is neither defined in M nor imported into M from some other module, a warning is issued that P/N is undefined. Here "occurs as callable" means that P/N is found as a literal in the body of a clause, or within a system meta-predicate, such as `assert/1`, `findall/3`, etc. Currently, occurrences of a term inside user-defined meta-predicates are not considered as callable by XSB's usage inference algorithm. Alternatively, if P/N is defined in M, it is *used* if P/N is exported by M, or if P/N occurs as callable in a clause for a predicate that is used in M. The compiler issues warnings about all unused predicates in a module. On the other hand, since all modules are compiled separately, the usage inference algorithm has no way of checking whether a predicate imported from a given module is actually exported by that module.

Usage inference can be highly useful during code development for ensuring that all predicates are defined within a set of files, for eliminating dead code, etc. In addition, import and export declarations are used by the `xsbdoc` documentation system to generate manuals for code [5]. For these reasons, it is sometimes the case that usage inference is desired even in situations where a given file is not ready to be made into a module, or it is not appropriate for the file to be a module for some other reason. In such a case the directives `document_export/1` and `document_import/1` can be used, and have the same syntax as `export/1` and `import/1`, respectively. These directives affect only usage inference and `xsbdoc`. A file is treated as a module if and only if it includes an `export/1` statement, and only `import/1` statements affect dynamic loading and name resolution for predicates.

[4] This behavior can be altered through the Prolog flag `unknown`.

[5] Further information on `xsbdoc` can be found in `$XSB_DIR/packages/xsbdoc`.

3.5 Standard Predicates in XSB

Whenever XSB is invoked, a large set of *standard* predicates are defined and can be called from the interpreter or other interface [6]. These predicates include the various ISO predicates [33], along with predicates for tabling, I/O, for interaction with the operating system, for HiLog, and for much other functionality. Standard predicates are listed in this manual under the index heading *Standard predicates* and at an implementation level are declared in the file `$XSB_DIR/syslib/std_xsb.P`. If a user wishes to redefine a standard predicate, she has several choices. First, the appropriate fact in `$XSB_DIR/syslib/std_xsb.P` should be commented out. Once this is done, a user may define the predicate as any other user predicate. Alternately, the compiler option `allow_redefinition` can be used to allow the compiler to redefine a standard predicate (Section 3.10.2). If a user wants to make a new definition or new predicate standard, the safest course is to put the predicate into a module in the `lib` directory, and add or modify an associated fact in `$XSB_DIR/syslib/std_xsb.P`.

3.6 The Dynamic Loader and its Search Path

XSB differs from some other Prolog system in its ability to `dynamically` load modules. In XSB, the loading of user modules and Prolog libraries (such as the XSB compiler) is delayed until predicates in them are actually needed, saving program space for large Prolog applications. Dynamic loading is done by default, unlike other systems where it is not the default for non-system libraries.

When a predicate imported from another module (see Section 3.4) is called during execution, the dynamic loader is invoked automatically if the module is not yet loaded into the system, The default action of the dynamic loader is to search for the byte code file of the module first in the system library directories (in the order `lib, syslib`, and then `cmplib`), and finally in the current working directory. If the module is found in one of these directories, then it will be loaded (*on a first-found basis*). Otherwise, an error message will be displayed on the current error stream reporting that the module was not found. Because system modules are dynamically loaded, the time it takes to compile a file is slightly longer the first time the compiler is invoked in a session than for subsequent compilations.

3.6.1 Changing the Default Search Path and the Packaging System

`library_directory(+Path)`

The default search path of the dynamic loader is based on the dynamic predicate `library_directory/1` so it can easily be changed. For instance, to make sure a user's home directory is loaded,

[6] Such predicates are sometimes called "built-ins" in other Prologs.

the goal `assert(library_directory(' /'))` needs to be executed from the command line or from within a program. If you always want XSB to search particular directories, the easiest way is to have a file named `.xsb/xsbrc.P` in the user's home directory. User-supplied library directories are searched by the dynamic loader *before* searching the default library directories. The `.xsb/xsbrc.P` file, which is automatically consulted by the XSB interpreter, might look like the following:

```
:- assert(library_directory('~/')).
:- assert(library_directory('/usr/lib/sbprolog')).
```

After loading the module of the above example the user's home directory is searched first, then `"/usr/lib/sbprolog/"`, and finally XSB's system library directories (`lib, syslib`, `cmplib`) as well as the current working directory. XSB also uses `library_directory/1` for internal purposes. For instance, before the user's `.xsb/xsbrc.P` is consulted, XSB puts the `packages` directory and the directory `.xsb/config/$CONFIGURATION` on the library search path. The directory `.xsb/config/$CONFIGURATION` is used to store user libraries that are machine or OS dependent. (`$CONFIGURATION` for a machine is something that looks like `sparc-sun-solaris2.6` or `pc-linux-gnu`, and is selected by XSB automatically at run time). If a user wished, say, to search the current working directory *before* her home directory, she could simply add

```
:- asserta(library_directory('./')).
```

to her `.xsb/xsbrc.P` file (or anywhere else). The file `.xsb/xsbrc.P` is not limited to setting the library search path. In fact, arbitrary Prolog code can go there so that XSB can be initialized in any manner desired.

We emphasize that in the presence of a `.xsb/xsbrc.P` file *it is the user's responsibility to avoid module name clashes with modules in XSB's system library directories.* Such name clashes can cause unexpected behavior as system code may try to load a user's predicates. The list of module names in XSB's system library directories can be found by looking through the directories `$XSB_DIR/{syslib,cmplib,lib}`.

Apart from the user libraries, XSB now has a simple packaging system. A *package* is an application consisting of one or more files that are organized in a subdirectory of one of the XSB system or user libraries. The system directory `$XSB_DIR/packages` has a number examples of such packages, many of which are documented in Volume 2 of this manual, or contain their own manuals. Packages are convenient as a means of organizing large XSB applications, and for simplifying user interaction with such applications. User-level packaging is implemented through the predicate

```
bootstrap_userpackage(+LibraryDir, +PackageDir, +PackageName).
```

which must be imported from the `packaging` module.

To illustrate, suppose you wanted to create a package, `foobar`, inside your own library, `my_lib`. Here is a sequence of steps you can follow:

1. Make sure that `my_lib` is on the library search path by putting an appropriate assert statement in your `xsbrc.P`.

2. Make a subdirectory `~/my_lib/foobar` and organize all the package files there. Designate one file, say, `foo.P`, as the entry point, *i.e.*, the application file that must be loaded first.

3. Create the interface program `~/my_lib/foobar.P` with the following content:

```
:- bootstrap_userpackage('~/my_lib', 'foobar', foobar), [foo].
```

   The interface program and the package directory do not need to have the same name, but it is convenient to follow the above naming schema.

4. Now, if you need to invoke the `foobar` application, you can simply type `[foobar].` at the XSB prompt. This is because both and `~/my_lib/foobar` have already been automatically added to the library search path.

5. If your application files export many predicates, you can simplify the use of your package by having `~/my_lib/foobar.P` import all these predicates, renaming them, and then exporting them. This provides a uniform interface to the `foobar` module, since all the package predicates are can now be imported from just one module, `foobar`.

In addition to adding the appropriate directory to the library search path, the `bootstrap_userpackage/3` predicate also adds information to the predicate `package_configuration/3`, so that other applications could query the information about loaded packages.

Packages can also be unloaded using the predicate `unload_package/1`. For instance,

```
:- unload_package(foobar).
```

removes the directory `~/my_lib/foobar` from the library search path and deletes the associated information from `package_configuration/3`.

Finally, if you have developed and tested a package that you think is generally useful and you would like to distribute it with XSB, please contact `xsb-development@sourceforge.net`.

3.6.2 Dynamically loading predicates in the interpreter

Modules are usually loaded into an environment when they are consulted (see Section 3.9). Specific predicates from a module can also be imported into the run-time environment through the standard predicate `import PredList from Module`. Here, `PredList` can either be a Prolog list or a comma list. (The `import/1` can also be used as a directive in a source module (see Section 3.4).

We provide a sample session for compiling, dynamically loading, and querying a user-defined module named `quick_sort`. For this example we assume that `quick_sort.P` is a file in the current working directory, and contains the definitions of the predicates `concat/3` and `qsort/2`, both of which are exported.

```
| ?- compile(quick_sort).
[Compiling ./quick_sort]
[quick_sort compiled, cpu time used: 1.439 seconds]

yes
| ?- import concat/3, qsort/2 from quick_sort.

yes
| ?- concat([1,3], [2], L), qsort(L, S).

L = [1,3,2]
S = [1,2,3]

yes.
```

The standard predicate `import/1` does not load the module containing the imported predicates, but simply informs the system where it can find the definition of the predicate when (and if) the predicate is called.

3.7 Command Line Arguments

There are several command line options for the emulator. The general synopsis obtained by the command `$XSB_DIR/bin/xsb -help` is:

```
xsb [flags] [-l]
xsb [flags] module
xsb [flags] -B boot_module [-D cmd_loop_driver] [-t]
xsb [flags] -B module.suffix -d
xsb [-h | -v | --help | --version]

module:
    Module to execute after XSB starts up.
```

```
    Module should have no suffixes, and either be an absolute pathname
    the file module.xwam must be on the library search path.
boot_module:
    This is a developer's option.
    The -B flags tells XSB which bootstrapping module to use instead
    of the standard loader.  The loader must be specified using its
    full pathname, and boot_module.xwam must exist.
module_to_disassemble:
    This is a developer's option.
    The -d flag tells XSB to act as a disassembler.
    The -B flag specifies the module to disassemble.
cmd_loop_driver:
    The top-level command loop driver to be used instead of the
    standard one.  Usually needed when XSB is run as a server.

                  -B : specify the boot module to use in lieu of the standard loader
                  -D : Sets top-level command loop driver to replace the default
                  -t : trace execution at the SLG-WAM instruction level
                        (for this to work, build XSB with the --debug option)
                  -d : disassemble the loader and exit
      -v, --version : print the version and configuration information about XSB
         -h, --help : print this help message

Flags:
               -e goal : evaluate goal when XSB starts up
                    -p : enable Prolog profiling through use of profile_call/1
                    -l : the interpreter prints unbound variables using letters
           --nobanner : don't show the XSB banner on startup
          --quietload : don't show the 'module loaded' messages
           --noprompt : don't show prompt (for non-interactive use)
                    -S : set default tabling method to call-subsumption
 --max_subgoal_depth N : set maximum tabled subgoal depth to N (default is maximum integer)
--max_subgoal_action A : set action on maximum subgoal depth: e(rror)/a(bstract)/w(arn)
         --max_tries N : allow up to N tries for interning terms
       --max_threads N : maintain information for up to N threads (MT engine only)
       --max_mqueues N : allow up to N message queues (MT engine only)
   --shared_predicates : make predicates thread-shared by default
           -g gc_type : choose heap garbage collection ("indirection","none" or "copying")
          -c N [unit] : initially allocate N units (default KB) for the trail/choice-point stack
          -m N [unit] : initially allocate N units (default KB) for the local/global stack
          -o N [unit] : initially allocate N units (default KB) for the SLG completion stack
                    -r : turn off automatic stack expansion
                    -T : print a trace of each called predicate

          unit: k/K memory in kilobytes; m/M in megabytes; g/G in gigabytes
```

Command-line Options These options tend to be most useful for developers.

`-t` Traces through code at SLG-WAM instruction level. This option is intended for developers and is not fully supported. It is also not available when the system is being used at the non-debug mode (see Section 10).

`-D` Tells XSB to use a top-level command loop driver specified here instead of the standard XSB interpreter. This is most useful when XSB is used as a server.

`-d` Produces a disassembled dump of `byte_code_file` to `stdout` and exits.

Flags The order in which flags appear makes no difference.

General Flags

`-e goal` Pass `goal` to XSB at startup. This goal is evaluated right before the first prompt is issued. For instance, `xsb -e "write(Hello!'), nl."'` will print a heart-warming message when XSB starts up.

`-p` Enables the engine to collect information that can be used for profiling. See Volume 2 of this manual for details.

`-l` Forces the interpreter to print unbound variables as letters, as opposed to the default setting which prints variables as memory locations prefixed with an underscore. For example, starting XSB's interpreter with this option will print the following:

```
| ?- Y = X, Z = 3, W = foo(X,Z).

Y = A
X = A
Z = 3
W = foo(A,3)
```

as opposed to something like the following:

```
| ?- Y = X, Z = 3, W = foo(X,Z).

Y = _h118
X = _h118
Z = 3
W = foo(_h118,3);
```

`-nobanner` Start XSB without showing the startup banner. Useful in batch scripts and for interprocess communication (when XSB is launched as a subprocess). For instance,

```
 xsb -e "writeln('hello world'),halt."
[xsb_configuration loaded]
```

```
[sysinitrc loaded]

XSB Version 3.1 (Incognito) of August 10, 2007
[i386-apple-darwin8.9.1; mode: optimal; engine: slg-wam; scheduling: local; word size


Evaluating command line goal:
| ?-  writeln('hello world'),halt.

| ?- hello world

End XSB (cputime 0.02 secs, elapsetime 0.02 secs)
```

Prints out quite a bit of verbiage. Using the `-nobanner` option reduces this verbiage somewhat.

```
xsb --nobanner -e "writeln('hello world'),halt."
[xsb_configuration loaded]
[sysinitrc loaded]

Evaluating command line goal:
| ?-  writeln('hello world'),halt.

| ?- hello world
```

`-quietload` Do not tell when a new module gets loaded. Again, is quseful in non-interactive activities and for interprocess communication. Continuing our example:

```
xsb --quietload --nobanner -e "writeln('hello world'),halt."
| ?-
| ?- hello world
```

`-noprompt` Do not show the XSB prompt. This is useful only in batch mode and in interprocess communication when you do not want the prompt to clutter the picture. Putting all this together, we finally get:

```
xsb --noprompt --quietload --nobanner -e "writeln('hello world'),halt."

hello world
```

So that XSB can be used to write reasonable scripts.

`-max_threads N` Allows XSB to maintain information for up to `N` threads. This means that XSB can currently run `N` threads that are active, or that are inactive, non-detached, and not yet joined. Has no effect if the engine has been configured without multi-threading.

`-S` Indicates that tabled predicates are to be evaluated using subsumption-based tabling as a default for tabled predicates whose tabling method is not specified by using `table Predspec as subsumptive` or `table Predspec as variant`(see Section 6.15.1). If this option is not specified, variant-based tabling will be used as the default tabling method by XSB.

`-shared_predicates` In the multi-threaded engine, makes all predicates thread-shared by default; has no effect in the single-threaded engine.

`-T` Generates a trace at entry to each called predicate (both system and user-defined). This option is available mainly for people who want to modify and/or extend XSB, and it is *not* the normal way to trace XSB programs. For the latter, the standard predicates `trace/0` or `debug/0` should be used (see Chapter 10). Note: This option is not available when the system is being used at the non-tracing mode (see Section 10).

`-max_subgoal_depth` ***N*** : set maximum tabled subgoal depth to *N* (default is maximum integer). This flag sets the depth of a subgoal upon which an action may be taken (such as throwing an error, abstracting, or issuing a warning.

`-max_subgoal_action` ***A*** : set action on maximum subgoal depth: e(rror)/a(bstract)/w(arn)

Memory Management Flags

`-g gc_type` Chooses the heap garbage collection strategy that is employed; choice of the strategy is between the default `indirection`; `copying`, which is not fully supported; or `none`. See [10] for a description of the indirection garbage collector, and [23] for the copying garbage collector.

`-c` ***size [units]*** Allocates *initial size* units of space to the trail/choice-point stack area. The trail stack grows upward from the bottom of the region, and the choice point stack grows downward from the top of the region. If units is not provided or is `k` or `K`, the size is allocated in kilobytes; if `m` or `M` in megabytes; and if `g` or `G` in gigabytes. Because this region is expanded automatically, this option is rarely needed. If this option is not speficied the default initial size is 768 KBytes.

`-m` ***size [units]*** Allocates *initial size* units of space to the local/global stack area. The global stack grows upward from the bottom of the region, and the local stack grows downward from the top of the region. If units is not provided or is `k` or `K`, the size is allocated in kilobytes; if `m` or `M` in megabytes; and if `g` or `G` in gigabytes. Because this region is expanded automatically, this option is rarely needed. If this option is not specified the default initial size is 768 KBytes.

`-o` ***size [units]*** Allocates *initial size* units of space to the completion stack area. If units is not provided or is `k` or `K`, the size is allocated in kilobytes; if `m` or `M` in megabytes; and if `g` or `G` in gigabytes. Because this region is expanded automatically, this option is rarely needed. If this option is not specified the default initial size is 768 KBytes.

`-r` Turns off automatic stack expansion. This can occasionally be useful for isolating memory management problems.

3.8 Memory Management

All execution stacks are automatically expanded in Version 3.3, including the local stack/heap region, the trail/choice point region, and the completion stack region. Execution stacks increase their size until it is not possible to do so with available system memory. At that point XSB tries to find the maximal amount of space that will still fit in system memory. For the main thread, each of these regions begin with an initial value set by the user at the command-line or with a default value (see Section 3.7). When a thread is created within an XSB process, the size of the thread's execution stacks may be set by `thread_create/3`, otherwise the default values indicated in Section 3.7 are used. Once XSB is running, these default values may be modified using the appropriate Prolog flags (see Section 6.12). In addition, whenever a thread exits, memory specific to that thread is reclaimed.

Heap garbage collection is automatically included in XSB [10, 23]. (To change the algorithm used for heap garbage collection or to turn it off altogether, see the predicate `garbage_collection/1` or Section 3.7 for command-line options). In Version 3.3 the default behavior is indirect garbage collection. Starting with Version 3.0, heap garbage collection may automatically invokes garbage collection of XSB's "string" table, which stores Prolog's atomic constants. Expansion and garbage collection of execution stacks can occur when multiple threads are active; however atom garbage collection will not be invoked if there is more than one active XSB thread.

The program area (the area into which XSB byte-code is loaded) is also dynamically expanded as needed. For dynamic code (created using `assert/1`, or standard predicates such as `load_dyn/1` and `load_dync/1`) index size is also automatically reconfigured. Space reclaimed for dynamic code depends on several factors. If there is only one active thread, space is reclaimed for retracted clauses and abolished predicates as long as (1) there are no choice points that may backtrack into the retracted or abolished code, and (2) if the dynamic predicate is tabled, all of its tables are completed. Otherwise, the code is marked for later garbage collection. If more than one thread is active, private predicates behave as just described, however space reclamation for shared predicates will be delayed until there is a single active thread. See Section 6.14 for details.

Space for tables is dynamically allocated as needed and reclaimed through use of `abolish_all_tables/0`, `abolish_table_pred/1`, `abolish_table_call/1` and other predicates. As with dynamic code, space for tables may be reclaimed immediately or marked for later garbage collection depending on whether choice points may backtrack into the abolished tables, on the number of active threads, etc. Tabling also includes various stacks used to copy information into or out of tables, most of which are dynamically allocated and expanded. These stacks may be thread-private or shared among threads: space for thread-private stacks is reclaimed when

a thread exits. See Section 6.15.3 for details.

Perhaps more than a standard Prolog system, XSB is used to evaluate queries in knowledge representation languages that have a higher level of declarativity than Prolog and as a result may consume a great deal of space. If XSB needs memory that is unobtainable from the operating sytsem, it will usually abort with a resource error, and become ready for a new query from its command line or API. In such a case, a user or program can use `statistics/[0,1,2]` to investigate whether and how XSB is consuming memory. Other options to bounding memory include the use of `bounded_call/4` or the use of the `max_memory` flag. Use of the `max_memory` flag is recommended in cases where XSB is embedded in a C program through the C/XSB interface, or is embedded in or communicating with a java program through Interprolog. In such a case, XSB will abort with a resource error whenever a memory allocation would exceed the user-defined threshold [7].

3.9 Compiling, Consulting, and Loading

Like other Prologs, XSB provides for both statically compiled code and dynamically asserted code. Static compiled code may be more optimized than asserted code, particularly for clauses that have large bodies, but certain types of indexing, such as trie and star indexing are (currently) available only for dynamically asserted predicates (see `index/2`).

3.9.1 Static Code

In XSB, there is no difference between compiled and consulted static code: "compiling" in XSB means creation of a file containing SLG-WAM byte-code; "consulting" means loading such a byte-code file, after compiling it (if the source file was altered later than the object file).

`consult(+Files,+OptionList)`

`consult(+Files)`

`[+Files]`

The standard predicate `consult/[1,2]` is the most convenient method for entering static source code rules into XSB's database [8]. Files is either s source file designator (see Section 3.3) or a list of source file designators, and `Options` is a list of options to be passed to XSB's compiler if the file needs to be compiled (see Section 3.10). `consult(Files)` is defined as `consult(Files,[])`, as is `[Files]`.

Consulting a file `File` (module) conceptually consists of the following five steps which are described in detail in the following paragraphs.

[7] In rare cases, XSB will exit if the inability to allocate more memory will leave it in an inconsistent state (e.g. if XSB cannot allocate needed memory during heap garbage collection).

[8] In XSB, `reconsult/[1,2]` is defined to have the same actions as `consult/[1,2]`.

Name Resolution: determine the file that `File` designates, including directory and drive location and extension, as discussed in Section 3.3.

Compilation: if the source file or header has changed later than the object file (or if there is no byte-code file) compile the file using `compile/2` with the options specified, creating a byte-code file. This strategy is used whether the source file is Prolog, C, or C++.

Loading: load the byte-code file into memory.

Importing: if the file is a module, import any exported predicates of that module to `usermod`.

Query Execution: execute any queries that the file may contain, i.e. any terms with principal functor `'?-'/1`, or with the principal functor `':-'/1` and that are not directives like the ones described in Section 3.10. The queries are executed in the order in which they appear in the source file.

Error conditions for `consult(+File,+Options)` are as follows:

- `File` is not instantiated
  - `instantiation_error`
- `File` is not an atom
  - `type_error(atom,File)`
- `File` does not exist in the current set of library directories
  - `existence_error(file,File)`
- `File` has an object code extension (e.g. `.xwam`)
  - `permission_error(compile,file,File)`
- `File` has been loaded previously in the session *and* there is more than one active thread.
  - `misc_error`

Error conditions of compiler options are determined by `compile/2` which `consult/[1,2]` calls.

In addition, `ensure_loaded/[1,2]` acts much like `consult/[1,2]`

`ensure_loaded(+FileName)` ISO

This predicate checks to see whether the object file for `FileName` is newer than the source code and header files for `FileName`, and compiles `FileName` if not. If `FileName` is loaded into memory, `ensure_loaded/1` does not reload it, unlike `consult/1` which will always reload. In addition, `ensure_loaded/2` can be used to load a file with dynamic code. It is fully documented in Section 6.14.1.

3.9.2 Dynamic Code

In XSB, most source code file can also be "consulted" dynamically via the predicates `load_dyn/[1,2]`, `load_dync/[1,2]` and `ensure_loaded/2`. These predicates act as `consult/2` in that if a given file `File` has already been dynamically loaded, old versions of predicates defined in `File` will be retracted and their new definitions made to correspond to those in `File` (except for predicates in which a `multifile/1` declaration is present in `File`). Dynamic loading can be performed using XSB's reader of canonical terms (which does not include operators, but does allow list and comma-list notation) via `load_dync/2`; dynamic loading using XSB's general reader for Hilog terms is performed via `load_dyn/2`.

The predicates mentioned above are described more fully in Chapter 6. Here, we simply compare the tradeoffs of static and dynamic loading.

- Advantages for Dynamic Loading
  - For large files, containing $10^4 - 10^7$ clauses, dynamic loading is much faster than XSB's compiler, especially when the canonical reader is used.
  - Dynamically loaded files have advantages of dynamic code including star-, trie, compound, and alternate indexes, as well as being modifiable via assert and retract.
- Advantages for Static Compilation
  - Although dynamically loaded predicates are compiled into SLG-WAM code, compiled static clauses are more optimized than dynamically predicates, particularly when the clauses have large bodies or when arithmetic is used. For facts and pure binary predicates (those containing a single literal in their body) however, static and dynamic byte code is essentially the same.
  - Dynamic loading does not allow module/export declarations, mode declarations, or unification factoring. It does however, allow files to import predicates, allows tabling and dynamic declarations (except for `auto_table` and `suppl_table`, and operator declarations (when a canonical read is not used).

3.9.3 The multifile directive

The default action upon loading a file or module is to delete all previous byte-code for predicates defined in the file. If this is not the desired behavior, the user may add to the file a declaration

```
:- multifile Predicate_List .
```

where `Predicate_List` is a list of predicates in *functor/arity* form. The effect of this declaration is to delete *only* those clauses of `predicate/arity` that were defined in the file

itself. *If a predicate P is to be treated as multifile, the* `multifile/1` *directive for P must appear in all files that contain clause definitions for P.* If P is dynamic, this means that the multifile declaration for P must appear in files defining P whether they are compiled and consulted, or dynamically loaded via `load_dyn/[1,2]` or `load_dync/[1,2]`.

3.10 The Compiler

The XSB compiler translates XSB source files into byte-code object files. It is written entirely in Prolog. Both the sources and the byte code for the compiler can be found in the XSB system directory `cmplib`. Prior to compiling, XSB filters the programs through *GPP*, a preprocessor written by Denis Auroux (auroux@math.polytechnique.fr). This preprocessor maintains high degree of compatibility with the C preprocessor, but is more suitable for processing Prolog programs. The preprocessor is invoked with the compiler option `xpp_on` as described below. The various features of GPP are described in Appendix A.

XSB also allows the programmer to use preprocessors other than GPP. However, the modules that come with XSB distribution require GPP. This is explained below (see `xpp_on/1` compiler option).

The following sections describe the various aspects of the compiler in more detail.

3.10.1 Invoking the Compiler

In addition to invoking the compiler through `consult/[1,2]`, the compiler can be invoked directly at the interpreter level (or in a program) through the Prolog predicates `compile/[1,2]`.

`compile(+Files,+OptionList)`

`compile(+Files)`

`compile/2` compiles all files specified, using the compiler options specified in `OptionList` (see Section 3.10.2 below for the precise details.) `Files` is either an absolute or relative filename, or a ground list of absolute or relative file names; and `OptionList` is a ground list of compiler options. Since options can be set globally via the predicate `set_global_compiler_options/1`, each option in `OptionsList` can optionally be prefixed by `+` or `-`, indicating that the option is to be turned on, or off, respectively. (No prefix turns the option on.)

```
| ?- compile(Files).
```

is just a notational shorthand for the query:

```
| ?- compile(Files, []).
```

For a given, `File` to be compiled, the source file name corresponding to `File` is obtained by concatenating a directory prefix and the extension `.P`, `.pl` or other filenames

as discussed in Section 3.3. The directory prefix must be in the dynamic loader path (see Section 3.6). Note that these directories are searched in a predetermined order (see Section 3.6), so if a module with the same name appears in more than one of the directories searched, the compiler will compile the first one it encounters. In such a case, the user can override the search order by providing an absolute path name. If `File` contains no extension, an attempt is made to compile the file `File.P`, `File.pl`, or other extensions before trying compiling the file with name `File`.

We recommend use of the extension `.P` for Prolog source file to avoid ambiguity. Optionally, users can also provide a header file for a module (denoted by the module name suffixed by `.H`). In such a case, the XSB compiler will first read the header file (if it exists), and then the source file. Currently the compiler makes no special treatment of header files. They are simply included in the beginning of the corresponding source files, and code can, in principle, be placed in either.

The result of the compilation (an SLG-WAM object code file) is stored in (⟨*filename*⟩.xwam), but `compile/[1,2]` does *not* load the object file it creates. (The standard predicate `consult/[1,2]` loads the object file into the system, after recompiling the source file if needed.) The object file created is always written into the directory where the source file resides: the user must therefore have write permission in that directory to avoid an error.

If desired, when compiling a module (file), clauses and directives can be transformed as they are read. This is indeed the case for definite clause grammar rules (see Chapter 11), but it can also be done for clauses of any form by providing a definition for predicate `term_expansion/2` (see Section 11.3).

Predicates `compile/[1,2]` can also be used to compile foreign language modules. In this case, the names of the source files should have the extension `.c` and a `.P` file must *not* exist. A header file (with extension `.H`) *must* be present for a foreign language module (see the chapter *Foreign Language Interface* in Volume 2).

Error Cases In the cases below, `File` refers to an element of `Files` if `Files` is a list and otherwise refers to `Files` itself.

- `Files` is a variable, or a list containing a variable element.
  - `instantiation_error`.
- `File` is a neither an atom nor a list of atoms.
  - `type_error(atom_or_list_of_atoms,File)`
- `File` does not exist in the current set of library directories
  - `existence_error(file,File)`
- `File` has an object code extension (e.g. `.xwam`)
  - `permission_error(compile,file,File)`

- `File` has been loaded previously in the session *and* there is more than one active thread.
  - `misc_error`
- `OptionList` is a partial list or contains an option that is a variable
  - `instantiation_error`
- `OptionList` is neither a list nor a partial list
  - `type_error(list,OptionsList)`
- `OptionList` contains an option, `Option` not described in Section 3.10.2
  - `domain_error(xsb_compiler_option,Option)`

3.10.2 Compiler Options

Compiler options can be set in three ways: from a global list of options (`set_global_compiler_options/1`), from the compilation command (`compile/2` and `consult/2`), and from a directive in the file to be compiled (see compiler directive `compiler_options/1`).

`set_global_compiler_options(+OptionsList)`
: `OptionsList` is a list of compiler options (described below). Each can optionally be prefixed by `+` or `-`, indicating that the option is to be turned on, or off, respectively. (No prefix turns the option on.) This evaluable predicate sets the global compiler options in the way indicated. These options will be used in any subsequent compilation, unless they are reset by another call to this predicate, overridden by options provided in the compile invocation, or overridden by options in the file to be compiled.

The following options are currently recognized by the compiler:

`singleton_warnings_off` Does not print out any warnings for singleton variables during compilation. This option can be useful for compiling XSB programs that have been generated by some other program.

`optimize` When specified, the compiler tries to optimize the object code. In Version 3.3, this option optimizes predicate calls, among other features, so execution may be considerably faster for recursive loops. However, due to the nature of the optimizations, the user may not be able to trace all calls to predicates in the program. As expected, the compilation phase will also be slightly longer. For these reasons, the use of the `optimize` option may not be suitable for the development phase, but is recommended once the code has been debugged.

`allow_redefinition` By default the compiler refuses to compile a file that contains clauses that would redefine a standard predicate (unless the `sysmod` option is in effect.) By specifying this option, the user can direct the compiler to quietly allow redefinition of standard predicates.

`xpp_on` Filter the program through a preprocessor before sending it to the XSB compiler. By default (and for the XSB code itself), XSB uses GPP, a preprocessor developed by Denis Auroux (auroux@math.polytechnique.fr) that has high degree of compatibility with the C preprocessor, but is more suitable for Prolog syntax. In this case, the source code can include the usual C preprocessor directives, such as `#define`, `#ifdef`, and `#include`. This option can be specified both as a parameter to compile/2 and as part of the `compiler_options/1` directive inside the source file. See Appendix A for more details on GPP.

When an `#include "file"` statement is encountered, XSB directs the GPP preprocessor to search for the files to include in the directories `$XSB_DIR/emu` and `$XSB_DIR/prolog_includes`. However, additional directories can be added to this search path by asserting into the predicate `gpp_include_dir/1`, **which must be imported from module** `parse` [9].

Note that when compiling XSB programs, GPP searches the current directory and the directory of the parent file that contains the include-directive *last*. If you want additional directories to be searched, then the following statements must be executed:

```
:- import gpp_include_dir/1 from parse.
:- assert(gpp_include_dir('some-other-dir')).
```

If you want Gpp to search directories in a different order, `gpp_options/1` can be used (see below).

Note: if you assert something into this predicate then you must also `retractall(gpp_include_dir(_))` after that or else subsequent Prolog compilations might not work correctly.

XSB predefines the constant `XSB_PROLOG`, which can be used for conditional compilation. For instance, you can write portable program to run under XSB and and other prologs that support C-style preprocessing and use conditional compilation to account for the differences:

```
#ifdef XSB_PROLOG
    XSB-specific stuff
#else
    other Prolog's stuff
#endif
    common stuff
```

`gpp_options` This dynamic predicate must be imported from module `parse`. If some atom is asserted into `gpp_options` then this atom is assumed to be the list of command line options to be used by the preprocessor (only the first asserted atom is ever considered).

[9] For compatability, XSB also supports the ISO predicate `include/1` which also allows extra files to be included during compilation.

If this predicate is empty, then the default list of options is used (which is `'-P -m -nostdinc -nocurinc'`, meaning: use Prolog mode and do not search the standard C directories and the directory of the parent file that contains the include-instruction).

As mentioned earlier, when XSB invokes Gpp, it uses the option `-nocurinc` so that Gpp will not search the directory of the parent file. If a particular application requires that the parent file directory must be searched, then this can be accomplished by executing `assert(gpp_options('-P -m -nostdinc'))`.

Note: if you assert something into this predicate then you must also `retractall(gpp_options(_))` after that or else subsequent Prolog compilations might not work correctly.

`xpp_dump` This causes XSB to dump the output from the GPP preprocessor into a file. If the file being compiled is named `file.P` then the dump file is named `file.P_gpp`. This option can be included in the list of options in the `compiler_options/1` directive, but usually it is used for debugging, as part of the `compile/2` predicate. If `xpp_dump` is specified directly in the file using `compiler_options/1` directive, then it should *not* follow the `gpp_on` option in the list (or else it will be ignored).

Note: multiple occurrences of `xpp_on` and `xpp_dump` options are allowed, but only the *first one* takes effect—all the rest are ignored!

`xpp_on/N` **and** `xpp_dump/N`

XSB also allows one to filter program files through a series of external preprocessors in addition to or instead of GPP. This can be specified with the unary versions of `xpp_on` and `xpp_dump`:

```
xpp_on(spec1,...,specN)
xpp_dump(spec1,...,specN)
```

Each `spec1`, ..., `specN` is a preprocessor specification of the form `preprocessor_name` or `preprocessor_name(options)`. The preprocessor name is an atom or a function symbol and `options` must be an atom. If `preprocessor_name` is `gpp`, then the GPP preprocessor will be invoked. Note that `gpp` can appear anywhere in the aforesaid sequence of specs (or not appear at all), so it is possible to preprocess XSB files before and/or after (or instead of) GPP. Note that `xpp_on(gpp)` and `xpp_dump(gpp)` are equivalent to the earlier 0-ary compiler options `xpp_on` and `xpp_dump`, respectively.

To use a preprocessor other than GPP two things must be done:

- A 4-ary Prolog predicate must be provided, which takes three input arguments and produces a syntactically correct shell (Unix or Windows) command for invoking the preprocessor in its fourth argument. The preprocessor must be taking its input either from the standard input or from a file and send the post-processed result to the standard output. The arguments to the shell-command-producing predicate are as follows:

  - File: this is the XSB input file to be processed. Usually this argument is left unused, but might be useful for producing error messages or debugging.
  - Preprocessor name: this is the name under which the preprocessor is *registered* (see below). It is the same as `processor_name` referred to above. This name is up to the programmer; it is to be used to refer to the preprocessor (it does not need to be related in any way to the shell-command-producing predicate or to the OS's pathname for the preprocessor).
  - Options: these are the command-line options that the preprocessor might need. If the preprocessor spec mentioned above is `foo(bar)` then the preprocessor name (argument 2) would be bound to `foo` and options (argument 3) to `bar`.
  - Shell command: this is the only output argument. It is supposed to be the shell command to be used to invoke the preprocessor. The shell command must *not* include the file name to be processed—that name is added automatically as the last option to the shell command.

- The preprocessor must be *registered* using the following query:

```
:- import register_xsb_preprocessor/2 from parse.
?- register_xsb_preprocessor(preproc_name,preproc_predicate(_,_,_,_)).
```

  Here `preproc_name` is the user-given name for the preprocessor and `preproc_predicate` is the 4-ary shell-command-producing predicate described earlier.

  The registration query must be executed *before* the start of the preprocessing of the input XSB file. Clearly, this implies that the shell-command-producing predicate must be in a different file than the one being preprocessed.

  Note: one *cannot* register the same preprocessor twice. The second time the same name is used, it is ignored. However, it *is* possible to register the same shell-command-producing predicate twice, if the user registers them under different preprocessor names.

The difference between `xpp_on/N` and `xpp_dump/N` is that the latter also saves the output of each preprocessing stage in a separate file. For instance, if the XSB file to be preprocessed is `abc.P` and the `xpp_dump/N` option has the form `xpp_dump(foo,gpp,bar)` then three files will be produced: `abc.P_foo`, `abc.P_gpp`, `abc.P_bar`, each containing the result of the respective stage in preprocessing.

Here is an example. Suppose that `foobar.P` includes the definition of the following predicate

```
make_append_cmd(_File,_Name,Options,ResultingCmd) :-
       fmt_write_string(ResultingCmd, '"/bin/cat" "%s"', arg(Options)).
```

and also has the following registration query:

```
?- parse:register_xsb_preprocessor(appendfile,make_append_cmd(_,_,_,_)).
```

Suppose that the file `abc.P` includes the following compiler directive:

```
:- compiler_options([xpp_on(appendfile('data.P'),gpp)]).
```

If the file `foobar.P` is loaded before compiling `abc.P` then the file `data.P` will be first appended to `foobar.P` and then the result will be processed by GPP. The final result will be parsed and compiled by XSB.

Note that although the parameters `_File` and `_Name` are not used by `make_append_cmd/4` in our example, when this predicate is called they will be bound to `foobar.P` and `appendfile`, respectively, and could be used for various purposes.

`quit_on_error` This causes XSB to exit if compilation of a program end with an error. This option is useful when running XSB from a makefile, when it is necessary to stop the build process after an error has been detected. For instance, XSB uses this option during its own build process.

`auto_table` When specified as a compiler option, the effect is as described in Section 3.10.4. Briefly, a static analysis is made to determine which predicates may loop under Prolog's SLD evaluation. These predicates are compiled as tabled predicates, and SLG evaluation is used instead.

`suppl_table` The intention of this option is to direct the system to table for efficiency rather than termination. When specified, the compiler uses tabling to ensure that no predicate will depend on more than three tables or EDB facts (as specified by the declaration `edb` of Section 3.10.4). The action of `suppl_table` is independent of that of `auto_table`, in that a predicate tabled by one will not necessarily be tabled by the other. During compilation, `suppl_table` occurs after `auto_table`, and uses table declarations generated by it, if any.

`spec_repr` When specified, the compiler performs specialization of partially instantiated calls by replacing their selected clauses with the representative of these clauses, i.e. it performs *folding* whenever possible. In general specialization with replacement is correct only under certain conditions. XSB's compiler checks for sufficient conditions that guarantee correctness, and if these conditions are not met, specialization with replacement is not performed for the violating calls.

`spec_off` When specified, the compiler does not perform specialization of partially instantiated calls.

`unfold_off` When specified, singleton sets optimizations are not performed during specialization. This option is necessary in Version 3.3 for the specialization of `table` declarations that select only a single chain rule of the predicate.

`spec_dump` Generates a `module.spec` file, containing the result of specializing partially instantiated calls to predicates defined in the `module` under compilation. The result is in Prolog source code form.

`ti_dump` Generates a `module.ti` file containing the result of applying unification factoring to predicates defined in the `module` under compilation. The result is in Prolog source code form. See page 55 for more information on unification factoring.

`ti_long_names` Used in conjunction with `ti_dump`, generates names for predicates created by unification factoring that reflect the clause head factoring done by the transformation.

`modeinfer` This option is used to trigger mode analysis. For each module compiled, the mode analyzer creates a *`module`*`.D` file that contains the mode information.

WARNING: Occasionally, the analysis itself may take a long time. As far as we have seen, the analysis times are longer than the rest of the compilation time only when the module contains recursive predicates of arity ≥ 10. If the analysis takes an unusually long time (say, more than 4 times as long as the rest of the compilation) you may want to abort and restart compilation without `modeinfer`.

`mi_warn` During mode analysis, the `.D` files corresponding to the imported modules are read in. The option `mi_warn` is used to generate warning messages if these `.D` files are outdated — *i.e.*, older than the last modification time of the source files.

`mi_foreign` This option is used *only* when mode analysis is performed on XSB system modules. This option is needed when analyzing `standard` and `machine` in `syslib`.

`sysmod` Mainly used by developers when compiling system modules and used for bootstrapping. If specified, standard predicates (see `/$XSB_DIR/syslib/std_xsb.P`) are automatically available for use only if they are primitive predicates (see the file `$XSB_DIR/syslib/machine.P` for a current listing of primitive predicates.) When compiling in this mode, non-primitive standard predicates must be explicitly imported from the appropriate system module. Also standard predicates are permitted to be defined.

`verbo` Compiles the files (modules) specified in "verbose" mode, printing out information about the progress of the compilation of each predicate.

`profile` This option is usually used when modifying the XSB compiler. When specified, the compiler prints out information about the time spent in certain phases of the compilation process.

`asm_dump, compile_off` Generates a textual representation of the SLG-WAM assembly code and writes it into the file `module.A` where `module` is the name of the module (file) being compiled.

WARNING: This option was created for compiler debugging and is not intended for general use. There might be cases where compiling a module with these options may cause generation of an incorrect `.A` and `.xwam` file. In such cases, the user can see the SLG-WAM instructions that are generated for a module by compiling the module as usual and then using the `-d module.xwam` command-line option of the XSB emulator (see Section 3.7).

`index_off` When specified, the compiler does not generate indices for the predicates compiled.

3.10.3 Specialization

From Version 1.4.0 on, the XSB compiler automatically performs specialization of partially instantiated calls. Specialization can be thought as a source-level program transformation of a program to a residual program in which partially instantiated calls to predicates in the original program are replaced with calls to specialized versions of these predicates. The expectation from this process is that the calls in the residual program can be executed more efficiently that their non-specialized counterparts. This expectation is justified mainly because of the following two basic properties of the specialization algorithm:

Compile-time Clause Selection The specialized calls of the residual program directly select (at compile time) a subset containing only the clauses that the corresponding calls of the original program would otherwise have to examine during their execution (at run time). By doing so, laying down unnecessary choice points is at least partly avoided, and so is the need to select clauses through some sort of indexing.

Factoring of Common Subterms Non-variable subterms of partially instantiated calls that are common with subterms in the heads of the selected clauses are factored out from these terms during the specialization process. As a result, some head unification (`get_*` or `unify_*`) and some argument register (`put_*`) WAM instructions of the original program become unnecessary. These instructions are eliminated from both the specialized calls as well as from the specialized versions of the predicates.

Though these properties are sufficient to get the idea behind specialization, the actual specialization performed by the XSB compiler can be better understood by the following example. The example shows the specialization of a predicate that checks if a list of HiLog terms is ordered:

```
ordered([]).
ordered([X]).
ordered([X,Y|Z]) :-
    X @=< Y, ordered([Y|Z]).
```

$\longrightarrow$

```
ordered([]).
ordered([X]).
ordered([X,Y|Z]) :-
    X @=< Y, _$ordered(Y, Z).

:- index _$ordered/2-2.
_$ordered(X, []).
_$ordered(X, [Y|Z]) :-
    X @=< Y, _$ordered(Y, Z).
```

The transformation (driven by the partially instantiated call `ordered([Y|Z])`) effectively allows predicate `ordered/2` to be completely deterministic (when used with a proper list as its argument), and to not use any unnecessary heap-space for its execution. We note that appropriate `:- index` directives are automatically generated by the XSB compiler for all specialized versions of predicates.

The default specialization of partially instantiated calls is without any folding of the clauses that the calls select. Using the `spec_repr` compiler option (see Section 3.10.2) specialization with replacement of the selected clauses with the representative of these clauses is performed. Using this compiler option, predicate `ordered/2` above would be specialized as follows:

```
ordered([]).
ordered([X|Y]) :- _$ordered(X, Y).

:- index _$ordered/2-2.
_$ordered(X, []).
_$ordered(X, [Y|Z]) :- X @=< Y, _$ordered(Y, Z).
```

We note that in the presence of cuts or side-effects, the code replacement operation is not always sound, i.e. there are cases when the original and the residual program are not computationally equivalent (with respect to the answer substitution semantics). The compiler checks for sufficient (but not necessary) conditions that guarantee computational equivalence, and if these conditions are not met, specialization is not performed for the violating calls.

The XSB compiler prints out messages whenever it specialises calls to some predicate. For example, while compiling a file containing predicate `ordered/1` above, the compiler would print out the following message:

```
% Specialising partially instantiated calls to ordered/1
```

The user may examine the result of the specialization transformation by using the `spec_dump` compiler option (see Section 3.10.2).

Finally, we have to mention that for technical reasons beyond the scope of this document, specialization cannot be transparent to the user; predicates created by the transformation do appear during tracing.

3.10.4 Compiler Directives

Consider a directive

```
:- foo(a).
```

That occurs in a file that is to be compiled. There are two logical interpretations of such a directive.

1. `foo(a)` is to be executed upon loading the file; or
2. `foo(a)` provides information used by the compiler in compiling the file.

By default, the interpretation of a directive is as in case (1) *except* in the case of the compiler directives listed in this section, which as their name implies, are taken to provide information to the compiler. Some of the directives, such as the `mode/1` directive, have no meaning as an executable directive, while others, such as `import/2` do. In fact as an executable directive `import/2` imports predicates into `usermod`. For such a directive, a statement beginning with `?-`, such as

```
?- import foo/1 from myfile.
```

indicates that the directive should be executed upon loading the file, and should have no meaning to the compiler. On the other hand, the statement

```
:- import foo/1 from myfile.
```

Indicates that `foo/1` terms in the file to be compiled are to be understood as `myfile:foo/1`. In other words, the statement is used by the compiler and will not be executed upon loading. For non-compiler directives the use of `?-` and `:-` has no effect — in both cases the directive is executed upon loading the file.

The following compiler directives are recognized in Version 3.3 of XSB

Including Files in a Compilation

`include(+FileName)` ISO

The ISO directive

```
:- include(FileName)
```

Causes the compiler to act as if the code from `FileName` were contained at the position where the directive was encountered. XSB's preprocessor can perform the same function via the command `#include FileName` and can support more sophisticated substitutions, but `include/1` should be used if code portability is desired.

Mode Declarations

The XSB compiler accepts `mode` declarations of the form:

`:- mode` $ModeAnnot_1, \ldots, ModeAnnot_n$.

where each *ModeAnnot* is a *mode annotation* (a *term indicator* whose arguments are elements of the set {`+,-,#,?`}). From Version 1.4.1 on, `mode` directives are used by the compiler for tabling directives, a use which differs from the standard use of modes in Prolog systems[10]. See Section 3.10.4 for detailed examples.

Mode annotations have the following meaning:

`+` This argument is an input to the predicate. In every invocation of the predicate, the argument position must contain a non-variable term. This term may not necessarily be ground, but the predicate is guaranteed not to alter this argument).

```
:- mode see(+), assert(+).
```

`-` This argument is an output of the predicate. In every invocation of the predicate the argument position *will always be a variable* (as opposed to the `#` annotation below). This variable is unified with the value returned by the predicate. We note that Prolog does not enforce the requirement that output arguments should be variables; however, output unification is not very common in practice.

```
:- mode cputime(-).
```

`#` This argument is either:

- An output argument of the predicate for which a non-variable value may be supplied for this argument position. If such a value is supplied, the result in this position is unified with the supplied supplied value. The predicate fails if this unification fails. If a variable term is supplied, the predicate succeeds, and the output variable is unified with the return value.

```
:- mode '='(#,#).
```

[10] The most common uses of `mode` declarations in Prolog systems are to reduce the size of compiled code, or to speed up a predicate's execution.

- An input/output argument position of a predicate that has only side-effects (usually by further instantiating that argument). The `#` symbol is used to denote the ± symbol that cannot be entered from the keyboard.

`?` This argument does not fall into any of the above categories. Typical cases would be the following:

- An argument that can be used both as input and as output (but usually not with both uses at the same time).

```
:- mode functor(?,?,?).
```

- An input argument where the term supplied can be a variable (so that the argument cannot be annotated as `+`), or is instantiated to a term which itself contains uninstantiated variables, but the predicate is guaranteed *not* to bind any of these variables.

```
:- mode var(?), write(?).
```

We try to follow these mode annotation conventions throughout this manual.

Finally, we warn the user that `mode` declarations can be error-prone, and since errors in mode declarations do not show up while running the predicates interactively, unexpected behavior may be witnessed in compiled code, optimized to take modes into account (currently not performed by XSB). However, despite this danger, `mode` annotations can be a good source of documentation, since they express the programmer's intention of data flow in the program.

Tabling Directives

Memoization is often necessary to ensure that programs terminate, and can be useful as an optimization strategy as well. The underlying engine of XSB is based on SLG, a memoization strategy, which, in our version, maintains a table of calls and their answers for each predicate declared as *tabled*. Predicates that are not declared as tabled execute as in Prolog, eliminating the expense of tabling when it is unnecessary.

The simplest way to use tabling is to include the directive

```
:- auto_table.
```

anywhere in the source file. `auto_table` declares predicates tabled so that the program will terminate.

To understand precisely how `auto_table` does this, it is necessary to mention a few properties of SLG. For programs which have no function symbols, or where function symbols always have a limited depth, SLG resolution ensures that any query will terminate after it has found all correct answers. In the rest of this section, we restrict consideration to such programs.

Obviously, not all predicates will need to be tabled for a program to terminate. The `auto_table` compiler directive tables only those predicates of a module which appear to static analysis to contain an infinite loop, or which are called directly through `tnot/1`. It is perhaps more illuminating to demonstrate these conditions through an example rather than explaining them. For instance, in the program.

```
:- auto_table.

p(a) :- s(f(a)).

s(X) :- p(f(a)).

r(X) :- q(X,W),r(Y).

m(X) :- tnot(f(X)).

:- mode ap1(-,-,+).
ap1([H|T],L,[H|L1]) :- ap1(T,L,L1).

:- mode ap(+,+,-).
ap([],F,F).
ap([H|T],L,[H|L1]) :- ap(T,L,L1).

mem(H,[H|T]).
mem(H,[_|T]) :- mem(H,T).
```

The compiler prints out the messages

```
% Compiling predicate s/1 as a tabled predicate
% Compiling predicate r/1 as a tabled predicate
% Compiling predicate m/1 as a tabled predicate
% Compiling predicate mem/2 as a tabled predicate
```

Terminating conditions were detected for `ap1/3` and `ap/3`, but not for any of the other predicates.

`auto_table` gives an approximation of tabled programs which we hope will be useful for most programs. The minimal set of tabled predicates needed to ensure termination for a given program is undecidable. It should be noted that the presence of meta-predicates such as `call/1` makes any static analysis useless, so that the `auto_table` directive should not be used in such cases.

Predicates can be explicitly declared as tabled as well, through the `table/1`. When `table/1` is used, the directive takes the form

```
:- table(F/A).
```

where `F` is the functor of the predicate to be tabled, and `A` its arity.

Another use of tabling is to filter out redundant solutions for efficiency rather than termination. In this case, suppose that the directive `edb/1` were used to indicate that certain predicates were likely to have a large number of clauses. Then the action of the declaration `:- suppl_table` in the program:

```
:- edb(r1/2).
:- edb(r2/2).
:- edb(r3/2).

:- suppl_table.

join(X,Z):- r1(X,X1),r2(X1,X2),r3(X2,Z).
```

would be to table `join/2`. The `suppl_table` directive is the XSB analogue to the deductive database optimization, *supplementary magic templates* [5]. `suppl_table/0` is shorthand for `suppl_table(2)` which tables all predicates containing clauses with two or more `edb` facts or tabled predicates. By specifying `suppl_table(3)` for instance, only predicates containing clauses with three or more `edb` facts or tabled predicates would be tabled. This flexibility can prove useful for certain data-intensive applications.

Indexing Directives

The XSB compiler by default generates an index on the principal functor of the first argument of a predicate. Indexing on the appropriate argument of a predicate may significantly speed up its execution time. In many cases the first argument of a predicate may not be the most appropriate argument for indexing and changing the order of arguments may seem unnatural. In these cases, the user may generate an index on any other argument by means of an indexing directive. This is a directive of the form:

```
:- index Functor/Arity-IndexArg.
```

indicating that an index should be created for predicate `Functor/Arity` on its `IndexArg`th argument. One may also use the form:

```
:- index(Functor/Arity, IndexArg, HashTableSize).
```

which allows further specification of the size of the hash table to use for indexing this predicate if it is a *dynamic* (i.e., asserted) predicate. For predicates that are dynamically loaded, this directive can be used to specify indexing on more than one argument, or indexing on a combination of arguments (see its description on page 233). For a compiled predicate the size of the hash table is computed automatically, so `HashTableSize` is ignored.

All of the values `Functor`, `Arity`, `IndexArg` (and possibly `HashTableSize`) should be ground in the directive. More specifically, `Functor` should be an atom, `Arity` an integer in the range 0..255, and `IndexArg` an integer between 0 and `Arity`. If `IndexArg` is equal to 0, then no index is created for that predicate. An `index` directive may be placed anywhere in the file containing the predicate it refers to.

As an example, if we wished to create an index on the third argument of predicate `foo/5`, the compiler directive would be:

```
:- index foo/5-3.
```

Unification Factoring

When the clause heads of a predicate have portions of arguments common to several clauses, indexing on the principal functor of one argument may not be sufficient. Indexing may be improved in such cases by the use of unification factoring. Unification Factoring is a program transformation that "factors out" common parts of clause heads, allowing differing parts to be used for indexing, as illustrated by the following example:

```
p(f(a),X) :- q(X).          p(f(X),Y) :- _$p(X,Y).
p(f(b),X) :- r(X).    ⟶    _$p(a,X) :- q(X).
                            _$p(b,X) :- r(X).
```

The transformation thus effectively allows $p/2$ to be indexed on atoms $a/0$ and $b/0$. Unification Factoring is transparent to the user; predicates created by the transformation are internal to the system and do not appear during tracing.

The following compiler directives control the use of unification factoring [11]:

`:- ti(F/A).` Specifies that predicate F/A should be compiled with unification factoring enabled.

`:- ti_off(F/A).` Specifies that predicate F/A should be compiled with unification factoring disabled.

`:- ti_all.` Specifies that all predicates defined in the file should be compiled with unification factoring enabled.

`:- ti_off_all.` Specifies that all predicates defined in the file should be compiled with unification factoring disabled.

By default, higher-order predicates (more precisely, predicates named *apply* with arity greater than 1) are compiled with unification factoring enabled. It can be disabled using the

[11] Unification factoring was once called transformational indexing, hence the abbreviation `ti` in the compiler directives

`ti_off` directive. For all other predicates, unification factoring must be enabled explicitly via the `ti` or `ti_all` directive. If both `:- ti(F/A).` (`:- ti_all.`) and `:- ti_off(F/A).` (`:- ti_off_all.`) are specified, `:- ti_off(F/A).` (`:- ti_off_all.`) takes precedence. Note that unification factoring may have no effect when a predicate is well indexed to begin with. For example, unification factoring has no effect on the following program:

```
p(a,c,X) :- q(X).
p(b,c,X) :- r(X).
```

even though the two clauses have $c/0$ in common. The user may examine the results of the transformation by using the `ti_dump` compiler option (see Section 3.10.2).

Other Directives

XSB has other directives not found in other Prolog systems.

`:- hilog` $atom_1, \ldots, atom_n$`.`
: Declares symbols $atom_1$ through $atom_n$ as HiLog symbols. The `hilog` declaration should appear *before* any use of the symbols. See Chapter 4 for a purpose of this declaration.

`:- ldoption(`*Options*`).`
: This directive is only recognized in the header file (`.H` file) of a foreign module. See the chapter *Foreign Language Interface* in Volume 2 for its explanation.

`:- compiler_options(`*OptionsList*`).`
: Indicates that the compiler options in the list *OptionsList* should be used to compile this file. This must appear at the beginning of the file. These options will override any others, including those given in the compilation command. The options may be optionally prefixed with `+` or `-` to indicate that they should be set on or off. (No prefix indicates the option should be set on.)

3.10.5 Inline Predicates

Inline predicates represent "primitive" operations in the (extended) WAM. Calls to inline predicates are compiled into a sequence of WAM instructions in-line, i.e. without actually making a call to the predicate. Thus, for example, relational predicates (like `>/2`, `>=/2`, etc.) compile to, essentially, a subtraction followed by a conditional branch. As a result, calls to inline predicates will not be trapped by the debugger, and their evaluation will not be visible during a trace of program execution. Inline predicates are expanded specially by the compiler and thus *cannot be redefined by the user without changing the compiler.*

The user does not need to import these predicates from anywhere. There are available no matter what options are specified during compiling.

Table 3.1 lists the inline predicates of XSB Version 3.3. Those predicates that start with `_$` are internal predicates that are also expanded in-line during compilation.

`'='/2`	`'<'/2`	`'=<'/2`	`'>='/2`	`'>'/2`
`':='/2`	`'=\='/2`	`is/2`	`'@<'/2`	`'@=<'/2`
`'@>'/2`	`'@>='/2`	`'=='/2`	`'\=='/2`	`fail/0`
`true/0`	`var/1`	`nonvar/1`	`halt/0`	`'!'/0`
`min/2`	`max/2`	`'><'/2`	`**/2`	`sign/1`
`'_$cutto'/1`	`'_$savecp'/1`	`'_$builtin'/1`		

Table 3.1: The Inline Predicates of XSB

We warn the user to be cautious when defining predicates whose functor starts with `_$` since the names of these predicates may interfere with some of XSB's internal predicates. The situation may be particularly severe for predicates like `'_$builtin'/1` that are treated specially by the XSB compiler.

3.11 A Note on ISO Compatibility

In Version 3.3, an effort has been made to ensure compatibility with the core Prolog ISO standard [33]. In this section, we summarize the differences with the ISO standard. XSB implements almost all ISO built-ins and evaluable functions, although there are certain semantic differences between XSB's implementation and that of the ISO standard in certain cases.

The main difference of XSB with the ISO standard is in terms of parsing. Version 3.3 of XSB does not support full ISO syntax [12]. In addition, XSB supports only the ASCII character set for atoms, predicates and functions, so that ISO predicates relating to different character sets, such as `char_conversion/2`, `current_char_conversion/2` and others are not supported.

Another difference is that XSB does not support the logical update semantics for assert and retract, but instead supports an immediate semantics. Despite the patholical examples that can be devised using the immediate semantics, the logical semantics for assert is not often critical for single-threaded applications. It is however, critical for multi-threaded applications, and XSB will support this in the future.

A somewhat more minor difference involves XSB's implementation of ISO streams. XSB can create streams from several Firstzd class objects, including pipes, atoms, and consoles

[12] XSB also does not support multiple character sets or Unicode, which is perhaps a bigger limitation than the lack of full ISO syntax.

in addition to files. However by default, XSB opens streams in binary mode, rather than text mode in opposition to the ISO standard, which opens streams in text mode. This makes no difference in UNIX or LINUX, for which text and binary streams are identical, but does make a difference in Windows, where text files are processed more than binary files.

Most other differences with the core standard are mentioned under portability notes for the various predicates.

XSB supports most new features mentioned in the revisions to the core standard [34], including `call_cleanup/2` and various library predicates such as `subsumes/2`, `numbervars/3` and so on. XSB also has strong support for the working multi-threading Prolog standard [35], and XSB has been one of the first Prologs to support this standard. However, because XSB has an atom-based module system it does *not* support the ISO standard for Prolog modules.

Chapter 4

Syntax

The syntax of XSB is taken from C-Prolog with extensions to support HiLog [13] [1], which adds certain features of second-order syntax to Prolog.

4.1 Terms

The data objects of the HiLog language are called *terms*. A *HiLog term* can be constructed from any logical symbol or a term followed by any finite number of arguments. In any case, a *term* is either a *constant*, a *variable*, or a *compound term*.

A *constant* is either a *number* (integer or floating-point) or an *atom*. Constants are definite elementary objects, and correspond to proper nouns in natural language.

4.1.1 Integers

The printed form of an integer in HiLog consists of a sequence of digits optionally preceded by a minus sign (`'-'`). These are normally interpreted as base 10 integers. It is also possible to enter integers in other bases (2 through 36); this can be done by preceding the digit string by the base (in decimal) followed by an apostrophe (`'`). If a base greater than 10 is used, the characters `A-Z` or `a-z` are used to stand for digits greater than 9.

Using these rules, examples of valid integer representations in XSB are:

```
1    -3456    95359    9'888    16'1FA4    -12'A0    20'
```

representing respectively the following integers in decimal base:

[1] Sporadic attempts are made to make XSB ISO-compliant, contact us if you have a problem with syntax.

```
1    -3456    95359    728    8100    -120    0
```

Note that the following:

```
+525    12'2CF4    37'12    20'-23
```

are not valid integers of XSB.

A base of 0 (zero) will return the ASCII code of the (single) character after the apostrophe; for example,

```
0'A = 65
```

4.1.2 Floating-point Numbers

A HiLog floating-point number consists of a sequence of digits with an embedded decimal point, optionally preceded by a minus sign (`'-'`), and optionally followed by an exponent consisting of uppercase or lowercase `'E'` and a signed base 10 integer.

Using these rules, examples of HiLog floating point numbers are:

```
1.0    -34.56    817.3E12    -0.0314e26    2.0E-1
```

Note that in any case there must be at least one digit before, and one digit after, the decimal point.

4.1.3 Atoms

A HiLog atom is identified by its name, which is a sequence of up to 1000 characters (other than the null character). Just like a Prolog atom, a HiLog atom can be written in any of the following forms:

- Any sequence of alphanumeric characters (including `'_'`), starting with a lowercase letter.
- Any sequence from the following set of characters (except of the sequence `'/*'`, which begins a comment):

```
+ - * / \ ^ < > = ` ~ : . ? @ # &
```

- Any sequence of characters delimited by single quotes, such as:

```
'sofaki'    '%'    '_$op'
```

If the single quote character is to be included in the sequence it must be written twice. For example:

```
'don''t'      ''''
```

- Any of the following:

```
!  ;  []  {}
```

Note that the bracket pairs are special. While `'[]'` and `'{}'` are atoms, `'['`, `']'`, `'{'`, and `'}'` are not. Like Prolog, the form `[X]` is a special notation for lists (see Section 4.1.6), while the form `{X}` is just "syntactic sugar" for the term `'{}'(X)`.

Examples of HiLog atoms are:

```
h   foo   ^=..   ::=   'I am also a HiLog atom'   []
```

4.1.4 Variables

Variables may be written as any sequence of alphanumeric characters (including `'_'`) beginning with either a capital letter or `'_'`. For example:

```
X   HiLog   Var1   _3   _List
```

If a variable is referred to only once in a clause, it does not need to be named and may be written as an *anonymous variable*, represented by a single underscore character `'_'`. Any number of anonymous variables may appear in a HiLog clause; all of these variables are read as distinct variables. Anonymous variables are not special at runtime.

4.1.5 Compound Terms

Like in Prolog, the structured data objects of HiLog are *compound terms* (or *structures*). The external representation of a HiLog compound term comprises a *functor* (called the *principal functor* or the *name* of the compound term) and a sequence of one or more terms called *arguments*. Unlike Prolog where the functor of a term must be an atom, in HiLog the functor of a compound term *can be any valid HiLog term*. This includes numbers, atoms, variables or even compound terms. Thus, since in HiLog a compound term is just a term followed by any finite number of arguments, all the following are valid external representations of HiLog compound terms:

```
foo(bar)              prolog(a, X)              hilog(X)
123(john, 500)        X(kostis, sofia)          X(Y, Z, Y(W))
f(a, (b(c))(d))       map(double)([], [])       h(map(P)(A, B))(C)
```

Like a functor in Prolog, a functor in HiLog can be characterized by its *name* and its *arity* which is the number of arguments this functor is applied to. For example, the compound term whose principal functor is `'map(P)'` of arity 2, and which has arguments `L1`, and `L2`, is written as:

```
map(P)(L1, L2)
```

As in Prolog, when we need to refer explicitly to a functor we will normally denote it by the form *Name/Arity*. Thus, in the previous example, the functor `'map(P)'` of arity 2 is denoted by:

```
map(P)/2
```

Note that a functor of arity 0 is represented as an atom.

In Prolog, a compound term of the form $p(t_1, t_2, \ldots, t_k)$ is usually pictured as a tree in which every node contains the name p of the functor of the term and has exactly k children each one of which is the root of the tree of terms $t_1, t_2, \ldots, t_k$.

For example, the compound term

```
s(np(kostis), vp(v(loves), np(sofia)))
```

would be pictured as the following tree:

```
          s
        /   \
      np       vp
      |       /  \
      |      v     np
      |      |     |
   kostis  loves  sofia
```

The principal functor of this term is `s/2`. Its two arguments are also compound terms. In illustration, the principal functor of the second argument is `vp/2`.

Likewise, any external representation of a HiLog compound term $t(t_1, t_2, \ldots, t_k)$ can be pictured as a tree in which every node contains the tree representation of the name t of the functor of the term and has exactly k children each one of which is the root of the tree of terms $t_1, t_2, \ldots, t_k$.

Sometimes it is convenient to write certain functors as *operators*. *Binary functors* (that is, functors that are applied to two arguments) may be declared as *infix operators*, and

unary functors (that is, functors that are applied to one argument) may be declared as either *prefix or postfix operators*. Thus, it is possible to write the following:

```
X+Y     (P;Q)     X<Y     +X     P;
```

More about operators in HiLog can be found in section 4.3.

4.1.6 Lists

As in Prolog, lists form an important class of data structures in HiLog. They are essentially the same as the lists of Lisp: a list is either the atom `'[]'`, representing the empty list, or else a compound term with functor `'.'` and two arguments which are the head and tail of the list respectively, where the tail of a list is also a list. Thus a list of the first three natural numbers is the structure:

```
      .
     / \
    1    .
        / \
       2    .
           / \
          3   []
```

which could be written using the standard syntax, as:

```
.(1,.(2,.(3,[])))
```

but which is normally written in a special list notation, as:

```
[1,2,3]
```

Two examples of this list notation, as used when the tail of a list is a variable, are:

```
[Head|Tail]      [foo,bar|Tail]
```

which represent the structures:

```
      .                .
     / \              / \
  Head   Tail       foo   .
                         / \
                       bar  Tail
```

respectively.

Note that the usual list notation `[H|T]` does not add any new power to the language; it is simply a notational convenience and improves readability. The above examples could have been written equally well as:

```
.(Head,Tail)      .(foo,.(bar,Tail))
```

For convenience, a further notational variant is allowed for lists of integers that correspond to ASCII character codes. Lists written in this notation are called *strings*. For example,

```
"I am a HiLog string"
```

represents exactly the same list as:

```
[73,32,97,109,32,97,32,72,105,76,111,103,32,115,116,114,105,110,103]
```

4.2 From HiLog to Prolog

From the discussion about the syntax of HiLog terms, it is clear that the HiLog syntax allows the incorporation of some higher-order constructs in a declarative way within logic programs. As we will show in this section, HiLog does so while retaining a clean first-order declarative semantics. The semantics of HiLog is first-order, because every HiLog term (and formula) is automatically *encoded (converted)* in predicate calculus in the way explained below.

Before we briefly explain the encoding of HiLog terms, let us note that the HiLog syntax is a simple (but notationally very convenient) encoding for Prolog terms, of some special form. In the same way that in Prolog:

```
1 + 2
```

is just an (external) shorthand for the term:

```
+(1, 2)
```

in the presence of an infix operator declaration for `+` (see section 4.3), so:

```
X(a, b)
```

is just an (external) shorthand for the Prolog compound term:

```
apply(X, a, b)
```

Also, in the presence of a `hilog` declaration (see section 3.10.4) for `h`, the HiLog term whose external representation is:

```
h(a, h, b)
```

is a notational shorthand for the term:

```
apply(h, a, h, b)
```

Notice that even though the two occurrences of `h` refer to the same symbol, only the one where `h` appears in a functor position is encoded with the special functor `apply/`$n, n \geq 1$.

The encoding of HiLog terms is performed based upon the existing declarations of *hilog symbols*. These declarations (see section 3.10.4), determine whether an atom that appears in a functor position of an external representation of a HiLog term, denotes a functor or the first argument of a set of special functors `apply`. The actual encoding is as follows:

- The encoding of any variable or parameter symbol (atom or number) that does not appear in a functor position is the variable or the symbol itself.
- The encoding of any compound term `t` where the functor f is an atom that is not one of the hilog symbols (as a result of a previous `hilog` declaration), is the compound term that has f as functor and has as arguments the encoding of the arguments of term t. Note that the arity of the compound term that results from the encoding of t is the same as that of t.
- The encoding of any compound term `t` where the functor f is either not an atom, or is an atom that is a hilog symbol, is a compound term that has `apply` as functor, has first argument the encoding of f and the rest of its arguments are obtained by encoding of the arguments of term$t$. Note that in this case the arity of the compound term that results from the encoding of t is one more than the arity of t.

Note that the encoding of HiLog terms described above, implies that even though the HiLog terms:

```
p(a, b)
h(a, b)
```

externally appear to have the same form, in the presence of a `hilog` declaration for `h` but not for `p`, they are completely different. This is because these terms are shorthands for the terms whose internal representation is:

```
p(a, b)
apply(h, a, b)
```

respectively. Furthermore, only `h(a,b)` is unifiable with the HiLog term whose external representation is `X(a, b)`.

We end this short discussion on the encoding of HiLog terms with a small example that illustrates the way the encoding described above is being done. Assuming that the following declarations of parameter symbols have taken place,

```
:- hilog h.
:- hilog (hilog).
```

before the compound terms of page 61 were read by XSB, the encoding of these terms in predicate calculus using the described transformation is as follows:

```
foo(bar)                    prolog(a,X)
apply(hilog,X)              apply(123,john,500)
apply(X,kostis,sofia)       apply(X,Y,Z,apply(Y,W))
f(a,apply(b(c),d))          apply(map(double),[],[])
apply(apply(h,apply(map(P),A,B)),C)
```

4.3 Operators

From a theoretical point of view, operators in Prolog are simply a notational convenience and add absolutely nothing to the power of the language. For example, in most Prologs `'+'` is an infix operator, so

```
2 + 1
```

is an alternative way of writing the term `+(2, 1)`. That is, `2 + 1` represents the data structure:

```
  +
 / \
2   1
```

and not the number 3. (The addition would only be performed if the structure were passed as an argument to an appropriate procedure, such as `is/2`).

However, from a practical or a programmer's point of view, the existence of operators is highly desirable, and clearly handy.

Prolog syntax allows operators of three kinds: *infix*, *prefix*, and *postfix*. An *infix* operator appears between its two arguments, while a *prefix* operator precedes its single argument and a *postfix* operator follows its single argument.

Each operator has a precedence, which is an integer from 1 to 1200. The precedence is used to disambiguate expressions in which the structure of the term denoted is not made explicit through the use of parentheses. The general rule is that the operator with the highest precedence is the principal functor. Thus if `'+'` has a higher precedence than `'/'`, then the following

```
a+b/c      a+(b/c)
```

are equivalent, and both denote the same term `+(a,/(b,c))`. Note that in this case, the infix form of the term `/(+(a,b),c)` must be written with explicit use of parentheses, as in:

```
(a+b)/c
```

If there are two operators in the expression having the same highest precedence, the ambiguity must be resolved from the *types* (and the implied *associativity*) of the operators. The possible types for an infix operator are

```
yfx      xfx      xfy
```

Operators of type `'xfx'` are not associative. Thus, it is required that both of the arguments of the operator must be subexpressions of lower precedence than the operator itself; that is, the principal functor of each subexpression must be of lower precedence, unless the subexpression is written in parentheses (which automatically gives it zero precedence).

Operators of type `'xfy'` are *right-associative*: only the first (left-hand) subexpression must be of lower precedence; the right-hand subexpression can be of the same precedence as the main operator. *Left-associative* operators (type `'yfx'`) are the other way around.

An atom named `Name` can be declared as an operator of type `Type` and precedence `Precedence` by the command;

`op(+Precedence,+Type,+Name)` ISO

The same command can be used to redefine one of the predefined XSB operators (obtainable via `current_op/3`). However, it is not allowed to alter the definition of the comma (`','`) operator. An operator declaration can be cancelled by redeclaring the `Name` with the same `Type`, but `Precedence` 0.

As a notational convenience, the argument `Name` can also be a list of names of operators of the same type and precedence.

It is possible to have more than one operator of the same name, so long as they are of different kinds: infix, prefix, or postfix. An operator of any kind may be redefined by a new declaration of the same kind. For example, the built-in operators `'+'` and `'-'` are as if they had been declared by the command:

```
:- op(500, yfx, [+,-]).
```

so that:

```
1-2+3
```

is valid syntax, and denotes the compound term:

```
(1-2)+3
```

or pictorially:

```
    +
   / \
  -   3
 / \
1   2
```

In XSB, the list functor `'.'/2` is one of the standard operators, that can be thought as declared by the command:

```
:- op(661, xfy, .).
```

So, in XSB,

```
1.2.[]
```

represents the structure

```
  .
 / \
1   .
   / \
  2   []
```

Contrasting this picture with the picture above for `1-2+3` shows the difference between `'yfx'` operators where the tree grows to the left, and `'xfy'` operators where it grows to the right. The tree cannot grow at all for `'xfx'` type operators. It is simply illegal to combine `'xfx'` operators having equal precedences in this way.

If these precedence and associativity rules seem rather complex, remember that you can always use parentheses when in any doubt.

In Version 3.3 of XSB the possible types for prefix operators are:

`fx` `fy` `hx` `hy`

and the possible types for postfix operators are:

`xf` `yf`

We end our discussion about operators by mentioning that prefix operators of type `hx` and `hy` are *proper HiLog operators*. The discussion of proper HiLog operators and their properties is deferred for the manual of a future version.

Chapter 5

Using Tabling in XSB: A Tutorial Introduction

XSB has two ways of evaluating predicates. The default is to use Prolog-style evaluation, but by using various declarations a programmer can also use tabled resolution which can provide a different, more declarative programming style than Prolog. In this section we discuss various aspects of tabling and their implementation in XSB. Our aim in this section is to provide a user with enough information to be able to program productively with tables in XSB. It is best to read this tutorial with a copy of XSB handy, since much of the information is presented through a series of exercises.

For the theoretically inclined, XSB uses SLG resolution which can compute queries to non-floundering normal programs under the well-founded semantics [78], and is guaranteed to terminate when these programs have the *bounded term-depth property*. This tutorial covers only enough of the theory of tabling to explain how to program in XSB. For those interested, the web site contains papers covering in detail various aspects of tabling (often through the links for individuals involved in XSB). An overview of SLG resolution, and practical evaluation strategies for it, are provided in [15, 69, 63, 28]. The engine of XSB, the SLG-WAM, is an extension of the WAM [82, 1], and is described in [60, 57, 27, 62, 14, 22, 36, 18, 19, 11, 50, 72, 51, 74] as it is implemented in Version 3.3 and its performance analyzed. Examples of large-scale applications that use tabling are overviewed in [41, 42, 16, 21, 56, 7, 17, 31, 75].

5.1 Tabling in the Context of a Prolog System

Before describing how to program using tabling it is perhaps worthwhile to review some of the goals of XSB's implementation of tabling. Among them are:

1. To execute tabled predicates at the speed of compiled Prolog.
2. To ensure that the speed of compiled Prolog is not slowed significantly by adding the option of tabling.
3. To ensure that the functionality of Prolog is not compromised by support for tabling.
4. To provide Prolog functionality in tabled predicates and operators whenever it is semantically sensible to do so.
5. To provide standard predicates to manipulate tables taken as data structures in themselves.

Goals 1 and 2 are addressed by XSB's engine, which in Version 3.3 is based on a virtual machine called the SLG-WAM. The overhead for SLD resolution using this machine is small, and usually less than 5%. Thus when XSB is used simply as a Prolog system (i.e., no tabling is used), it is reasonably competitive with other Prolog implementations based on a WAM emulator written in C or assembly. For example, when compiled as a threaded interpreter (see Chapter 3) XSB Version 3.3 is about two times slower than Quintus 3.1.1 or emulated SICStus Prolog 3.1. Goals 3, 4 and 5 have been nearly met, but there are a few instances in which interaction of tabling with a Prolog construct has not been accomplished, or is perhaps impossible. Accordingly we discuss these instances throughout this chapter. XSB is still under development however, so that future versions may support more transparent mixing of Prolog and tabled code.

5.2 Definite Programs

Definite programs, also called *Horn Clause Programs*, are Prolog programs without negation or aggregation. In XSB, this means without the `\+/1`, `fail_if/1`, `not/1`, `tnot/1`, `setof/3`, `bagof/3`, `tt findall/3` or other aggregation operators. Consider the Prolog program

```
path(X,Y) :- path(X,Z), edge(Z,Y).
path(X,Y) :- edge(X,Y).
```

together with the query `?- path(1,Y)`. This program has a simple, declarative meaning: there is a path from `X` to `Y` if there is a path from `X` to some node `Z` and there is an edge from `Z` to `Y`, or if there is an edge from `X` to `Y`. Prolog, however, enters into an infinite loop when computing an answer to this query. The inability of Prolog to answer such queries, which arise frequently, comprises one of its major limitations as an implementation of logic.

A number of approaches have been developed to address this problem by reusing partial answers to the query `path(1,Y)` [25, 76, 4, 79, 80]. The ideas behind these algorithms can be described in the following manner. Calls to tabled predicates, such as `path(1,Y)` in the above example, are stored in a searchable structure together with their proven instances.

This collection of *tabled subgoals* paired with their *answers*, generally referred to as a *table*, is consulted whenever a new call, C, to a tabled predicate is issued. If C is sufficiently similar to a tabled subgoal S, then the set of answers, $\mathcal{A}$, associated with S may be used to satisfy C. In such instances, C is resolved against the answers in $\mathcal{A}$, and hence we refer to the call C as a *consumer* of $\mathcal{A}$ (or S). If there is no such S, then C is entered into the table and is resolved against program clauses as in Prolog — i.e., using SLD resolution. As each answer is derived during this process, it is inserted into the table entry associated with C if it contains information not already in $\mathcal{A}$. In this second case, we refer to C as a *generator*, or *producer*, as resolution of C in this manner produces the answers stored in its table entry. If the answer is in fact added to this set, then it is additionally scheduled to be returned to all consumers of C. If instead it is rejected as redundant, then the evaluation simply fails and backtracks to generate more answers.

Notice that since consuming subgoals resolve against unique answers rather than repeatedly against program clauses, tabling will terminate whenever

1. a finite number of subgoals are encountered during query evaluation, and
2. each of these subgoals has a finite number of answers.

Indeed, it can be proven that for any program with the *bounded term depth property* — roughly, where all terms generated in a program have a maximum depth — SLG computation will terminate. These programs include the important class of *Datalog* programs.

Predicates can be declared tabled in a variety of ways. A common form is the compiler directive

`:- table` $P_1, \ldots, P_n$.

where each P_i is a predicate indicator or callable term. More generally

`:- table` $P_1, \ldots, P_n$ `as` *Options*.

allows a user to specify different types of tabling through `Options` along with other properties of the designated predicates For static predicates, these directives must be added to the file containing the clauses of the predicate(s) to be tabled, and the directives cause the predicates to be compiled with tabling [1]. For dynamic predicates, the executable directives

`?- table` $P_1, \ldots P_n$.

and

`?- table` $P_1, \ldots, P_n$ `as` *Options*.

cause a P_i to be tabled (with the appropriate options) if no clauses have been asserted for P_i.

[1] In Version 3.3, tabling does not work together with multi-file predicates.

Exercises Unless otherwise noted, the file `$XSB_DIR/examples/table_examples.P` contains all the code for the running examples in this section. Invoke XSB with its default settings (i.e., don't supply additional options) when working through the following exercises.

Exercise 5.2.1 *Consult* `$XSB_DIR/examples/table_examples.P` *into XSB and and try the goal*

```
?- path(1,X).
```

and continue typing `;<RETURN>` *until you have exhausted all answers. Now, try rewriting the* `path/2` *predicate as it would be written in Prolog — and without a tabling declaration. Will it now terminate for the provided* `edge/2` *relation? (Remember, in XSB you can always hit* `<ctrl>-C` *if you go into an infinite loop).* □

The return of answers in tabling aids in filtering out redundant computations – indeed it is this property which makes tabling terminate for many classes of programs. The `same generation` program furnishes a case of the usefulness of tabling for optimizing a Prolog program.

Exercise 5.2.2 *If you are* still *curious, load in the file* `cyl.P` *in the* `$XSB_DIR/examples` *directory using the command.*

```
?- load_dync(cyl.P).
```

and then type the query

```
?- same_generation(X,X),fail.
```

Now rewrite the `same_generation/2` *program so that it does not use tabling and retry the same query. What happens? (Be patient — or use* `<ctrl>-C`*).* □

Exercise 5.2.3 *The file* `table_examples.P` *contains a set of facts*

```
ordered_goal(one).
ordered_goal(two).
ordered_goal(three).
ordered_goal(four).
```

Clearly, the query `?- ordered_goal(X)` *will return the answers in the expected order.* `table_examples.P` *also contains a predicate*

```
:- table table_ordered_goal/1.
table_ordered_goal(X):- ordered_goal(X).
```

which simply calls `ordered_goal/1` *and tables its answers (tabling is unnecessary in this case, and is only used for illustration). Call the query* `?- table_ordered_goal(X)` *and backtrack through the answers. In what order are the answers returned?*

The examples stress two differences between tabling and SLD resolution beyond termination properties. First, that each solution to a tabled subgoal is returned only once — a property that is helpful not only for `path/2` but also for `same_generation/2` which terminates in Prolog. Second, because answers are sometimes obtained using program clauses and sometimes using the table, answers may be returned in an unaccustomed order.

Tabling Dynamic Predicates Dynamic predicates may be tabled just as static predicates, as the following exercise shows.

Exercise 5.2.4 *For instance, restart XSB and at the prompt type the directive*

```
?- table(dyn_path/2).
```

and

```
?- load_dyn(dyn_examples).
```

Try the queries to `path/2` *of the previous examples. Note that it is important to dynamically load* `dyn_examples.P` *— otherwise the code in the file will be compiled without knowledge of the tabling declaration.* □

In general, as long as the directive `table/1` is executed before asserting (or dynamically loading) the predicates referred to in the directive, any dynamic predicate can be tabled.

Letting XSB Decide What to Table Other tabling declarations are also provided. Often it is tedious to decide which predicates must be tabled. To address this, XSB can automatically table predicates in files. The declaration `auto_table` chooses predicates to table to assist in termination, while `suppl_table` chooses predicates to table to optimize data-oriented queries. Both are explained in Section 3.10.2. [2].

[2]The reader may have noted that `table/1`, is referred to as a *directive*, while `auto_table/0` and `suppl_table/0` were referred to as *declarations*. The difference is that at the command line, user can execute a directive but not a compiler declaration.

5.2.1 Call Variance vs. Call Subsumption

The above description gives a general characterization of tabled evaluation for definite programs but glosses over certain details. In particular, we have not specified the criteria for

- *Call Similarity* – whereby a newly issued subgoal S is determined to be "sufficiently similar" to a tabled subgoal S_{tab} so that S can use the answers from the table of S_{tab} rather than re-deriving its own answers. In the first case where S uses answers of a tabled subgoal it is termed a consumer; in the second case when S produces its own answers it is called a generator or producer.
- *Answer Similarity* – whereby a derived answer to a tabled subgoal is determined to contain information similar to that already in the set of answers for that subgoal.

Different measures of similarity are possible. XSB's engine supports two measures for call similarity: variance and subsumption. XSB's engine supports a variance-based measure for answer similarity, but allows users to program other measures in certain cases. We discuss call similarity here, but defer the discussion of answer similarity until Section 5.4.

Determining Call Similarity via Variance By default, XSB determines that a subgoal S is similar to a tabled subgoal S_{tab} if S is a *variant* of S_{tab}, that is if S and S_{tab} are identical up to variable renaming [3]. As an example `p(X,Y,X)` is a variant of `p(A,B,A)`, but not of `p(X,Y,Y)`, or `p(X,Y,Z)`. Under variance-based call similarity, or *call variance*, when a tabled subgoal S is encountered, a search for a table entry containing a variant subgoal S_{tab} is performed. Notice that if S_{tab} exists, then *all* of its answers are also answers to S, and therefore will be resolved against it. Call variance was used in the original formulation of SLG resolution [15] for the evaluation of normal logic programs according to the well-founded semantics and interacts well with many of Prolog's extra-logical constructs.

Determining Call Similarity via Subsumption Call similarity can also be based on *call subsumption*. A term T_1 *subsumes* a term T_2 if T_2 is more specific than T_1 [4]. Furthermore, we say that T_1 *properly subsumes* T_2 if T_2 subsumes T_1, but is not a variant of T_1. Under call subsumption, when a tabled subgoal S is encountered, a search is performed for a table entry containing a *subsuming* subgoal S_{tab}. Notice that, if such an entry exists, then its answer set $\mathcal{A}$ logically contains all the solutions to satisfy C. The subset of answers $\mathcal{A}' \subseteq \mathcal{A}$ which unify with C are said to be *relevant to* C.

[3] Formally, S and S_{tab} are variants if they have an mgu θ such that the domain and range of $\theta 1$ consists only of variables.

[4] Formally, T_1 subsumes T_2 if there is a substitution θ whose domain consists only of variables from T_1 such that $T_1\theta = T_2$.

Notice that call subsumption permits greater reuse of computed results, thus avoiding even more program resolution, and thereby can lead to time and space performances superior to call variance. In addition, beginning with Version 3.2, call-subsumption based tabling fully supports well-founded negation under the default local scheduling strategy. However, there are downsides to this paradigm. First of all, subsumptively tabled predicates do not interact well with certain Prolog constructs with which variant-tabled predicates can (see Example 5.2.4 below). Second, call subsumption does not yet support calls with tabled attributed variables or answer subsumption [5].

Example 5.2.1 The terms T_1: `p(f(Y),X,1)` and T_2: `p(f(Z),U,1)` are *variants* as one can be made to look like the other by a renaming of the variables. Therefore, each *subsumes* the other.
The term t_3: `p(f(Y),X,1)` *subsumes* the term t_4: `p(f(Z),Z,1)`. However, they are *not variants*. Hence t_3 *properly subsumes* t_4. □

The above examples show how a variant-based tabled evaluation can reduce certain redundant subcomputations over SLD. However, even more redundancy can be eliminated, as the following example shows.

Exercise 5.2.5 Begin by abolishing all tables in XSB, and then type the following query

```
?- abolish_all_tables.
?- path(X,Y), fail.
```

Notice that only a single table entry is created during the evaluation of this query. You can check that this is the case by invoking the following query

```
?- get_calls_for_table(path/2,Call).
```

Now evaluate the query

```
?- path(1,5), fail.
```

and again check the subgoals in the table. Notice that two more have been added. Further notice that these new subgoals are *subsumed* by that of the original entry. Correspondingly, the answers derived for these newer subgoals are already present in the original entry. You can check the answers contained in a table entry by invoking `get_returns_for_call/2` on a tabled subgoal. For example:

```
?- get_returns_for_call(p(1,_),Answer).
```

[5] Beginning with Version 3.2, XSB supports attributed variables in answers under call subsumption, although not in calls.

Compare these answers to those of `p(X,Y)` and `p(1,5)`. Notice that the same answer can, and in this case does, appear in multiple table entries.

Now, let's again abolish all the tables and change the evaluation strategy of `path/2` to use subsumption.

```
?- abolish_all_tables.
        ?- table path/2 as subsumptive.
```

And re-perform the first few queries:

```
        ?- path(X,Y),fail.
?- get_calls_for_table(path/2,Call).
?- path(1,5).
?- get_calls_for_table(path/2,Call).
```

Notice that this time the table has not changed! Only a single entry is present, that for the original query `p(X,Y)`.

When using call subsumption, XSB is able to recognize a greater range of "redundant" queries and thereby make greater use of previously computed answers. The result is that less program resolution is performed and less redundancy is present in the table. However, subsumption is not a panacea. The elimination of redundant answers depends upon the presence of a subsuming subgoal in the table when the call to `p(1,5)` is made. If the order of these queries were reversed, one would find that the same entries would be present in this table as the one constructed under variant-based evaluation.

Declarations for Call Variance and Call Subsumption By default tabled predicate use call variance. However, call subsumption can be made the default by giving XSB the `-S` option at invocation (refer to Section 3.7). More versatile constructs are provided by XSB so that the tabling method can be selected on a *per predicate* basis. Use of the directive

```
table p/n as subsumptive
```

or

```
table p/n as variant
```

described in Section 6.15.1, ensures that a tabled predicate is evaluated using the desired strategy regardless of the default tabling strategy.

5.2.2 Table Scheduling Strategies

Recall that SLD resolution works by selecting a goal from a list of goals to be proved, and selecting a program clause C to resolve against that goal. During resolution of a top level

goal G, if the list of unresolved goals becomes empty, G succeeds, while if there is no program clause to resolve against the selected goal from the list resolution against G fails. In Prolog clauses are selected in the order they are asserted, while literals are selected in a left-to-right selection strategy. Other strategies are possible for SLD, and in fact completeness of SLD for definite programs depends on a non-fixed literal selection strategy. This is why Prolog, which has a fixed literal selection strategy is not complete for definite programs, even when they have bounded term-depth.

Because tabling uses program clause resolution, the two parameters of clause selection and literal selection also apply to tabling. Tabling makes use of a dynamic literal selection strategy for certain non-stratified programs (via the delaying mechanism described in Section 5.3.2), but uses the same left-to-right literal selection strategy as Prolog for definite programs. However, in tabling there is also a choice of when to return derived answers to subgoals that consume these answers. While full discussion of scheduling strategies for tabling is not covered here (see [27]) we discuss two scheduling strategies that have been implemented for XSB Version 3.3 [6].

- *Local Scheduling* Local Scheduling depends on the notion of a *subgoal dependency graph*. For the state of a tabled evaluation, a non-completed tabled subgoal S_1 directly depends on a non-completed subgoal S_2 when S_2 is in the SLG tree for S_1 – that is when S_2 is called by S_1 without any intervening tabled predicate. The edges of the subgoal dependency graph are then these direct dependency relations, so that the subgoal dependency graph is directed. As mentioned, the subgoal dependency graph reflects a given state of a tabled evaluation and so may changed as the evaluation proceeds, as new tabled subgoals are encountered, or encountered in different contexts, as tables complete, and so on. As with any directed graph, the subgoal dependency graph can be divided up into strongly connected components, consisting of tabled subgoals that depend on one another. Local scheduling then fully evaluates each maximal SCC (a SCC that does not depend on another SCC) before returning answers to any subgoal outside of the SCC [7].

- *Batched Scheduling* Unlike Local Scheduling, Batched Scheduling allows answers to be returned outside of a maximal SCC as they are derived, and thus resembles Prolog's tuple at a time scheduling.

Both Local and Batched Scheduling have their advantages, and we list points of comparison.

- *Time for left recursion* Batched Scheduling is somewhat faster than Local Scheduling

[6] Many other scheduling strategies are possible. For instance, [29] describes a tabling strategy implemented for the SLG-WAM that emulates magic sets under semi-naive evaluation. This scheduling strategy, however, is not available in Version 3.3 of XSB.

[7] XSB's implementation maintains a slight over-approximation of SCCs – see [27].

for left recursion as Local Scheduling imposes overhead to prevent answers from being returned outside of a maximal SCC.

- *Time to first answer* Because Batched Scheduling returns answers out of an SCC eagerly, it is faster to derive the first answer to a tabled predicate.
- *Stack space* Local evaluation generally requires less space than batched evaluation as it fully explores a maximal SCC, completes the SCC's subgoals, reclaims space, and then moves on to a new SCC.
- *Integration with cuts* As discussed in Exercise 5.2.6 and throughout Section 5.2.3, Local Scheduling integrates better with cuts, although this is partly because tabled subgoals may be fully evaluated before the cut takes effect.
- *Efficiency for call subsumption* Because Local Evaluation completes tables earlier than Batched Evaluation it may be faster for some uses of call subsumption, as subsumed calls can make use of completed subsuming tables.
- *Negation and tabled aggregation* As will be shown below, Local Scheduling is superior for tabled aggregation as only optimal answers are returned out of a maximal SCC. Local Scheduling also can be more efficient for non-stratified negation as it may allow delayed answers that are later simplified away to avoid being propagated.

On the whole, advantages of Local Scheduling outweigh the advantages of Batched Scheduling, and for this reason Local Scheduling is the default scheduling strategy for Version 3.3 of XSB. XSB can be configured to use batched scheduling via the configuration option `-enable-batched-scheduling` and remaking XSB. This will not affect the default version of XSB, which will also remain available.

5.2.3 Interaction Between Prolog Constructs and Tabling

Tabling integrates well with most non-pure aspects of Prolog. Predicates with side-effects like `read/1` and `write/1` can be used freely in tabled predicates as long as it is remembered that only the first call to a goal will execute program clauses while the rest will look up answers from a table. However, other extra-logical constructs like the cut (`!`) pose greater difficulties. Tabling with call subsumption is also theoretically precluded from correct interaction with certain meta-logical predicates.

Cuts and Tabling The semantics for cuts in Prolog is largely operational, and is usually defined based on an ordered traversal of an SLD search tree. Tabling, of course, has a different operational semantics than Prolog – it uses SLG trees rather than SLD trees, for instance – so it is not surprising that the interaction of tabling with cuts is operational. In Prolog, the semantics for a cut can be expressed in the following manner: a cut executed in

the body of a predicate P frames from the top (youngest end) of the choice point stack down to and including the call for P. In XSB *a cut is allowed to succeed as long as it does not cut over a choice point for a non-completed tabled subgoal, otherwise, the computation aborts.* This means, among other matters, that the validity of a cut depends on the *scheduling strategy* used for tabling, that is on the strategy used to determine when an answer is to be returned to a consuming subgoal. Scheduling strategy was discussed Section 5.2.2: for now, we assume that XSB's default local scheduling is used in the examples for cuts.

Exercise 5.2.6 *Consider the program*

```
:- table cut_p/1, cut_q/1, cut_r/0, cut_s/0.

cut_p(X) :- cut_q(X), cut_r.
cut_r :- cut_s.
cut_s :- cut_q(_).
cut_q(1).   cut_q(2).
```

What solutions are derived for the goal `?- cut_p(X)`*? Suppose that* `cut_p/1` *were rewritten as*

```
cut_p(X) :- cut_q(X), once(cut_r).
```

How should this cut over a table affect the answers generated for `cut_p/1`*? What happens if you rewrite* `cut_p/1` *in this way and compile it in XSB?* □

In Exercise 5.2.6, `cut_p(1)` and `cut_p(2)` should both be true. Thus, the cut in the literal `once(cut_r)` must not inadvertently cut away solutions that are demanded by `cut_p/1`. In the default local scheduling of XSB Version 3.3 tabled subgoals are fully evaluated whenever possible before returning any of their answers. Thus the first call `cut_q(X)` in the body of the clause for `cut_p/1` is fully evaluated before proceeding to the goal `once(cut_r)`. Because of this any choice points for `cut_q(X)` are to a completed table. For other scheduling strategies, such as batched scheduling, non-completed choice points for `cut_p/1` may be present on the choice point stack so that the cut would be disallowed. In addition, it is also possible to construct examples where a cut is allowed if call variance is used, but not if call subsumption is used.

Example 5.2.2 *A further example of using cuts in a tabled predicate is a tabled meta-interpreter.*

```
:- table demo/1.

demo(true).
```

```
demo((A,B)) :- !, demo(A), demo(B).
demo(C) :- call(C).
```

More elaborate tabled meta-interpreters can be extremely useful, for instance to implement various extensions of definite or normal programs. □

In XSB's compilation, the cut above is compiled so that it is valid to use with either local or batched (a non-default) evaluation. An example of a cut that is valid neither in batched nor in local evaluation is as follows.

Example 5.2.3 *Consider the program*

```
:- table cut_a/1, cut_b/1.

cut_a(X):- cut_b(X).
cut_a(a1).

cut_b(X):- cut_a(X).
cut_b(b1).
```

For this program the goal `?- cut_a(X)` *produces two answers, as expected:* `a1` *and* `b1`*. However, replacing the first class of the above program with*

```
cut_a(X):- once(cut_b(X)).
```

will abort both in batched or in local evaluation. □

To summarize, the behavior of cuts with tables depends on dynamic operational properties, and we have seen examples of programs in which a cut is valid in both local and batched scheduling, in local but not batched scheduling, and in neither batched nor local scheduling. In general, any program and goal that allows cuts in batched scheduling will allow them in local scheduling as well, and there are programs for which cuts are allowed in local scheduling but not in batched.

Finally, we note that in Version 3.3 of XSB a "cut" over tables implicitly occurs when the user makes a call to a tabled predicate from the interpreter level, but does not generate all solutions. This commonly occurs in batched scheduling, but can also occur in local scheduling if an exception occurs. In such a case, the user will see the warning `"Removing incomplete tables..."` appear. Any complete tables will not be removed. They can be abolished by using one of XSB's predicates for abolishing tables.

Call Subumption and Meta-Logical Predicates Meta-logical predicates like `var/1` can be used to filter the choices made during an evaluation. However, this is dangerous when used in conjunction with call subsumption, since call subsumption assumes that if a specific relation holds — e.g., `p(a)` — then a more general query — e.g., `p(X)` — will also hold.

Example 5.2.4 *Consider the following simple program*

```
p(X) :- var(X), X = a.
```

to which the queries

```
?- p(X).
?- p(a).
```

are posed. Let us compare the outcome of these queries when `p/1` *is (1) a Prolog predicate, (2) a variant-tabled predicate, and (3) a subsumptive-tabled predicate.*

Both Prolog and variant-based tabling yield the same solutions: `X = a` *and* `no`*, respectively. Under call subsumption, the query* `?- p(X).` *likewise results in the solution* `X = a`*. However, the query* `?- p(a).` *is subsumed by the tabled subgoal* `p(X)` *— which was entered into the table when that query was issued — resulting in the incorrect answer* `yes`*.* □

As this example shows, *incorrect answers* can result from using meta-logical with subsumptive predicates in this way.

5.2.4 Potential Pitfalls in Tabling

Over-Tabling While the judicious use of tabling can make some programs faster, its indiscriminate use can make other programs slower. Naively tabling `append/3`

```
append([],L,L).
append([H|T],L,[H|T1]) :- append(T,L,T1).
```

is one such example. Doing so can, in the worst case, copy N sublists of the first and third arguments into the table, transforming a linear algorithm into a quadratic one.

Exercise 5.2.7 *If you need convincing that tabling can sometimes slow a query down, type the query:*

```
?- genlist(1000,L), prolog_append(L,[a],Out).
```

and then type the query

```
?- genlist(1000,L), table_append(L,[a],Out).
```

`append/3` *is a particularly bad predicate to table. Type the query*

```
?- table_append(L,[a],Out).
```

leaving off the call to `genlist/2`*, and backtrack through a few answers. Will* `table_append/3` *ever succeed for this predicate? Why not?*

Suppose DCG predicates (Section 11) are defined to be tabled. How is this similar to tabling append? □

We note that XSB has special mechanisms for handling tabled DCGs. See Section 11 for details.

Tabled Predicates and Tracing Another issue to be aware of when using tabling in XSB is tracing. XSB's tracer is a standard 4-port tracer that interacts with the engine at each call, exit, redo, and failure of a predicate (see Chapter 10). When tabled predicates are traced, these events may occur in unexpected ways, as the following example shows.

Exercise 5.2.8 *Consider a tabled evaluation when the query* `?- a(0,X)` *is given to the following program*

```
:- table mut_ret_a/2, mut_ret_b/2.
mut_ret_a(X,Y) :- mut_ret_d(X,Y).
mut_ret_a(X,Y) :- mut_ret_b(X,Z),mut_ret_c(Z,Y).

mut_ret_b(X,Y) :- mut_ret_c(X,Y).
mut_ret_b(X,Y) :- mut_ret_a(X,Z),mut_ret_d(Z,Y).

mut_ret_c(2,2).      mut_ret_c(3,3).

mut_ret_d(0,1).      mut_ret_d(1,2).     mut_ret_d(2,3).
```

`mut_ret_a(0,1)` *can be derived immediately from the first clause of* `mut_ret_a/2`*. All other answers to the query depend on answers to the subgoal* `mut_ret_b(0,X)` *which arises in the evaluation of the second clause of* `mut_ret_a/2`*. Each answer to* `mut_ret_b(0,X)` *in turn depends on an answer to* `mut_ret_a(0,X)`*, so that the evaluation switches back and forth between deriving answers for* `mut_ret_a(0,X)` *and* `mut_ret_b(0,X)`*.*

Try tracing this evaluation, using creep and skip. Do you find the behavior intuitive or not? □

5.3 Normal Programs

Normal programs extend definite programs to include default negation, which posits a fact as false if all attempts to prove it fail. As shown in Example 1.0.1, which presented one of Russell's paradoxes as a logic program, the addition of default negation allows logic programs to express contradictions. As a result, some assertions, such as `shaves(barber,barber)` may be undefined, although other facts, such as `shaves(barber,mayor)` may be true. Formally, the meaning of normal programs may be given using the *well-founded semantics* and it is this semantics that XSB adopts for negation (we note that in Version 3.3 the well-founded semantics is implemented only for variant-based tabling).

5.3.1 Stratified Normal Programs

Before considering the full well-founded semantics, we discuss how XSB can be used to evaluate programs with *stratified negation*. Intuitively, a program uses stratified negation whenever there is no recursion through negation. Indeed, most programmers, most of the time, use stratified negation.

Exercise 5.3.1 *The program*

```
win(X):- move(X,Y),tnot(win(Y)).
```

is stratified when the `move/2` *relation is a binary tree. To see this, load the files* `tree1k.P` *and* `table_examples.P` *from the directory* `$XSB_DIR/examples` *and type the query*

```
?- win(1).
```

`win(1)` *calls* `win(2)` *through negation,* `win(2)` *calls* `win(4)` *through negation, and so on, but no subgoal ever calls itself recursively through negation.*

The previous example of `win/1` over a binary tree is a simple instance of a stratified program, but it does not even require tabling. A more complex example is presented below.

Exercise 5.3.2 *Consider the query* `?- lrd_s` *to the following program*

```
lrd_p:- lrd_q,tnot(lrd_r),tnot(lrd_s).
lrd_q:- lrd_r,tnot(lrd_p).
lrd_r:- lrd_p,tnot(lrd_q).
lrd_s:- tnot(lrd_p),tnot(lrd_q),tnot(lrd_r).
```

Should `lrd_s` *be true or false? Try it in XSB. Using the intuitive definition of "stratified" as not using recursion through negation, is this program stratified? Would the program still be stratified if the order of the literals in the body of clauses for* `lrd_p`*,* `lrd_q`*, or* `lrd_r` *were changed?*

The rules for `p`, `q` and `r` are involved in a positive loop, and no answers are ever produced. Each of these atoms can be failed, thereby proving `s`. Exercise 5.3.2 thus illustrates an instance of how tabling differs from Prolog in executing stratified programs since Prolog would not fail finitely for this program [8].

Completely Evaluated Subgoals Knowing when a subgoal is completely evaluated can be useful when programming with tabling. Simply put, a subgoal S is *completely evaluated* if an evaluation can produce no more answers for S. The computational strategy of XSB makes great use of complete evaluation so that understanding this concept and its implications can be of great help to a programmer.

Consider a simple approach to incorporating negation into tabling. Each time a negative goal is called, a separate table is opened for the negative call. This evaluation of the call is carried on to termination. If the evaluation terminates, its answers if any, are used to determine the success of failure of the calling goal. This general mechanism underlies early formulations for tabling stratified programs [38, 67]. Of course this method may not be efficient. Every time a new negative goal is called, a new table must be started, and run to termination. We would like to use information already derived from the computation to answer a new query, if at all possible — just as with definite programs.

XSB addresses this problem by keeping track of the *state* of each subgoal in the table. A call can have a state of *complete*, *incomplete* or *not_yet_called*. Calls that do have table entries may be either *complete* or *incomplete*. A subgoal in a table is marked *complete* only after it is determined to be completely evaluated; otherwise the subgoal is *incomplete*. If a tabled subgoal is not present in the table, it is termed *not_yet_called*. XSB contains predicates that allow a user to examine the state of a given table (Section 6.15).

There are in fact two ways that a tabled subgoal S can be determined to be completely evaluated. If S is part of an SCC $\mathcal{S}$, (a mutually recorsive component), then S can be completed once it is ensure that all resolution steps have been done to all subgoals in $\mathcal{S}$. Otherwise, if there is a derivation of an answer that is identical to S, S can be completed before the rest of the subgoals in $\mathcal{S}$ since further evaluation of S itself will not produce useful information. In this case, we sometimes say that S is *early completed*.

Using these concepts, we can overview how tabled negation is evaluated for stratified programs. If a literal `tnot(S)` is called, where `S` is a tabled subgoal, the evaluation checks

[8] LRD-stratifiedstratification may be reminiscent of the Subgoal Dependency Graphs of Section 5.2.2 but differ in several respects, most notably in that stratification considers only cycles through negative dependencies.

the state of `S`. If `S` is *complete* the engine simply determines whether the table contains an answer for `S`. Otherwise the engine *suspends* the computation path leading to `tnot(S)` until `S` is completed (and calls `S` if necessary). Whenever a suspended subgoal `tnot(S)` is completed with no answers, the engine resumes the evaluation at the point where it had been suspended. We note that because of this behavior, tracing programs that heavily use negation may produce behavior unexpected by the user.

`tnot/1` vs. $'\backslash +'/1$ Subject to some semantic restrictions, an XSB programmer can intermix the use of tabled negation (`tnot/1`) with Prolog's negation ($'\backslash +'/1$, or equivalently `fail_if/1` or `not/1`). These restrictions are discussed in detail below — for now we focus on differences in behavior or these two predicates in stratified programs. Recall that $'\backslash +'$ (`S`) calls S and if S has a solution, Prolog executes a cut over the subtree created by $'\backslash +'$ (`S`), and fails. `tnot/1` on the other hand, does not execute a cut, so that all subgoals in the computation path begun by the negative call will be completely evaluated. The major reason for not executing the cut is to ensure that XSB evaluates ground queries to Datalog programs with negation with polynomial data complexity. As seen [15], this property cannot be preserved if negation "cuts" over tables.

There are other small differences between `tnot/1` and $'\backslash +'/1$ illustrated in the following exercise.

Exercise 5.3.3 *In general, making a call to non-ground negative subgoal in Prolog may be unsound (cf. [47]), but the following program illustrates a case in which non-ground negation is sound.*

```
ngr_p:- \+ ngr_p(_).
ngr_p(a).
```

One tabled analog is

```
:- table ngr_tp/1.
ngr_tp(a).

ngr_tp:- tnot(ngr_tp(_)).
```

Version 3.3 of XSB will flounder on the call to `ngr_tp`*, but not on the call to* `ngr_p/0`*. On the other hand if* `sk_not/1` *is used*

```
ngr_skp:- sk_not(ngr_tp(_)).
```

the non-ground semantics is allowed.

`sk_not/1` works by asserting a new tabled subgoal, abstractly

```
:- table '_$ngr_tp'
'_$skolem_ngr_tp' :- ngr_tp(_).
```

to avoid the problem with variables. In addition, since `sk_not/1` creates a new tabled predicate, it can be used to call non-tabled predicates as well, ensuring tabling.

The description of `tnot/1` in Section 6.5 describes other small differences between $'\backslash +'$/1 and `tnot/1` as implemented in XSB. Before leaving the subject of stratification, we note that the concepts of stratification also underly XSB's evaluation of tabled findall: `tfindall/3`. Here, the idea is that a program is stratified if it contains no loop through tabled findall (See the description of predicate `tfindall/3` on page 198).

5.3.2 Non-stratified Programs

As discussed above, in stratified programs, facts are either true or false, while in non-stratified programs facts may also be undefined. XSB represents undefined facts as *conditional answers*.

Conditional Answers

Exercise 5.3.4 *Consider the behavior of the* `win/1` *predicate from Exercise 5.3.1.*

```
win(X):- move(X,Y),tnot(win(Y)).
```

when the when the `move/2` *relation is a cycle. Load the file* `$XSB_DIR/examplescycle1k.P` *into XSB and again type the query* `?- win(1)`*. Does the query succeed? Try* `tnot(win(1))`*.*

Now query the table with the standard XSB predicate `get_residual/2`*, e.g.* `?- get_residual(win(1),X)`*. Can you guess what is happening with this non-stratified program?*

The predicate `get_residual/2` (Section 6.15) unifies its first argument with a tabled subgoal and its second argument with the (possibly empty) delay list of that subgoal. The truth of the subgoal is taken to be conditional on the truth of the elements in the delay list. Thus `win(1)` is conditional on `tnot(win(2))`, `win(2)` in `tnot(win(3))` and so on until `win(1023)` which is conditional on `win(1)`.

From the perspective of the well-founded semantics, `win(1)` is undefined. Informally, true answers in the well-founded semantics are those that have a (tabled) derivation. False answers are those for which all possible derivations fail — either finitely as in Prolog or by failing positive loops. `win(1)` fits in neither of these cases – there is no proof of `win(1)`, yet it does not fail in the sense given above and is thus undefined.

However this explanation does not account for why undefined answers should be represented as conditional answers, or why a query with a conditional answer *and* its negation

should both succeed. These features arise from the proof strategy of XSB, which we now examine in more detail.

Exercise 5.3.5 *Consider the program*

```
:- table simpl_p/1,simpl_r/0,simpl_s/0.
simpl_p(X):- tnot(simpl_s).

simpl_s:- tnot(simpl_r).
simpl_s:- simpl_p(X).

simpl_r:- tnot(simpl_s),simpl_r.
```

Try the query `?- simpl_p(X)`*. If you have a copy of XSB defined using Batched Scheduling load the examples program and query* `?- simpl_p(X)` *– be sure to backtrack through all possible answers. Now try the query again. What could possibly account for the difference in behavior between Local and Batched Scheduling?*

At this point, it is worthwhile to examine closely the evaluation of the program in Exercise 5.3.5. The query `simpl_p(X)` calls `simpl_s` and `simpl_r` and executes the portion of the program shown below in bold:

simpl_p(X):- tnot(simpl_s).

simpl_s:- tnot(simpl_r).
simpl_s:- simpl_p(X).

simpl_r:- tnot(simpl_s),*simpl_r.*

Based on evaluating only the bold literals, the three atoms are all undefined since they are neither proved true, nor fail. However if the evaluation could only look at the literal in italics, *simpl_r*, it would discover that *simpl_r* is involved in a positive loop and, since there is only one clause for *simpl_r*, the evaluation could conclude that the atom was false. This is exactly what XSB does, it *delays* the evaluation of `tnot(simpl_s)` in the clause for `simpl_r` and looks ahead to the next literal in the body of that clause. This action of looking ahead of a negative literal is called *delaying*. A delayed literal is moved into the *delay list* of a current path of computation. Whenever an answer is derived, the delay list of the current path of computation is copied into the table. If the delay list is empty, the answer is unconditional; otherwise it is conditional. Of course, for definite programs any answers will be unconditional — we therefore omitted delay lists when discussing such programs.

In the above program, delaying occurs for the negative literals in clauses for `simpl_p(X)`, `simpl_s`, and `simpl_r`. In the first two cases, conditional answers can be derived, while

in the third, `simpl_r` will fail as mentioned above. Delayed literals eventually become evaluated through *simplification*. Consider an answer of the form

```
simpl_p(X):- tnot(simpl_s)|
```

where the `|` is used to represent the end of the delay list. If, after the answer is copied into the table, `simpl_s` turns out to be false, (after being initially delayed), the answer can become unconditional. If `simpl_s` turns out to be true, the answer should be removed, it is false.

In fact, it is this last case that occurs in Exercise 5.3.5. The answer

```
simpl_p(X):- tnot(simpl_s)|
```

is derived, and returned to the user (XSB does not currently print out the delay list). The answer is then removed through simplification so that when the query is re-executed, the answer does not appear.

We will examine in detail how to alter the XSB interface so that evaluation of the well-founded semantics need not be confusing. It is worthwhile to note that the behavior just described is uncommon.

Version 3.3 of XSB handles dynamically stratified programs through delaying negative literals when it becomes necessary to look to their right in a clause, and then simplifying away the delayed literals when and if their truth value becomes known. However, to ensure efficiency, literals are never delayed unless the engine determines them to not to be stratified under the LRD-stratified evaluation method.

When Conditional Answers are Needed A good Prolog programmer uses the order of literals in the body of a clause to make her program more efficient. However, as seen in the previous section, delaying can break the order that literals are evaluated within the body of a clause. It then becomes natural to ask if any guarantees can be made that XSB is not delaying literals unnecessarily.

Such a guarantee can in fact be made, using the concept of *dynamic stratification* [55]. Without going into the formalism of dynamic stratification, we note that a program is dynamically stratified if and only if it has a two-valued model. It is also known that computation of queries to dynamically stratified programs is not possible under any fixed strategy for selecting literals within the body of a clause. In other words, some mechanism for breaking the fixed-order literal selection strategy must be used, such as delaying.

However, by redefining dynamic stratification to use an arbitrary fixed-order literal selection strategy (such as the left-to-right strategy of Prolog), a new kind of stratification is characterized, called *Left-to-Right Dynamic Stratification*, or *LRD-stratification*. LRD-stratified is not as powerful as dynamic stratification, but is more powerful than other

fixed-order stratification methods, and it can be shown that for ground programs, XSB delays only when programs are not LRD-stratified. In the language of [63] XSB is *delay minimal*.

Programming in the Well-founded Semantics XSB delays literals for non-LRD-stratified programs and later simplifies them away. In Local Scheduling, all simplification will be done before the first answer is returned to the user. In Batched Scheduling it is usually better to make a top-level call for a predicate, `p` as follows:

```
?- p,fail ; p.
```

when the second `p` in this query is called, all simplification on `p` will have been performed. However, this query will succeed if `p` is true *or* undefined.

Exercise 5.3.6 *Write a predicate* `wfs_call(+Tpred,?Val)` *such that if* `Tpred` *is a ground call to a tabled predicate,* `wfs_call(+Tpred,?Val)` *calls* `Tpred` *and unifies* `Val` *with the truth value of* `Tpred` *under the well-founded semantics.* Hint: use `get_residual/2`.

How would you modify `wfs_call(?Tpred,?Val)` *so that it properly handled cases in which* `Tpred` *is non-ground.*

Trouble in Paradise: Answer Completion The engine for XSB performs both program clause and answer resolution, along with delay and simplification. What it does not do is to perform an operation called *answer completion* which is needed in certain (pathological?) programs.

Exercise 5.3.7 *Consider the following program:*

```
:- table ac_p/1,ac_r/0,ac_s/0.
ac_p(X):- ac_p(X).
ac_p(X):- tnot(ac_s).

ac_s:- tnot(ac_r).
ac_s:- ac_p(X).

ac_r:- tnot(ac_s),ac_r.
```

Using either the predicate from Exercise 5.3.6 or some other method, determine the truth value of `ac_p(X)`*. What should the value be? (hint: what is the value of* `ac_s/1`*?).*

For certain programs, XSB will delay a literal (such as `ac_p(X)` that it will not be able to later simplify away. In such a case, an operation, called *answer completion* is needed to remove the clause

```
ac_p(X):- ac_p(X)|
```

Without answer completion, XSB may consider some answers to be undefined rather than false. It is thus is sound, but not complete for terminating programs to the well-founded semantics. Answer completion is not available for Version 3.3 of XSB, as it is expensive and the need for answer completion arises rarely in practice. However answer completion will be included at some level in future versions of XSB.

5.3.3 On Beyond Zebra: Implementing Other Semantics for Non-stratified Programs

The Well-founded semantics is not the only semantics for non-stratified programs. XSB can be used to (help) implement other semantics that lie in one of two classes. 1) Semantics that extend the well-founded semantics to include new program constructs; or 2) semantics that contain the well-founded partial model as a submodel.

An example of a semantics of class 1) is (WFSX) [3], which adds explicit (or provable) negation to the default negation used by the Well-founded semantics. The addition of explicit negation in WFSX, can be useful for modeling problems in domains such as diagnosis and hierarchical reasoning, or domains that require updates [43], as logic programs. WFSX is embeddable into the well-founded semantics; and this embedding gives rise to an XSB meta-interpreter, or, more efficiently, to the preprocessor described in Section *Extended Logic Programs* in Volume 2. See [70] for an overview of the process of implementing extensions of the well-founded semantics.

An example of a semantics of class 2) is the stable model semantics. Every stable model of a program contains the well-founded partial model as a submodel. As a result, the XSB can be used to evaluate stable model semantics through the *residual program*, to which we now turn.

The Residual Program Given a program P and query Q, the residual program for Q and P consists of all (conditional and unconditional) answers created in the complete evaluation of Q.

Exercise 5.3.8 *Consider the following program.*

```
:- table ppgte_p/0,ppgte_q/0,ppgte_r/0,ppgte_s/0,
         ppgte_t/0,ppgte_u/0,ppgte_v/0.
ppgte_p:- ppgte_q.          ppgte_p:- ppgte_r.

ppgte_q:- ppgte_s.          ppgte_r:- ppgte_u.
ppgte_q:- ppgte_t.          ppgte_r:- ppgte_v.
```

```
ppgte_s:- ppgte_w.          ppgte_u:- undefined.
ppgte_t:- ppgte_x.          ppgte_v:- undefined.

ppgte_w:- ppgte(1).         ppgte_x:- ppgte(0).
ppgte_w:- undefined.        ppgte_x:- undefined.

ppgte(0).

:- table undefined/0.
undefined:- tnot(undefined).
```

Write a routine that uses `get_residual/2` *to print out the residual program for the query* `?-ppgte_p,fail`*. Try altering the tabling declarations, in particular by making* `ppgte_q/0`*,* `ppgte_r/0`*,* `ppgte_s/0` *and* `ppgte_t/0` *non-tabled. What effect does altering the tabling declarations have on the residual program?*

When XSB returns a conditional answer to a literal L, it does not propagate the delay list of the conditional answer, but rather delays L itself, even if L does not occur in a negative loop. This has the advantage of ensuring that delayed literals are not propagated exponentially through conditional answers.

Stable Models Stable models are one of the most popular semantics for non-stratified programs. The intuition behind the stable model semantics for a ground program P can be seen as follows. Each negative literal $notL$ in P is treated as a special kind of atom called an *assumption*. To compute the stable model, a guess is made about whether each assumption is true or false, creating an assumption set, A. Once an assumption set is given, negative literals do not need to be evaluated as in the well-founded semantics; rather an evaluation treats a negative literal as an atom that succeeds or fails depending on whether it is true or false in A.

Example 5.3.1 *Consider the simple, non-stratified program*

```
writes_manual(terry)-¬writes_manual(kostis),has_time(terry).
writes_manual(kostis)-¬writes_manual(terry),has_time(kostis).
has_time(terry).
has_time(kostis).
```

there are two stable models of this program: in one `writes_manual(terry)` *is true, and in another* `writes_manual(kostis)` *is true. In the Well-Founded model, neither of these literals is true. The residual program for the above program is*

```
writes_manual(terry)-¬writes_manual(kostis).
writes_manual(kostis)-¬writes_manual(terry).
has_time(terry).
has_time(kostis).
```

Computing stable models is an intractable problem, meaning that any algorithm to evaluate stable models may have to fall back on generating possible assumption sets, in pathological cases. For a ground program, if it is ensured that residual clauses are produced for *all* atoms, using the residual program may bring a performance gain since the search space of algorithms to compute stable models will be correspondingly reduced. In fact, by using XSB in conjunction with a Stable Model generator, Smodels [53], an efficient system has been devised for model checking of concurrent systems that is 10-20 times faster than competing systems [46]. In addition, using the XASP package (see the separate manual, [12] in XSB's packages directory) a consistency checker for description logics has also been created [71].

5.4 Answer Subsumption

By default XSB adds an answer A to a table T only if A is not a variant of some other answer already in T, a technique termed *answer variance*. While answer variance is sufficient to allow tabling to compute the well-founded semantics and to terminate for programs with bounded term-depth, other choices of when and how to add an answer can be made. Using *partial order answer subsumption*, A would be added to T only if A is maximal with respect to other answers in T according to a given partial order $>_O$. Furthermore if A is added, any answers in T that A subsumes (i.e., is greater than in $>_O$) are deleted. When using *lattice answer subsumption*, A itself may not be added to T, rather the join is taken of A and another answer A' in T, with A' being deleted. Despite its conceptual simplicity, answer subsumption can be a powerful tool. Partial order answer subsumption allows a table to retain only answers that are maximal according to a metric or to a preference relation; lattice answer subsumption can form the basis of multi-valued logics, quantitative logics, and of abstract interpretations for programs and process logics.

5.4.1 Types of Answer Subsumption

Partial Order Answer Subsumption.

We illustrate the use of partial order answer subsumption through a shortest-path predicate (Figure 5.1) that counts the number of edges between two vertices.

As mentioned above, partial-order answer subsumption retains in a table T only those answers that are maximal according to a given partial order $>_O$. In the case of the shortest-path predicate of Figure 5.1, $sp(A_1, A_2, A_3) >_O sp(B_1, B_2, B_3)$ if, $A_1 = B_1$, $A_2 = B_2$, and

```
sp(X,Y,1):- edge(X,Y).
sp(X,Z,N):- sp(X,Y,N1),edge(Y,Z),N is N1 + 1.
```

Figure 5.1: A Shortest Path Predicate

$A_3 < B_3$. Note that that minimal distances are maximal in $<_O$, and that $<_O$ is undefined if A_3 or B_3 is non-numeric. In XSB, partial order answer subsumption is specified for `sp/3` using the declaration

```
:- table sp(_,_,po(</2)).
```

In a given state of computation, only those answers that are maximal according to $>_O$ are available for resolution. Thus, for a finite graph with cycles, `sp/3` will terminate using answer subsumption, but not with answer variance. Other partial orders beyond distance metrics may be useful. For instance, $>_O$ may specify a preference ordering between derived atoms so that answer subsumption provides an alternative to default-based methods for computing preferences.

Lattice Answer Subsumption.

An upper semi-lattice is a partial order for which any two elements have a unique least upper bound. Because the ordering for the third argument of `sp/3` is total, it also forms an upper semi-lattice, and so can be computed using lattice answer subsumption. [9]. In XSB lattice answer subsumption for `sp/3` is declared as

```
:- table sp(_,_,lattice(min/3)).
```

with `min/3` defined as `min(X,Y,Z):- Z is min(X,Y).` Operationally, this means that whenever an answer $sp(A_1, A_2, A_3)$ is derived, if there is another answer $sp(B_1, B_2, B_3)$ where $A_1 = B_1$ and $A_2 = B_2$ the join J_3 of A_3 and B_3 is taken, and only $sp(A_1, A_2, J_3)$ is available for resolution. As with a partial order, the join operation ensures termination for shortest path over a finite graph with cycles.

As the following proposition shows, lattice answer subsumption can be modeled either starting with a lattice, or starting with a function with appropriate properties.

Proposition 5.4.1 *Let* op *be an associative, commutative, and idempotent binary function. Then there is a partial order P, such that P is an upper semi-lattice with join* op.

Conversely, if a function does not have the above properties, it is not suitable for lattice answer subsumption. Accordingly the aggregate functions count and sum cannot be com-

[9] The terminology lattice answer subsumption is employed even though only the join of the lattice is used.

puted using lattice answer subsumption [10]. Lattice answer subsumption has a variety of applications. [74] shows how it is used for social-network analysis and Section 5.4.2 shows its use for an application of multi-valued logics, [70] describes how a similar formalism can implement a quantitative logic, and [58] describes how XSB's `PITA` package is based on answer subsumption (see Volume 2 of this manual).

Partial Order Answer Subsumption with Abstraction.

Computation over an abstract domain may require certain maximal answers to be abstracted. In many cases, abstraction can be modeled by a join operation, but in others the abstraction represents an implicit induction step in the following sense. Given a set $\mathcal{A}$ of answers, it may be detected that the program computed does not have a finite model. An abstraction operation then is applied so that $\mathcal{A}$ and its extensions can be symbolically represented by a single answer A. Using answer subsumption, this abstraction can be taken only if needed during program execution. Abstractly, partial order answer subsumption with abstraction uses the declaration

```
:- table p(_,_,po(rel/2,abs/3)).
```

where `rel/2` is a partial order, and `abs/3` is the abstraction operation. Section 5.4.2 provides a detailed example of how such an approach is used to analyze a process logic.

5.4.2 Examples of Answer Subsumption

Answer Subsumption and Abstract Interpretation

Net-style formalisms, such as Petri Nets, Workflow Nets, etc. have been used extensively for process modeling. Reachability is a central problem in analyzing properties of such nets, to which properties such as liveness, deadlock-freedom, and the existence of home states can be reduced. However, many interesting net formalisms cannot guarantee a finite number of configurations in a given net, so abstraction methods must be applied for their analysis.

For instance, the lack of finiteness is a problem in analyzing Place/Transition (PT) Nets. PT nets have no guard conditions or after-effects, and do not distinguish between token types. However, PT nets do allow a place to hold more than one token, leading to a potentially infinite number of configurations. This can be seen in the simple network of Figure 5.2 (from [24]) in which transitions are denoted by squares and places by circles. Each transition removes one token from the places that are the sources of its input edges and adds one token to each place at the target of each of its output edges. Starting from the configuration in Figure 5.2, repeated application of transition `t1` leads to place `s2` containing

[10] Since count and sum are not idempotent their semantics is based on multi-sets, rather than sets. Incorporating these as tabling features requires modifying their semantics to be set-based, in a manner similar to aggregation ASP systems.

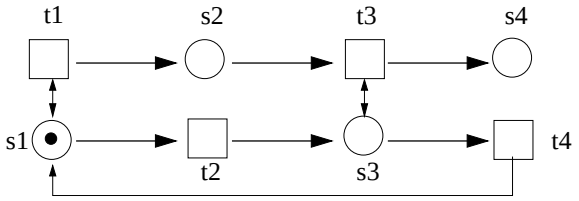

Figure 5.2: A PT-net and configuration with an infinite number of reachable configurations

```
:- table reachable(_,po(omega_gte/2,omega_abs/3)).
reachable(InConf,NewConf):-
        reachable(InConf,NewConf),
        hasTransition(Conf,NewConf).
reachable(InConf,NewConf):- hasTransition(InConf,NewConf).
```

Figure 5.3: Top-level predicate for PT net reachability

an unbounded number of tokens; repeated application of the sequence `t1,t2,t3,t4` leads to place `s4` containing an unbounded number of tokens.

Despite such examples, reachability in PT nets is decidable and can be determined using an abstraction method called ω-sequences, (see e.g. [24]). The main idea in determining ω sequences is to define a partial order $\geq_\omega$ on configurations as follows. If configurations C_1 and C_2 are both reachable, C_1 and C_2 have tokens in the same set PL of places, C_1 has at least as many tokens in each place as C_2, and there exists a non-empty $PL_{sub} \subseteq PL$, such that for each $pl \in Pl_{sub}$ C_1 has strictly more tokens than C_2, then $C_1 >_\omega C_2$. When evaluating reachability, if C_2 is reached first, and then C_1 was subsequently reached, C_1 is abstracted by marking each place in PL_{sub} with the special token ω which is taken to be greater than any integer. If C_1 was reached first and then C_2, C_2 is treated as having already been seen.

Tabling combined with partial order answer subsumption requires slightly over 100 lines of code to model reachability in PT nets using ω-sequences. Due to space restrictions, the program cannot be fully described here, but the top-level reachability predicate is shown in Figure 5.3. Despite its succinctness, it can evaluate reachability in networks with millions of states in a few minutes. This use of tabling to determine reachability in PT nets can be seen as a special case of tabling for abstract interpretation (cf. [37] and other works). However the framework for answer subsumption described here allows tabling to be used to efficiently perform abstract interpretation within a general Prolog system

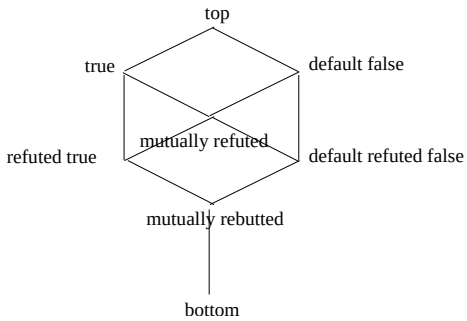

Figure 5.4: A Truth Lattice for a Simplified Version of Courteous Argumentation Theory

Scalability for multi-valued and quantitative logics

The technique of program justification (cf. e.g. [54]) has been used for debugging tabled programs that cannot be debugged by traditional means. Here, we consider justification in the context of the Silk system, currently under development at Vulcan, Inc. Silk is a commercial knowledge representation and rule system built on top of Flora-2, which is implemented using XSB. One of the salient features of Silk is its default reasoning, which is based on a parameterized argumentation theory evaluated under the well-founded semantics [81]. One issue in using Silk is that knowledge engineers must have a way of understanding the reasoning of the system, a task complicated by the use of the well-founded semantics and the intricacies of the argumentation theory. We describe an experimental approach to justification of Silk-style argumentation theories using multi-valued logics.

As noted in [81], argumentation theories in Silk are usually extensions of the default theories of Courteous Logic Programs (CLP) and are based on two user-defined predicates: `opposes/2` and `overrides/2`. Two atoms *oppose* each other if no model of a program can contain both atoms: an atom and its explicit negation oppose each other, but opposition can capture many other types of contradictions. Given two opposing atoms, one atom may *override* the other, and so be given preference. For atoms A_1 and A_2, if A_1 and A_2 are both derivable and oppose each other but neither overrides the other, A_1 and A_2 mutually *rebut* each other. If in addition A_1, say, overrides A_2, A_1 *refutes* A_2 [11]. Within Silk and Flora-2, the compilation of an argumentation theory ensures that rebutted atoms have an undefined truth value, as do atoms that refute themselves (i.e. if the `overrides/2` predicate is cyclic). However, for justification, it is meaningful to distinguish those facts that are undefined due to a negative loop in the argumentation theory from those that are undefined due to a negative loop in the program itself. In addition, it is meaningful to distinguish an atom that is true because it overrides some other atom, from an atom whose derivation does not depend on the argumentation theory. Similar distinctions can be made for default false literals leading to the truth lattice shown in Figure 5.4.

[11] In [81] argumentation theories are built on named rules, here we base them on derived atoms.

5.4.3 Term-Sets

XSB provides support for a programming technique for representing sets of terms, called term-sets. (While it is not closely related to answer subsumption, it is partially implemented through tabling and a table declaration, and so this facility is documented here.)

We begin in an example. We can represent a set of Prolog terms by using a particular term of the form `{Var:Goal}` where Goal has (only) `Var` free in it. Then we will use this *set-term* to represent the set of terms obtained by evaluating `Goal` and taking the values of `Var` that are obtained. I.e., they would be the terms in the list `L` returned by the Prolog call to `setof(Var,Goal,L)`. For example, the set-term:

```
{X : member(X,[a,b,c])}
```

represents the set of terms `{a,b,c}`.

Now a *term-set* is a Prolog term that may contain set-terms as subterms. For example,

```
m({X:member(X,[a,b,c])},g(d,{Y:member(Y,[e,f,g])}),h)
```

is a term-set, and it represents the set of terms obtained from it by replacing (recursively) any embedded set-term by a term in that set-term. So the above term-set represents the 9 terms:

```
m(a,g(d,e),h)        m(a,g(d,f),h)        m(a,g(d,g),h)
m(b,g(d,e),h)        m(b,g(d,f),h)        m(b,g(d,g),h)
m(c,g(d,e),h)        m(c,g(d,f),h)        m(c,g(d,g),h)
```

This example shows an advantage of this representation. Say a term-set has k sub-set-terms each of which is of the member form in this example where each member has a list of atoms of length n. To represent this set of terms explicitly takes $O(n^k)$ space, whereas to represent them with the term-set takes only $O(n \times k)$ space. So a term-set representation can take exponentially less space than an explicit representation.

It is relatively easy to write a predicate, `member_termset/2`, which takes a variable and a term-set and nondeterministically generates all concrete terms represented by the term-set, called *extensionalizing* the term-set. Some care must be taken since a call to goal to extensionalize a set-term may itself return a term-set. Also term-sets can be self-recursive and thus represent infinitely many Prolog terms. For example, consider the term-set:

```
{X : p(X)} where
  p(a).
  p(f({X:p(X)})).
```

This term-set contains the infinitely many terms:

```
a, f(a), f(f(a)), f(f(f(a))), ...
```

A particularly intriguing use of term-sets is in conjunction with tabling. Consider the term-set `{X:p(1,2,X)}` where `p/3` is tabled. If `p(1,2,_}` has been called and so its table is filled, then extensionalizing the previous term-set is just a table lookup; in some sense we can think of such a term-set a standing for a pointer into a table to a set of terms. This can be elegantly used to solve an important problem in handling parse trees in context-free parsing.

Consider the following DCG for the language a*:

```
:- table a/3.
a(a(P1,P2)) --> a(P1),a(P2).
a(a) --> [a].
```

which recognizes a string and constructs its parse trees.

To generate all answers, this DCG will take time exponential in the length of the input string; not surprising since there are exponentially many parses. But say we give it an input string of n `a`'s followed by one `b`. In this case it will take exponential time to fail, since it will construct all the exponentially many partial parse trees. We would like the grammar in this case to fail in polynomial time. By representing the parse trees as a term-set, while recognizing the string, and then after the string is recognized, extensionalize the set-term representing the parse trees, we can get the behavior we want. The set-term representing the parse trees for any grammar will be constructed in polynomial time; the extensionalization will take exponential time only if there are exponentially many parses.

We can cause XSB to automatically use the term-set representation by adding to the above program the declaration:

```
:- table a(termset,_,_).
```

which tells XSB to use the term-set representation of the first argument of `a/3`.

With this declaration, XSB will transform the above program into the following:

```
:- table a/3.

a(a(P1,P2),S0,S) :- '_$a'(P1,S0,S1),'_$a'(P2,S1,S).
a(a,S0,S1) --> 'C'(S0,a,S1).

:- table '_$a'/3 as subsumptive.
'_$a'({X:'_$a'(X,S0,S)},S0,S) :- a(_,S0,S).
```

A new predicate `'_$a'/3` is introduced, and all calls to the original predicate `a/3` are replaced by calls to the new one. It is defined to call the original `a/3` but to return the term-set instead of the concrete parse tree in the argument declared to be a term-set.

We can see that a call to a/3 in this new program will have exactly as many answers as the corresponding call to a/2 in the original recognizing DCG, since given values for S0 and S, a call to '_$a'/2 returns only one value in its first argument. So a call to a/3 with have the polynomial complexity of the recognizer. So now with this representation to get the concrete parse tree for a string, one writes, for example:

```
| ?- a(Pts,[a,a,a,a,a,a,a],[]), member_termset(Parse,Pts).
```

which uses the term-set representation while recognizing the input string, and then extensionalizes it to the produce the actual parse tree. With this way of handling parse trees in arbitrary context-free grammars, the complexity of parsing to create the term-set is always polynomial, and then extensionalizing the term-set may be exponential if all parses are desired and there are exponentially many of them. Of course, if the parsing call to a/3 fails, then there is no extensionalization to do, and the process is polynomial.

Note that the transformation uses subsumptive tabling for the newly introduced auxiliary predicate. This is important for this example, since the parsing calls to '_$a'/3 will normally have S0 bound and S free, yet when extensionalizing the constructed term-set to obtain the parse trees, the calls will have both S0 and S bound. We do not want to recompute the parse during extensionalizion, which would happen were we to be using variant tabling, and so we use subsumptive tabling.

Problems in graph traversal provide another example of the effective use of term-sets. For graph reachability, we have the very familiar:

```
:- table reach/2.
reach(X,Y) :- edge(X,Y).
reach(X,Y) :- reach(X,Z), edge(Z,Y).
```

which is linear in the number of edges in the graph. But say that we now want to construct the path from X to Y when Y *is* reachable from X. One simple way to do it (collecting the intermediate nodes in the path in reverse order) is:

```
:- table path/3.
path(X,Y,[]) :- edge(X,Y).
path(X,Y,[Z|Path]) :- path(X,Z,Path), edge(Z,Y).
```

For an acyclic edge graph, this works fine, but for a graph with cycles, this will go into an infinite loop. Indeed, it must, since in a cyclic graph there *are* infinitely many different paths between some nodes. However, we can use term-set to handle this situation more flexibly. We modify the above program by adding:

```
:- table path(_,_,termset).
```

With this declaration, every call to `path/3` (for a finite edge graph) will terminate in time linear in the number of edges. And all the paths will be presented in the term-set returned in the third argument. Here we have an advantage similar to the one we had in the grammar example above: if there is no path from our source to our target node, we will find that out in linear time. Without the term-set declaration, this might take exponential time, while the program builds all the paths to all the nodes that *are* reachable from our source node. Also, if we want only *one* possible path from our source to our target, we can easily retrieve only one member of the term-set during extensionalization, and the whole process is still linear.

Now consider what happens with when the graph has cycles. In this case, the term-set may be recursive and represent the infinitely many paths between nodes. For example, the term-set representing all paths from `a` to `a` in the graph with a single edge from `a` to `a` will have the same structure as the example of an infinite term-set given at the beginning of this subsection. Once the path term-set is constructed (in time linear in the number of edges for a single source), producing paths reduces to processing the term-set structure. For example to generate all paths between nodes which do not contain repeated intermediate nodes, one could write an extensionalization predicate that passes a list of term-sets in the process of being expanded, and refuse to re-expand one currently being expanded. This is the technique often used in Prolog without tabling to compute reachability in cyclic graphs.

All of these examples can be seen as special cases of constructing proof trees or justifications of goals. Indeed, term-sets could be effectively used in the construction of a justification or explanation system.

5.5 Tabling for Termination

As noted throughout this manual, tabling adds important termination properties to programs and queries. In this section we state more precisely what these termination properties are, and how the properties can be strengthened through declarations and settings for *subgoal abstraction* and for bounded rationality through *answer abstraction*.

Before doing so, it is important to set the context for where issues of termination may arise. Consider first a pure normal program in which every predicate is tabled. This means a program where rules may only call other rules, possibly through negation (`tnot/1` or `sk_not/1` in XSB); but where there are no calls to builtins for arithmetic, all-solutions predicates, or other built-ins. If such a fully-tabled pure normal program does not have function symbols, XSB will always terminate for any query. For instance, XSB will terminate for fully tabled pure datalog programs – even if the head of a rule is "unsafe" in that it contains variables that do not occur in the body of that rule [12].

[12] Evaluations that call non-ground negative literals will terminate through floundering, although this can be avoided in most cases by using `sk_not/1`.

While datalog programs are useful for certain kinds of knowledge representation, they are not powerful enough for general programming as they do not allow recursive structures such as lists. Thus, for the rest of this section we consider pure programs that may contain function symbols. Consider a pure definite program in which every predicate is tabled. Such a program would call each tabled subgoal (up to variance) exactly once if call variance were used, and at most once if call subsumption were used. In addition, tabling guarantees that each answer will be returned to each call to a tabled subgoal at most once. This means that there are two sources of non-termination. Either there can be an infinite number of subgoals, or there can be an infinite number of answers [13].

An Infinite Number of Subgoals If a definite program produces an infinite number of subgoals *but* has a finite number of answers, the program can be made to terminate by abstracting the subgoal. For instance, consider the program fragment:

```
:- table p/1.
p(X) :- p(f(X)).
```

The goal `?- p(1)` can create an infinite number of tabled subgoals: `p(f(1))`, `p(f(f(1)))`, `p(f(f(f(1))))` and so on. Note that since all of the subgoals are ground, none subsume one another, so that call subsumption will not help here, (although it would help if the goal were `?- p(X)`).

Infinite Answers Of course, subgoal abstraction can't handle cases where there are an infinite number of answers, as in the program fragment:

```
p(f(X)) :- p(X).
```

when given the query `p(X)`.

We consider each case in turn.

5.5.1 Subgoal Abstraction

In a nutshell, subgoal abstraction allows a goal like `p(f(f(f(1))))` to be rewritten as

```
p(f(f(X))),X = f(1).
```

If all subgoals that have a term depth (or term size) over a given finite threshold are abstracted, any query can produce only a finite number of subgoals (since there are a finite number of predicate, function and constant symbols in any program). If a program is

[13] Using the forest of trees model of tabling (cf. Section 10.3) non-termination requires that there are an infinite number of trees or that at least one tree have infinite size.

definite, it can be shown that any query to a program will terminate if that program uses subgoal abstraction [76]. For normal programs, the situation is not much different at a conceptual level. A goal such as `tnot(p(f(f(f(1))))` would execute as `p(f(f(X)))` and then ensure that none of the answers to this goal have a binding for `X` that allows it to unify with `f(1)`. Using this intuition, it can be shown that if a program has a two-valued well-founded model and a finite number of true answers it will terminate using tabling with subgoal abstraction [59].

Despite its theoretical power, subgoal abstraction can also cause problems if used indiscriminately. if the second argument of the subgoal

```
?- member(e,[a,b,c,d,e])
```

is abstracted forming the goal

```
?- member(e,[a,b,c|X])
```

leading to an infinite number of answers. a goal that terminates without abstraction will not terminate after abstraction. Note that any program containing `member/2` and at least one constant does not have a finite model. While an experienced programmer would never want to table `member/2`, he well may want to table a grammar or other program that performs recursion through a finite structure.

Declaring Subgoal Abstraction

The implementation of subgoal abstraction in XSB is still in progress. and may be changed in future versions as we gain experience in how subgoal abstraction is best used in practice. Abstraction is performed for goals called positively; but not for goals called negatively including `tnot/1` and `sk_not/1`; rather, such goals will throw an exception if they surpass the specified depth. In addition, subgoal abstraction is only implemented for call variance, *and applies equally all terms, whether they are lists or non-lists.*

Subgoal abstraction can be declared by setting a value for the maximum depth of a subgoal and for the action to take when a subgoal is encountered that reaches that depth.

- **depth** The maximum depth can be set to n for a set of predicates $\langle PredSpec \rangle$ via including the specifier `subgoal_abstract(n)` as part of the tabling declaration

  `:- table` $\langle PredSpec \rangle$ `as ...,subgoal_abstract(n),...`

  Specifying `subgoal_abstract(0)` turns abstraction off for predicates in $\langle PredSpec \rangle$. The depth can also be set globally by seting the flag `max_table_subgoal_depth` to the desired maximal depth. If the subgoal depth has been set of a given predicate via a tabling declaration the declared depth will override the global depth.

- **action** When a subgoal is encountered of maximum depth, abstraction is enabled if the Prolog flag `max_table_subgoal_action` to `abstract`. Other possible values for the action are `error` and `fail` (cf. pg. 207).

Unless otherwise specified, XSB starts up with `max_table_subgoal_action` set to `error` and `max_table_subgoal_depth` set to the maximum integer possible under the compilation method for which XSB has been configured. Under this default behavior, XSB will throw an error if a subgoal has depth greater than `max_table_subgoal_depth`. As an alternative to setting flags, call abstraction can be set by calling XSB with the command-line arguments `-max_subgoal_action a` and `-max_subgoal_depth n` where `n` is the size of the desired depth.

5.5.2 Bounded Rationality through Answer Abstraction

In XSB, a programmer can use a form of answer abstraction called *bounded-rationality* to ensure that only a finite number of answers are generated by a query [14]. For instance if the query `p(X)` to the program

```
p(f(X)) :- p(X).
p(0).
```

were evaluated using this approach with a depth limit of 3, the answers, `p(0)`, `p(f(0))`, `p(f(f(0)))` and `p(f(f(f(X))))` would be generated, *however* `p(f(f(f(X))))` would have the truth value of *undefined*. Note that by doing things in this way, both of the goals `p(f(f(f(0))))`, and `p(f(f(f(1))))` will unify with `p(f(f(f(X))))` and so will succeed with a truth value of *undefined*. Similarly `tnot(p(f(f(f(0)))))`, and `tnot(p(f(f(f(1)))))` will both succeed with a value of *undefined* (perhaps better called *unknown* in this context). Since all predicates and function symbols have a maximum arity (256 in XSB) bounding the depth of an answer ensures that only a finite number of answers are returned [15].

Semantically XSB is computing an approximation to the three-valued well-founded model of a program, called a *bounded model*. To see this, suppose the proof of a query Q does not depend on negation. If Q has a derivation that does not require any answers whose depth is greater than n, it is proven as usual. Similarly, if Q is false in the well-founded model of a program, and none of the subgoals explored in the derivation of Q derive answers whose depth is greater than n, XSB will derive that Q is false. Thus, the approximation that XSB computes is *informationally sound* in the sense that no incorrect answer will be derived, although the truth value of some atoms won't be known that might

[14] Bounded rationality was designed by Benjamin Grosof and Terrance Swift.

[15] If a program has a infinite number of true answers and a finite numebr of false answers, one possible approach might be to "dualize" the program so that only false answers are computed. However, since most programs with function symbols have an infinite number of both true and false answers, this approach won't work in general.

have been if the depth bound had been set higher. Due to the halting problem, there is no way to know in general what depth to set for answer abstraction, or whether any bound needs to be set at all.

If a bounded model is derived, answers that are undefined in the well-founded model can be distinguished from answers that are undefined through bounded rationality. If an answer A was abstracted due to a depth check (and for no other reason), the query `get_residual(A,Delay)` would bind `Delay` to `[brat_undefined]`, where `brat_undefined/0` is simply a predicate defined as

```
brat_undefined:- tnot(brat_undefined)
```

which in a delay list indicates that an answer was made undefined through bounded-rationality based answer abstraction.

Using Bounded Rationality

Bounded rationality is currently implemented only for tabling with call variance, and lists are not currently included in the depth check. Similarly to the use of subgal abstraction, answer abstraction can be declared by setting a value for the maximum depth of an answer and for the action to take when an answer is encountered that reaches that depth.

- **depth** The maximum depth can be set to `n` for a set of predicates via including the specifier `answer_abstract(n)` as part of their tabling declaration

  `:- table` $< PredSpec >$ `as ...,answer_abstract(n),...`

  Specifying `answer_abstract(0)` turns answer abstraction off for predicates in $< PredSpec >$. The depth can also be set globally by seting the flag `max_table_answer_depth` to the desired maximal depth. If the answer depth of a given predicate has been set via a tabling declaration, the predicate-specific declared depth will override the global depth.

- **action** When an answer is encountered of maximum depth, abstraction is enabled if the Prolog flag `max_table_answer_action` to `abstract`. Other possible values for the action are `error` and `fail` (cf. pg. 207).

Unless otherwise specified, XSB starts up with

- `max_table_answer_action` and
- `max_table_answer_list_action`

set to `error` and `max_table_answer_depth` and `max_table_answer_depth` set to the maximum integer possible under the compilation method for which XSB has been configured. Under this default behavior, XSB will throw an error if a subgoal has depth greater than `max_table_subgoal_depth`.

5.6 Incremental Table Maintenance

XSB allows the user to declare that the system should incrementally maintain particular tables. A table T is *incremental* if XSB ensures that its answers are consistent with all dynamic facts and rules upon which T depends (subject to transactionality conditions explained below). After a database update or series of updates Δ, a table T that depends on Δ may be updated

- *Eagerly*: by issuing a command to update all tables that depend on Δ; or
- *Lazily*: by updating T and all tables upon which T depends the next time that T is called.

In either case, if tables are thought of as database views, then the table maintenznce subsystem enables what is known in the database community as incremental view maintenance [16].

5.6.1 Examples

To demonstrate incremental table maintenance (informally called *incremental tabling*), we consider first the following simple program that does not use incremental tabling:

```
:- table p/2.
p(X,Y) :- q(X,Y),Y =< 5.

:- dynamic q/2.
q(a,1).    q(b,3).   q(c,5).    q(d,7).
```

and the following queries and results:

```
| ?- p(X,Y),writeln([X,Y]),fail.
[c,5]
[b,3]
[a,1]

no
| ?- assert(q(d,4)).

yes
| ?- p(X,Y),writeln([X,Y]),fail.
[c,5]
```

[16] In the current version of XSB, there are certain restrictions on how incremental tabling can be used.

```
[b,3]
[a,1]

no
```

Here we see that the table for `p/2` depends on the contents of the dynamic predicate `q/2`. We first evaluate a query, `p(X,Y)`, which creates a table. Then we use `assert/1` to add a fact to the `q/2` predicate and re-evaluate the query. We see that the answers haven't changed, and this is because the table is already created and the second query just retrieves answers directly from that existing table. But in this case we have answers that are inconsistent with the current definition of `p/2`. I.e., if the table didn't exist (e.g. if `p/2` weren't tabled), we would get a different answer to our `p(X,Y)` query, this time including the `[d,4]` answer. Without incremental table maintenance, the only solution to this problem is for the XSB programmer to explicitly abolish a table whenever changing (with assert or retract) a predicate on which the table depends.

By declaring that the tables for `p/2` should be incrementally maintained, XSB will automatically keep the tables for `p/2` correct.

A Quasi Forward-Chaining Approach Consider a slight rewrite of the above program:

```
:- table p/2 as incremental.
p(X,Y) :- q(X,Y),Y =< 5.

:- dynamic q/2 as incremental.
q(a,1).    q(b,3).    q(c,5).     q(d,7).
```

in which `p/2` is declared to be incrementally tabled (with `:- table p/2 as incremental`) and `q/2` is declared to be both dynamic and incremental, meaning that an incremental table depends on it [17]. Consider the following goals and execution:

```
| ?- import incr_assert/1 from increval.

yes
| ?- p(X,Y),writeln([X,Y]),fail.
[c,5]
[b,3]
[a,1]
```

[17] The declarations `use_incremental_tabling/1` and `use_incremental_dynamic/1` are deprecated from Version 3.3 of XSB forward – in other words backwards compatability will be maintained for a time, but these declarations will not be further supported.

```
no
| ?- incr_assert(q(d,4)).

yes
| ?- p(X,Y),writeln([X,Y]),fail.
[d,4]
[c,5]
[b,3]
[a,1]

no
```

Here again we call `p(X,Y)` and generate a table for it and its answers. Then we update `q/2` by using the incremental version of assert, `incr_assert/1`, which was explicitly imported. Now when we call `p(X,Y)` again, the table has been updated and we get the correct answer.

In this case after every `incr_assert/1` and/or `incr_retract(all)/1`, the tables are incrementally updated to reflect the change. The system keeps track of what tabled goals depend on what other tabled goals and (incremental) dynamic goals, and tries to minimize the amount of recomputation necessary. Incrementally tabled predicates may depend on other tabled predicates. In this case, those tabled predicates must also be declared as incremental (or opaque) [18]. The algorithm used is described in [66, 65].

An Eager Updating Approach There is a more efficient way to program incremental updates when there are several changes made to the base predicates at one time. In this case the `incr_assert_inval/1` and `incr_retract(all)_inval/1` predicates should be used for each individual update. These operations leave the dependent tables unchanged (and thus inconsistent.) When the updates are finished, the user then calls `incr_table_update/0`. which updates all tables that depend on any changed dynamic rules or facts. The following execution for our running program shows an example of this.

```
| ?- import incr_assert_inval/1, incr_table_update/0 from increval.

yes
| ?- p(X,Y),writeln([X,Y]),fail.
[c,5]
[b,3]
[a,1]
```

[18] An *opaque* predicate P is tabled and is used in the definition of some incrementally tabled predicate but should not be maintained incrementally. In this case the system assumes that the programmer will abolish tables for P in such a way so that re-calling it will always give semantically correct answers.

```
no
| ?- incr_assert_inval(q(d,4)), incr_assert_inval(q(d,1)),

yes
| ?- incr_table_update.

| ?- p(X,Y),writeln([X,Y]),fail.
[d,4]
[d,1]
[c,5]
[b,3]
[a,1]

no
```

A Lazy Updating Approach But what if a user forgets to call `incr_table_update/0`? Or, what if it is important that some tables be updated, while others can remain inconsistent? Beginning with Version 3.3.7 of XSB, *lazy incremental table maintenance* is supported. In this case if a query Q is called to a table that is marked to be inconsistent with the underlying dynamic code, but that table has not been updated, Q will be dynamically updated along with all tables upon which Q depends – and only those tables will be updated. In this manner, if incremental table maintenance is used, inconsistent answers to a query Q will never be returned. However, if table inspection predicates are used (cf. Chapter 6.15) inconsistent answers may be shown. We note, however, that the use of these predicates is much less common than direct queries to tables; but if using table inspection predicates on incrementally maintained tables, the user should ensure that `incr_table_update/0` is called before inspecting the tables.

Updating conditional answers As discussed earlier in this chapter, answers that are undefined in the well-founded semantics are represented as conditional answers. Beginning with version 3.3.7, incremental updates work correctly with conditional answers (before this version they only worked correctly on stratified tables: those with only unconditional answers). No special care needs to be taken for conditional answers, and they can be updated through any of the previously described methods. The following example illustrates one such approach.

Consider the program

```
:- dynamic data/1 as incremental.

:- table opaque_undef/0 as opaque.
opaque_undef:- tnot(opaque_undef).
```

```
:- table p/1 as incremental.
p(_X):- opaque_undef.
p(X):- data(X).
```

Note that `opaque_undef/1` upon which `p/1` depends is explicitly declared as opaque. When the above program is loaded, XSB will behave as follows.

```
| ?- p1(1).

undefined
| ?- incr_assert(data(1)).

yes
| ?- p1(1).

yes
| ?- incr_retract(data(1)).

yes
| ?- p1(1).

undefined
| ?- get_residual(p1(1),C).

C = [opaque_undef]
```

Declaring Predicates to be Incremental

In XSB, tables can have numerous properties: *subsumptive, variant, incremental, opaque, dynamic, private*, and *shared*, and can use answer subsumption or call abstraction. XSB also has variations in forms of dynamic predicates: *tabled, incremental, private*, and *shared*. XSB extends the `table` and `dynamic` compiler and executable directives with modifiers that allow users to indicate the kind of tabled or dynamic predicate they want. For example,

```
:- table p/3,s/1 as subsumptive,private.

:- table q/3 as incremental,variant.

:- dynamic r/2,t/1 as incremental.
```

We note that

```
:- table p/3 as dyn.
```

```
and
:- dynamic p/3 as tabled.
```

are equivalent.

In the current version of XSB, many combinations involving incremental tabling are not supported and will throw an error (cf. page 245 and page 235, respectively). Incremental tabling has not yet been ported to the multi-threaded engine and and it currently works only for predicates that use both call and answer variance.

5.6.2 Incremental Tabling using Interned Tries

Sometimes it is more convenient or efficient to maintain facts in interned tries rather than as dynamically asserted facts (cf. Chapter 8). Tables based on interned tries can be automatically updated when terms are interned or uninterned just as they can be automatically updated when a fact is asserted or retracted. Consider the example from Section 5.6.1 rewritten to use interned tries. As usual, an incrementally updated table is declared as such:

```
:- table p/2 as incremental.
p(X,Y) :- trie_interned(q(X,Y),inctrie),Y =< 5.
```

However, the declaration for dynamic data changes: rather than using the declaration `:- dynamic q/2 as incremental`, a trie is specified as incremental in its creation.

```
  trie_create(Trie_handle,[incremental,alias(inctrie)]),
```

As described in Chapter 8, the trie handle returned is an integer, but can be aliased just as with any other trie. The trie may then be initially loaded:

```
trie_intern(q(a,1),inctrie),trie_intern(q(b,3),inctrie),
trie_intern(q(c,5),inctrie),trie_intern(q(d,7),inctrie).
```

At this stage a query to `p/2` acts as before:

```
| ?- p(X,Y),writeln([X,Y]),fail.
[c,5]
[b,3]
[a,1]
```

The following sequence ensures that `p/2` is incrementally updated as `inctrie` changes:

```
| ?- import incr_trie_intern/2.

yes
| ?- incr_trie_intern(inctrie,q(d,4)).

yes
| ?- p(X,Y),writeln([X,Y]),fail.
[d,4]
[c,5]
[b,3]
[a,1]

no
```

There are also `incr_trie_intern_inval/2`, and `incr_trie_unintern_inval/2` predicates which do not immediately update dependent tables. Lazy incremental table maintenance works for changes made to interned tries just as it does for regular dynamic code and for trie-indexed dynamic code.

5.6.3 View Consistency

In addition to the success continuations that are standard in most languages, Prolog has failure continuations – choice points to take upon backtracking. The presence of these failure continuations leads to an issue of view consistency, even within a single-threaded computation. Suppose that a user

1. Makes a query to a completed incrementally tabled subgoal Q. Q has more than one solution and the first one is returned, leaving a choice point into the table for Q.
2. Makes an update to dynamic code upon which Q depends
3. Makes another query to Q

What is the relation between the queries and the update. Presumably, the first query in step 1) should not reflect the changes made in step 2) if a user backtracks for further answers to that query – this can be seen as ensuring view consistency.. However it is less clear whether the second query to Q in step 4) should return the same answers as the first query in step 1), or whether the second query should reflect the database update. Arguments can be made for either approach.

- *Prolog-style semantics* If the second query reflects the database change, it is consistent with the database, but is not consistent with the first query [19];

[19] This approach could be viewed as an extension of the ISO semantics for dynamic code in Prolog, which XSB does not currently support.

- *Delayed update semantics* If the second query does not reflect the dynamic code change, it is consistent with the first query but not with the dynamic code change.

XSB chooses the latter of these approaches. If a user has failure continuations into a query Q, then Q and all tables that depend on Q will not be updated until these failure continuations have been exhausted or removed. However, all updates are ensured to be applied once this is the failure continuations are removed.

5.6.4 Summary and Implementation Status

Thus the user has four choices: tables may be updated as soon as the database is changed (e.g., via `incr_assert/1`); at some point after a series of database changes (e.g. via `incr_assert_inval/1` and `incr_table_update/0`); or lazily whenever a given table is called. In addition, if the changes are so massive that there is no point in incrementally updating the table, the tables can be abolished so that the tables will be reconstructed whenever they are re-queried.

In the current version of XSB, incremental tabling has not yet been ported to the multi-threaded engine. In addition, incremental tabling only works for predicates that use both call and answer variance. However, incremental tabling does work with for the full well-founded semantics, for trie indexed dynamic code (in addition to regular dynamic code) and with interned tries as described in Section 5.6.2. The space reclamation predicates `abolish_all_tables/0` and `abolish_table_call/[1,2]` both can be safely used with incremental tables, but `abolish_table_pred/[1,2]` if the predicate it abolishes is incremental.

5.6.5 Predicates for Incremental Table Maintenance

A Note on Terminology Suppose `p/1` and `q/1` are incrementally tabled, and that there is a clause

```
p(X):- q(X).
```

In this case we say that `p(X)` *depends_on* `q(X)` and that `q(X)` *affects* `p(X)`. A recursive predicate both depends on and affects itself.

Declarations The following directives support incremental tabling based on changes in dynamic code:

`table +PredSpecs as incremental` Tabling

is a executable predicate that indicates that each tabled predicate specified in `PredSpec`

is to have its tables maintained incrementally. `PredSpec` is a list of skeletons, i.e. open terms, or `Pred/Arity` specifications [20]. The tables must use call variance and answer variance and must compiled and loaded into the single-threaded engine. If a predicate is already declared as subsumptively tabled, an error is thrown. This predicate, when called as a compiler directive, implies that its arguments are tabled predicates. See page 245 for further discussion of tabling options.

We also note that any tabled predicate that is called by a predicate tabled as incremental must also be tabled as incremental or as opaque. On the other hand, a dynamic predicate `d/n` that is called by a predicate tabled as incremental may or may not need to be declared as incremental. However if `d/n` is not declared incremental, then changes to it will not be propagated to incrementally maintained tables.

`dynamic +PredSpecs as incremental` Tabling

is an executable predicate that indicates that each predicate in `PredSpecs` is dynamic and used to define an incrementally tabled predicate and will be updated using `incr_assert/1` and/or `incr_retractall/1` (or relatives.) This predicate, when called as a compiler directive, implies that its arguments are dynamic predicates. See page 235 for further discussion of dynamic options.

`table +PredSpecs as opaque` Tabling

is an executable predicate that indicates that each predicate P in `PredSpecs` is tabled and is used in the definition of some incrementally tabled predicate but should not be maintained incrementally. In this case the system assumes that the programmer will abolish tables for P in such a way so that re-calling it will always give semantically correct answers. In other words, instead of maintaining information to support incremental table maintenance, the system re-calls the opaque predicate whenever its results are required to recompute an answer. One example of an appropriate use of opaque is for tabled predicates in a DCG used to parse some string. Rather than incrementally maintain all dependencies on all input strings, the user can declare these intermediate tables as opaque and abolish them before any call to the DCG. This predicate, when called as a compiler directive, implies that its arguments are tabled predicates.

Basic Incremental Maintenance Predicates The following predicates are used to manipulate incrementally maintained tables:

`incr_assert(+Clause)` module: `increval`
`incr_assertz(+Clause)` module: `increval`
`incr_asserta(+Clause)` module: `increval`
`incr_retract(+Clause)` module: `increval`

[20] No explicit module references are allowed.

`incr_retractall(+Term)` module: `increval`

are versions of `assert/1` and other standard Prolog predicates. They modify dymamic code just as their Prolog counterparts, but they then immediately updates all incrementally maintained tables that depend on `Clause`.

Error Cases are the same as `assert<a/z>/1`, `retract/1` and `retractall/1` with the additional error condition:

- The head of the clause `Clause` or the `Term` refers to a predicate that is not incremental and dynamic.
  - `type error(dynamic_incremental, Term)`

`incr_assert_inval(+Clause)` module: `increval`
`incr_assertz_inval(+Clause)` module: `increval`
`incr_asserta_inval(+Clause)` module: `increval`
`incr_retractall_inval(+Clause)` module: `increval`
`incr_retract_inval(+Term)` module: `increval`

are versions of `assert/1` and other standard Prolog predicates. They modify dymamic code just as their Prolog counterparts, and mark any incrementally maintained tables that depend on the modification as invalid (in need of updating). The tables may be updated by an explicit call to `incr_table_update/[0,1,2]`, or the table will be dynamically recomputed when a query is made to it.

`incr_table_update` module: `increval`

may be called after base predicates have been changed (by `incr_assert_inval/1` and/or
`incr_retractall_inval/1` or friends). This predicate updates all the incrementally maintained tables whose contents change as a result of those changes to the base predicates. This update operation is separated from the operations that change the base predicates (`incr_assert_inval/1` and `incr_retractall_inval/1`) so that a set of base predicate changes can be processed all at once, which may be much more efficient that updating the tables at every base update. Beginning with Version 3.3.7, it is not absolutely necessary to call this predicate, as tables will be incrementally updated upon demand. However, using this predicate allows a choice of incurring the cost of update at a time other than querying an updated goal.

Error Cases

- A table T that is to be incrementally updated is not yet complete.
  - `permission_error(update, incomplete_table Goal)`

`incr_table_update(-GoalList)` module: `increval`

acts as `incr_table_update/0` in its action to update the incrementally maintained tables after changes to base predicates. It returns the list of goals whose tables were changed in the update process.

`incr_table_update(+SkelList,-GoalList)` module: `increval`

acts as `incr_table_update/1` in its action to update incrementally maintained tables after changes to base predicates. The first argument is a list of predicate skeletons (open terms) for incrementally maintained tables. The predicate returns in `GoalList` a list of goals whose skeletons appear in `SkelList` and whose tables were changed in the update process. So `SkelList` acts as a filter to restrict the goals that are returned to those of interest. If `SkelList` is a variable, all affected goals are returned in `GoalList`.

`incr_invalidate_call(+Goal)` module: `increval`

is used to directly invalidate a call to an incrementally maintained table, `Goal`. A subsequent invocation of `incr_table_update/[0,1,2]` will cause `Goal` to be recomputed *and all incrementally maintained tables that* `Goal` *affects will be updated*; similarly, a call to `Goal` will automatically perform incremental updating for `Goal` along with any tables that `Goal` depends on that are in need of updating. This predicate can be used if a tabled predicate depends on some external data and not (only) on dynamic incremental predicates. If, for example, an incrementally maintained predicate depends on a relation stored in an external relational database (perhaps accessed through the ODBC interface), then this predicate can be used to invalidate the table when the external relation changes. The application programmer must know when the external relation changes and invoke this predicate as necessary.

Error Cases

- `Goal` is tabled, but not incrementally tabled
  - `permission_error(invalidate,non-incremental predicate,Goal)`

Incremental Maintenance using Interned Tries The following predicates are used for modifying incremental tries, and can be freely intermixed with predicates for modifying incremental dynamic code, as well as with predicates for invalidating or updating tables (Section 5.6.5).

`incr_trie_intern(+TrieIdOrAlias,+Term)` module: `intern`

is a version of `trie_intern/2` for tries declared as incremental. A call to this predicate interns `Term` in `TrieIdOrAlias` and then updates all incrementally maintained tables that depend on this trie.

`incr_trie_uninternall(+TrieIdOrAlias,+Term)` module: `intern`

is a version of `trie_unintern/2` for tries declared as incremental. A call to this predicate removes all terms unifying with `Term` in `TrieIdOrAlias` and then updates all incrementally maintained tables that depend on this trie.

`incr_trie_intern_inval(+TrieIdOrAlias,+Term)` module: `intern`

works for tries declared as incremental in a similar manner as `incr_trie_intern/2` except that it does not update the incrementally maintained tables, but only marks them as invalid. The tables may be updated by an explicit call to `incr_table_update/[0,1,2]`, or updated lazily.

`incr_trie_uninternall_inval(+TrieIdOrAlias,+Term)` module: `intern`

works for tries declared as incremental in a similar manner as `incr_trie_uninternall/2` except that it does not update the incrementally maintained tables, but only marks them as invalid. The tables may be updated by an explicit call to `incr_table_update/[0,1,2]` or updated lazily.

Introspecting Dependencies among Incremental Subgoals In order to efficiently perform incremental updates, each incrementally tabled subgoal S contains information about other subgoals upon which S directly depends or which S directly affects. These relations form a labelled directed graph for which the nodes are incrementally tabled subgoals present in XSB; a given subgoal in the graph may or may not have been completed. In addition, there is an edge from S_1 to S_2 labelled depends (affects) if S_1 directly depends on (directly affects) S_2. We call this graph the *incrementally tabled subgoal dependency graph*, or just the incremental dependency graph. The predicates in this section allow a user to inspect properties of the dependency graph that can be useful in debugging or profiling a computation [21].

As explained below, nodes for the dependency graph can be accessed via the predicate `is_incremental_subgoal/1`, while edges can be accessed via `incr_directly_depends/2`. The predicates `get_incr_scc/[1,2]` and `get_incr_scc_with_deps/[3,4]` can be used to efficiently materialize the dependency graph in Prolog, including SCC information.

`is_incremental_subgoal(?Subgoal)` module: `increval`

This predicate non-deterministically unifies `Subgoal` with incrementally tabled subgoals that are currently table entries.

`incr_directly_depends(?Goal`$_1$`,?Goal`$_2$`)` module: `increval`

accesses the dependency structures used by the incremental table maintenance subsystem to provide information about which incremental table calls depend on which others. At least one of `Goal`$_1$ and `Goal`$_2$ must be bound.

- If `Goal`$_1$ is bound, then this predicate will return in `Goal`$_2$ through backtracking the goals for all incrementally maintained tables on which `Goal`$_1$ directly depends.

[21] The predicates for traversing the incremental dependency graph are somewhat analogous to those for traversing the residual dependency graph (Section 6.15.2).

- If $\texttt{Goal}_2$ is bound, then it returns in $\texttt{Goal}_2$ through backtracking the goals for all incrementally maintained tables that $\texttt{Goal}_2$ directly affects – in other words all goals that directly depend on $\texttt{Goal}_2$.

Error Cases

- Neither $\texttt{Goal}_1$ nor $\texttt{Goal}_2$ is bound
  - `instatiation_error`
- $\texttt{Goal}_1$ and/or $\texttt{Goal}_2$ is bound, but is not incrementally tabled
  - `table_error`

`incr_trans_depends(?Goal`$_1$`,?Goal`$_2$`)` module: `increval`

is similar to `incr_directly_depends/2` except that it returns goals according to the transitive closure of the "directly depends" relation. Error conditions are the same as `incr_directly_depends/2`.

`get_incr_sccs(?SCCList)` module: `increval`
`get_incr_sccs_with_deps(?SCCList,?DepList)` module: `increval`
`get_incr_sccs(+SubgoalList,?SCCList)` module: `increval`
`get_incr_sccs_with_deps(+SubgoalList,?SCCList,?DepList)` module: `increval`

Most linear algorithms for SCC detection over a graph use destructive assignment on a stack to maintain information about the connecteness of a component; as a result such algorithms are difficult to write efficiently in Prolog.

`get_incr_sccs/1` unifies `SCCList` with SCC information for the incremental dependency graph that is represented as a list whose elements are of the form

```
ret(Subgoal,SCC).
```

`SCC` is a numerical index for the SCCs of Subgoal. Two subgoals are in the same SCC iff they have the same index, however no other dependency information can be otherwise directly inferred from the index.

If dependency information is also desired, `get_incr_scc_with_dependencies/2` should be called. In addition to the SCC information as above, `DepList` is unified with a list of dependency terms of the form

```
depends(SCC1,SCC2)
```

for each pair `SCC1` and `SCC1` such that some subgoal with index `SCC1` directly depends on some subgoal with index `SCC1`.

Ordinarily a user will want to see the entire dependency graph and in such a case the predicates described above should be used. However, note that if the dependency graph is the result of several indepdendent queries it may not be connected. `get_incr_scc/2` takes as input a list of incremental subgoals, `SubgoalList`. For

each `Subgoal` in `SubgoalList`, this predicate finds the set of subgoals connected to `Subgoal` by any mixture of depends and affects relations, unions these sets together, and finds the SCCs of all subgoals in the unioned set.

These predicates implement Tarjan's algorithm [77] in C working directly on XSB's data structures. The algorithm is $\mathcal{O}(|V|+|E|)$ where $|V|$ is the number of vertices and $|E|$ the number of edges in the dependency graph. As a result, these predicates provide an efficient means to materialize the dependency graph, even if SCC information per se is not required.

Error Cases

- `SCCList` contains a predicate that is not tabled
  - `permission_error`

5.7 Compatability of Tabling Modes and Predicate Attributes

As discussed in this chapter, there are several choices for how to table a predicate. Either call subsumption or call variance may be used, incremental tabling might or might not be used, and answer subsumption might or might not be used. Furthermore, a tabled predicate, like any other predicate, may be static or dynamic and thread shared or thread private. Together, there are 48 different combinations, not all of which are supported in Version 3.3 of XSB. To analyze further, all combinations are supported for call-variance and for thread private predicates. However, call subsumption has not been fully integrated with dynamic code or thread shared predicates, and cannot currently be combined with incremental tabling or with answer subumption. Similarly incremental tabling is not yet supported in the multi-threaded engine (it is supported for "thread private" computations only in the sequential engine). The compatabilities are listed in Table 5.1. Further combinations will be supported in future versions of XSB as resources allow.

The combinations in Table 5.1 allow full well-founded computation, constrained variables in calls and answers (including the residual program), and safe space reclamation, with the following exceptions. Answer subsumption does support non lrd-stratified programs; and call subsumption does not yet support attributed variables in calls.

variant	static	private	nonincremental	no answer subsumption	yes
variant	static	private	nonincremental	answer subsumption	yes
variant	static	private	opaque	no answer subsumption	yes
variant	static	private	opaque	answer subsumption	no
variant	static	private	incremental	no answer subsumption	yes
variant	static	private	incremental	answer subsumption	no
variant	static	shared	nonincremental	no answer subsumption	yes
variant	static	shared	nonincremental	answer subsumption	yes
variant	static	shared	opaque	no answer subsumption	no
variant	static	shared	opaque	answer subsumption	no
variant	static	shared	incremental	no answer subsumption	no
variant	static	shared	incremental	answer subsumption	no
variant	dynamic	private	nonincremental	no answer subsumption	yes
variant	dynamic	private	nonincremental	answer subsumption	yes
variant	dynamic	private	opaque	no answer subsumption	no
variant	dynamic	private	opaque	answer subsumption	no
variant	dynamic	private	incremental	no answer subsumption	no
variant	dynamic	private	incremental	answer subsumption	no
variant	dynamic	shared	nonincremental	no answer subsumption	yes
variant	dynamic	shared	nonincremental	answer subsumption	yes
variant	dynamic	shared	opaque	no answer subsumption	no
variant	dynamic	shared	opaque	answer subsumption	no
variant	dynamic	shared	incremental	no answer subsumption	no
variant	dynamic	shared	incremental	answer subsumption	no
subsumptive	static	private	nonincremental	no answer subsumption	yes
subsumptive	static	private	nonincremental	answer subsumption	yes
subsumptive	static	private	opaque	no answer subsumption	no
subsumptive	static	private	opaque	answer subsumption	no
subsumptive	static	private	incremental	no answer subsumption	no
subsumptive	static	private	incremental	answer subsumption	no
subsumptive	static	shared	nonincremental	no answer subsumption	no
subsumptive	static	shared	nonincremental	answer subsumption	no
subsumptive	static	shared	opaque	no answer subsumption	no
subsumptive	static	shared	opaque	answer subsumption	no
subsumptive	static	shared	incremental	no answer subsumption	no
subsumptive	static	shared	incremental	answer subsumption	no
subsumptive	dynamic	private	nonincremental	no answer subsumption	yes
subsumptive	dynamic	private	nonincremental	answer subsumption	yes
subsumptive	dynamic	private	opaque	no answer subsumption	no
subsumptive	dynamic	private	opaque	answer subsumption	no
subsumptive	dynamic	private	incremental	no answer subsumption	no
subsumptive	dynamic	private	incremental	answer subsumption	no
subsumptive	dynamic	shared	nonincremental	no answer subsumption	no
subsumptive	dynamic	shared	nonincremental	answer subsumption	no
subsumptive	dynamic	shared	opaque	no answer subsumption	no
subsumptive	dynamic	shared	opaque	answer subsumption	no
subsumptive	dynamic	shared	incremental	no answer subsumption	no
subsumptive	dynamic	shared	incremental	answer subsumption	no

Table 5.1: Support for different tabling modes in XSB Version 3.3

Chapter 6

Standard Predicates and Predicates of General Use

This chapter describes standard predicates, which are always available to the Prolog interpreter, and do not need to be imported or loaded explicitly as do other Prolog predicates. By default, it is a compiler error to redefine standard predicates.

In the description below, certain standard predicates depend on HiLog semantics; the description of such predicates have the token HiLog at the right of the page. Similarly predicates that depend on SLG evaluation are marked as Tabling, and predicates whose semantics is defined by the ISO standard (or whose implementation is reasonably close to that definition) are marked as `ISO`. Occasionally, however, we include in this section predicates that are not standard. In such cases we denote their module in `text` font towards the middle of the page.

6.1 Input and Output

XSB's I/O is based on ISO-style streams, although it also supports older DEC-10 style file handling. The use of streams provides a unified interface to a number of different classes of sources and sinks. Currently these classes include textual and binary files, console input and output, pipes, and atoms; in the future sockets and urls may be handled under the stream interface. When streams are opened, certain actions may occur depending on the class of the source or sink and on the wishes of the user. For instance when a file `F` is opened for output mode, an existing file `F` may be truncated (in write mode) or not (in append mode). In addition, various operations may or may not be valid depending on the class of stream. For instance, repositioning is valid for an atom or file but not a pipe or console.

XSB provides several default I/O streams, which make it easier for a user to embed XSB in other applications. These streams include the default input and output streams.

They also include the standard error stream, to which XSB writes all error messages. By default the standard error stream is the same as the standard output stream, but it can be redirected either by UNIX shell-style I/O redirection or by the predicates `file_reopen/4` and `file_clone/3`. Similarly there is the standard warning stream (to which all system warnings are written), the standard message stream, the standard debugging stream (to which debugging information is written), and the standard feedback stream (for interpreter prompts, yes/no answers, etc). All of these streams are aliased by default to standard output, and can be redirected by the predicates the predicates `file_reopen/4` and `file_clone/3`.

Streams may also be aliased: the default input and output streams can be denoted by `user_input` and `user_output` and they refer to the standard input and standard output streams of the process [1]. Similarly, XSB's error, warning and message streams uses the aliases `user_error`, `user_warning` and `user_message` respectively.

Streams are distinguished by their `class` – whether they are file or atom, etc.; as well as by various properties. These properties include whether a stream is positionable or not and whether a (file) stream is textual or binary.

- `Console` The default streams mentioned above are console streams, which are textual and not repositionable.
- `File` A file stream corresponds to an operating system file and is repositionable. On Windows, binary files and textual files differ, while on UNIX they are the same.
- `Atom` XSB can read from an atom, just as it can from a file. Atoms are considered to be textual and repositionable. Writing to atoms via streams is not currently available in XSB, although the predicate `term_to_atom/[2,3]` contains much of the functionality that such streams would provide.
- `Pipe` XSB can also open pipes either directly, or as part of its ability to spawn processes. When made into streams, pipes are textual and not repositionable.

6.1.1 I/O Stream Implementation

A user may note that XSB's I/O streams are small integers, but they should not be confused with the file descriptors used by the OS. The OS file descriptors are objects returned by the C `open` function; XSB I/O streams indices into the internal XSB table of open files and associated information. The OS does not know about XSB I/O streams, while XSB (obviously) does know about the OS file descriptors. An OS file descriptor may be returned by certain predicates (e.g. `pipe_open/2` or user-defined I/O). In the former case, a file

[1] For backwards compatibility, the default input stream can also be aliased by `user` or `userin`, and the default output stream by `user` or `userout`.

descriptor can be promoted to XSB stream by `open/{3,4}` and in the latter by using the predicate `fd2iostream/2`.

When it starts, XSB opens a number of standard I/O streams that it uses to print results, errors, debugging info, etc. The descriptors are described in the file `prolog_includes/standard.h`. This file provides the following symbolic definitions:

```
#define STDIN           0
#define STDOUT          1
#define STDERR          2
#define STDWARN         3    /* output stream for xsb warnings  */
#define STDMSG          4    /* output for regular xsb messages */
#define STDDBG          5    /* output for debugging info       */
#define STDFDBK         6    /* output for XSB feedback
                                (prompt/yes/no/Aborting/answers) */

#define AF_INET     0     /* XSB-side socket request for Internet domain */
#define AF_UNIX     1     /* XSB-side socket request for UNIX domain */
```

These definitions can be used in user programs, if the following is provided at the top of the source file:

```
compiler_options([xpp_on]).
#include "standard.h"
```

If this header is used, the various streams can be used as any other output stream – e.g. `?- write(STDWARN,'watch it!')`. (Note: the XSB preprocessor is not invoked on clauses typed into an interactive XSB session, so the above applies only to programs loaded from a file using `consult` and such.)

6.1.2 ISO Streams

`open(+SourceSink,+Mode,-Stream)` ISO

`open/1` creates a stream for the source or sink designated in `SourceSink`, and binds `Stream` to a structure representing that stream.

- If `SourceSink` is an atom, or the term `file(File)` where `File` is an atom, the stream is a file stream. In this case `Mode` can be
  - `read` to create an input stream. In Windows, whether the file is textual or binary is determined by the file's properties.
  - `write` to create an output stream. Any previous file with a similar path is removed and a (textual) file is created which becomes a record of the output stream.

  - `write_binary` to create an output stream. Any previous file with a similar path is removed and a file is created which becomes a record of the output stream. The file created is binary in Windows, while in UNIX `write_binary` has the same effect as `write`.
  - `append` to create an output stream. In this case the output stream is appended to the contents of the file, if it exists, and otherwise a new file is created for (textual) output
  - `append_binary` to create an output stream. In this case the output stream is appended to the contents of the file, if it exists, and otherwise a new file is created for (binary) output
- If `SourceSink` is the term `atom(Atom)` where `Atom` is an atom, the stream is an atom stream. In this case `Mode` currently can only be `read`. This stream class, which reads from interned atoms, is analogous to C's `sscanf()` function.
- If `SourceSink` is the term `pipe(FIleDescriptor)` where `FileDescriptor` is an integer, then a pipe stream is opened in the mode for `FileDescriptor`.

ISO Compatability Note: This predicate extends the ISO definition of `open/3` to include strings and pipes as well as the file modes `write_binary` and `append_binary`.

Error Cases

- `SourceSink` or `Mode` is not instantiated
  - `instantiation_error`
- `Mode` is not a valid I/O mode
  - `domain_error(io_mode,Mode)`
- `SourceSink` is a file and cannot be opened, or opened in the desired mode
  - `permission_error(open,file,SourceSink)`

`open(+File,+Mode,-Stream,+Options)` ISO

`open/4` behaves as does `open/3`, but allows a list of options to be given. The current options are a subset of ISO options and are:

- `alias(A)` allows the stream to be aliased to an atom `A`.
- `type(T)` has no effect on file streams in UNIX, which are always textual, but in Windows if `T` is `binary` a binary file is opened.

Error Cases Error cases are the same as `open/3` but with the addition:

- `Option_list` contains an option `O` that is not a (currently implemented) stream option.
  - `domain_error(stream_option,O)`
- An element of `OptionsList` is alias(A) and A is already associated with an existing thread, queue, mutex or stream

  - `permission_error(create,alias, A)`
- An element of `OptionsList` is alias(A) and A is not an atom
  - `type_error(atom,A)`

ISO Compatability Note: The ISO option `reposition(Boolean)` currently has no effect on streams, because whether or not the stream is repositionable or not depends on the stream class. The ISO option `eof_action(Action)` currently has no effect on file streams. If these options are encountered in `Options`, a warning is issued to `STDWARN`.

`close(+Stream_or_alias,+OptionsList)` ISO

`close/2` closes the stream or alias `Stream_or_alias`. `OptionsList` allows the user to declare whether a permission error will be raised in XSB upon a resource or system error from the closing function (e.g. `fclose()` or other system function). If `OptionsList` is non-empty and contains only terms unifying with `force(true)` then such an error will be ignored (possibly leading to unacknowledged loss of data). Otherwise, a permission error is thrown if `fclose()` or other system function returns an error condition. If the stream class of `Stream_or_alias` is an atom, then the only action taken is to close the stream itself – the interned atom itself is not affected.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable, nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open stream
  - `existence_error(stream,Stream_or_alias)`
- `OptionList` contains an option `O` that is not a closing option.
  - `domain_error(close_option,O)`
- `OptionList` contains conflicting options
  - `domain_error(close_option,OptionList)`
- Closing the stream produces an error (and `OptionsList` is a non-empty list containing terms of the form `force(true)`).
  - `permission_error(close,file,Stream_or_alias)`

`close(+Stream_or_alias)` ISO

`close/1` closes the stream or alias `Stream_or_alias`.
Behaves as `close(Stream_or_alias,[force(false)])`.

`set_input(+Stream_or_alias)` ISO

Makes file `Stream_or_alias` the current input stream.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable, nor a a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not an open input stream
  - `existence_error(stream,Stream_or_alias)`

`set_output(+Stream_or_alias)` ISO

Makes file `Stream_or_alias` the current output stream.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable, nor a a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open output stream
  - `existence_error(stream,Stream_or_alias)`

`stream_property(?Stream,?Property)` ISO

This predicate backtracks through the various stream properties that unify with `Property` for the stream `Stream`. Currently, the following properties are defined.

- `stream_class(C)` gives the stream class for a file: i.e. `file`, `atom`, `console` or `pipe`.
- `file_name(F)` is a property of `Stream`, if `Stream` is a file stream and `F` is the file name associate with `Stream`. The full operating system path is used.
- `type(T)` is a property of `Stream`, if `Stream` is a file stream and `T` is the file type of `Stream`: `text` or `binary`.
- `mode(M)` is a property of `Stream`, if `M` represents the I/O mode with which `Stream` was opened: i.e. `read`, `write`, `append`, `write_binary`, etc., as appropriate for the class of `Stream`.
- `alias(A)` is a property of `Stream`, if `Stream` was opened with alias `A`.
- `input` is a property of `Stream`, if `Stream` was opened in the I/O mode: `read`.
- `output` is a property of `Stream`, if `Stream` was opened in the I/O mode: `write`, `append`, `write_binary`, or `append_binary`.

- `reposition(Bool)` is true, if `Stream` is repositionable, and false otherwise.
- `end_of_stream(E)` returns `at` if the end of stream condition for `Stream` is true, and `not` otherwise.
- `position(Pos)` returns the current position of the stream as determined by `fseek` or the byte-offset of the current stream within an atom. In either case, if an end-of-stream condition occurs, the token `end_of_file` is returned.
- `eof_action(Action)` is `reposition` if the stream class is `console`, `eof_code` if the stream class is `file`, and `error` is the stream class is `pipe` or `atom`.

`flush_output(+Stream_or_alias)` ISO

Any buffered data in `Stream_or_alias` gets flushed. If `Stream` is not buffered (i.e. if it is of class `atom`), no action is taken.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable, nor a a stream term nor an alias.
  - `domain_error(Stream_or_alias,Stream)`
- `Stream` is not associated with an open output stream
  - `existence_error(Stream_or_alias,Stream)`
- Flushing (i.e. `fflush()`) returns an error.
  - `permission_error(flush,stream,Stream)`

`flush_output` ISO

Any buffered data in the current output stream gets flushed.

`set_stream_position(+Stream_or_alias,+Position)` ISO

If the stream associated with `Stream_or_alias` is repositionable (i.e. is a file or atom), sets the stream position indicator for the next input or output operation. Position is a positive integer, taken to be the number of bytes the stream is to be placed from the origin.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable, nor a a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Position` is not instantiated to a positive integer.
  - `domain_error(stream_position,Position)`

- `Stream_or_alias` is not associated with an open stream
  - `existence_error(stream,Stream_or_alias)`
- `Stream_or_alias` is not repositionable, or repositioning returns an error.
  - `permission_error(resposition,stream,Stream_or_alias)`

`at_end_of_stream(+Stream_or_alias)` ISO

Succeeds if `Stream_or_alias` has position at or past the end of stream.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable, nor a a stream term nor an alias.
  - `domain_error(stream,Stream_or_alias)`
- `Stream_or_alias` is not an open stream
  - `existence_error(stream,Stream_or_alias)`

`at_end_of_stream` ISO

Acts as `at_end_of_stream/1` but using the current input stream.

Other Predicates using ISO Streams

`file_reopen(+FileName,+Mode,+Stream,-RetCode)`

Takes an existing I/O stream, closes it, then opens it and attaches it to a file. This can be used to redirect I/O from any of the standard streams to a file. For instance,

```
| ?- file_reopen('/dev/null', w, 3, Error).
```

redirects all warnings to the Unix black hole.

On success, `RetCode` is 0; on error, the return code is negative.

`file_clone(+SrcStream,?DestStream,-RetCode)`

This is yet another way to redirect I/O. It is a Prolog interface to the C `dup` and `dup2` system calls. If `DestStream` is a variable, then this call creates a new XSB I/O stream that is a clone of `SrcStream`. This means that I/O sent to either stream goes to the same place. If `DestStream` is not a variable, then it must be a number corresponding to a valid I/O stream. In this case, XSB closes `DestStream` and makes it into a clone of `SrcStream`.

For instance, suppose that 10 is a I/O Stream that is currently open for writing to file `foo.bar`. Then

```
| ?- file_clone(10,3,_).
```

causes all messages sent to XSB standard warnings stream to go to file `foo.bar`. While this could be also done with `file_reopen`, there are things that only `file_clone` can do:

```
| ?- file_clone(1,10,_).
```

This means that I/O stream 10 now becomes clone of standard output. So, all subsequent I/O will now go to standard output instead of `foo.bar`.

On success, `RetCode` is 0; on error, the return code is negative.

`file_truncate(+Stream, +Length, -Return)` module: `file_io`

The regular file referenced by the Stream`Stream` is chopped to have the size of `Length` bytes. Upon successful completion `Return` is set to zero.

Portability Note: Under Windows (including Cygwin) `file_truncate/2` is implemented using `_chsize()`, while on Unix `ftruncate()` is used. There are minor semantic differences between these two system calls, which are reflected by the behavior of `file_truncate/2` on different platforms.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable, nor a a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open stream
  - `existence_error(stream,Stream_or_alias)`
- `Length` is a variable
  - `instantiation_error`
- `Length` is neither a variable nor an integer
  - `type_error(integer,Length)`

`tmpfile_open(-Stream)`

Opens a temporary file with a unique filename. The file is deleted when it is closed or when the program terminates.

`flush_all_output_streams` module: `error_handler`

Flushes output streams, both user and system `STDOUT`, `STDERR`, etc. This convenience predicate is written as

```
flush_all_open_streams:-
        stream_property(S,mode(X)),(X = append ; X = write),flush_output(S),fail.
flush_all_open_streams.
```

6.1.3 DEC-IO Style File Handling

`see(+File_or_stream)`

Makes `File_or_stream` the current input stream.

- If there is an open input stream associated with the file that has `File_or_stream` as its file name, and that stream was opened previously, then it is made the current input stream.
- Otherwise, the specified file is opened for input and made the current input stream. If the file does not exist, `see/1` throws a permission error.

Note that `see/1` is incompatible with ISO aliases – calling `see(Alias)` with an ISO alias will try to open a file named `Alias` rather than using the alias. Also note that different file names (that is, names which do not unify) represent different input streams (even if these different file names correspond to the same file).

Error Cases

- `File_or_stream` is a variable
  - `instantiation_error`
- `File_or_stream` is neither a variable nor an atomic file identifier nor a stream identifier.
  - `domain_error(stream_or_path,F)`
- File `File_or_stream` is directory or file is not readable.
  - `permission_error(open,file,F)`
- File `File_or_stream` does not exist.
  - `existence_error(stream_or_path,F)`

`seeing(?F)`

`F` is unified with the name of the current input stream. This is exactly the same with predicate `current_input/1` described in Section 6.12, and it is only provided for upwards compatibility reasons.

`seen`

Closes the current input stream. Current input reverts to `"userin"` (the standard input stream).

`tell(+F)`

Makes file `F` the current output stream.

- If there is an open output stream associated with F and that was opened previously by `tell/1`, then that stream is made the current output stream.
- Otherwise, the specified file is opened for output and made the current output stream. If the file does not exist, it is created.

Also note that different file names (that is, names which do not unify) represent different output streams (even if these different file names correspond to the same file).

The implementation of the ISO predicate `set_output/1`, is essentially that of `tell/1`.

Error Cases

- `File_or_stream` is a variable
  - `instantiation_error`
- `File_or_stream` is neither a variable nor an atomic file identifier nor a stream identifier.
  - `domain_error(stream_or_path,F)`
- File `File_or_stream` is directory or file is not readable.
  - `permission_error(open,file,F)`
- File `File_or_stream` does not exist.
  - `existence_error(stream_or_path,F)`

`telling(?F)`

`F` is unified with the name of the current output stream. This predicate is exactly the same with predicate `current_output/1` described in Section 6.12, and it is only provided for upwards compatibility reasons.

`told`

Closes the current output stream. Current output stream reverts to "userout" (the standard output stream).

`file_exists(+F)`

Succeeds if file `F` exists. `F` must be instantiated to an atom at the time of the call, or an error message is displayed on the standard error stream and the predicate aborts.

Error Cases

`instantiation_error` `F` is uninstantiated.

`url_encode(+Filename,-EncodedFilename)`

This predicate is useful when one needs to create a file whose name contains forbidden characters, such as `>`, `<`, and the like. It takes a string and encodes any forbidden character using an appropriate %-sequence of characters that is acceptable as a file name in any OS: Unix, Windows, or Mac. For instance,

```
| ?- url_encode('http://foo''>$',X).

X = http%3a%2f%2ffoo%27%3e%24
```

`url_decode(+Filename,-EncodedFilename)`

This predicate performs the inverse operation with respect to `url_encode/2`. For instance,

```
| ?- url_decode('http%3a%2f%2ffoo%27%3e%24',X).

X = http://foo'>$
```

6.1.4 Character I/O

`nl` ISO

A new line character is sent to the current output stream.

`nl(+Stream_or_alias)` ISO

A new line character is sent to the designated output stream.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open stream
  - `existence_error(stream,Stream_or_alias)`

`get_char(+Stream_or_alias,?Char)` ISO

Unifies `Char` with the next ASCII character from `Stream_or_alias`, advancing the position of the stream. `Char` is unified with -1 if an end of file condition is detected.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open input stream
  - `existence_error(stream,Stream_or_alias)`
- `Char` is not a variable or character.
  - `domain_error(character_or_variable,Char)`

`get_char(?Char)` ISO

Behaves as `get_char/2`, but reads from the current input stream.

Error Cases

- `Char` is not a variable or character.
  - `domain_error(character_or_variable,Char)`

`get_code(+Stream_or_alias,?Code)` ISO

`Code` unifies with the ASCII code of the next character from `Stream_or_alias`. The position of the stream is advanced.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open input stream
  - `existence_error(stream,Stream_or_alias)`
- `Code` is not a variable or character code
  - `domain_error(character_code_or_variable,Code)`

`get_code(?Code)` ISO

Behaves as `get_code/2`, but reads from the current input stream.

Error Cases

- `Code` is not a variable or character code
  - `domain_error(character_code_or_variable,Code)`

`get0(?N)`

`N` is the ASCII code of the next character read from the current input stream (regarded as a text stream). If the current input stream reaches its end of file, a `-1` is returned. This predicate does not check for errors, so that it is faster (and potentially less safe) than, e.g. `get_code/1`.

`get(?N)`

`N` is the ASCII code of the next non-blank printable character from the current input stream (regarded as a text stream). If the current input stream reaches its end of file, a `-1` is returned.

`peek_char(+Stream_or_alias,?Char)` ISO

`Char` is the next ASCII character from `Stream_or_alias`. The position in `Stream_or_alias` is unchanged. `Char` is unified with -1 if an end of file condition is detected.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`

- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open input stream
  - `existence_error(stream,Stream_or_alias)`
- `Char` is not a variable or character.
  - `domain_error(character_or_variable,Char)`

`peek_char(?Char)` ISO

`Char` is the next ASCII character from the current input stream. The position in the current input stream is unchanged. `Char` is unified with -1 if an end of file condition is detected.

Error Cases

- `Char` is not a variable or character.
  - `domain_error(character_or_variable,Char)`

`peek_code(+Stream_or_alias,?Code)` ISO

`Code` is the next ASCII coder from `Stream_or_alias`. The position in `Stream_or_alias` is unchanged. `Code` is unified with -1 if an end of file condition is detected.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open input stream
  - `existence_error(stream,Stream_or_alias)`
- `Code` is not a variable or character.
  - `domain_error(character_code_or_variable,Code)`

`peek_code(?Code)` ISO

Behaves as `peek_code/1`, but the current input stream is used.

Error Cases

- `Char` is not a variable or character.
  - `domain_error(character_code_or_variable,Code)`

`put_char(+Stream,+Char)` ISO

Puts the ASCII character `Char` to `Stream_or_alias`.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open input stream
  - `existence_error(stream,Stream_or_alias)`
- `Char` is a not a character
  - `type_error(character,Char)`

`put_char(+Char)` ISO

Puts the ASCII code of the character `Char` to the current output stream.

Error Cases

- `Code` is a not a character.
  - `type_error(character,Char)`

`put_code(+Stream,+Code)` ISO

Puts the ASCII code of the character `Char` to `Stream_or_alias`.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open input stream
  - `existence_error(stream,Stream_or_alias)`
- `Code` is a not a character code
  - `type_error(character_code,Code)`

`put_code(+Code)` ISO

Puts the ASCII code `Code` to the current output stream. **Error Cases**

- `Code` is a not a character code.
  - `type_error(character_code,Code)`

`put(+Code)`

Puts the ASCII character code `N` to the current output stream.

Error Cases

- `Code` is a not a character code.

- `type_error(character_code,Code)`

`tab(+N)`

Puts `N` spaces to the current output stream.

Error Cases

- `Code` is a not a positiveInteger
  - `domain_error(positiveInteger,Code)`

`get_byte/1` ISO

`get_byte/2` ISO

`put_byte/1` ISO

`put_byte/2` ISO

`put_byte/1` ISO

`put_byte/2` ISO

In XSB, these predicates are simply aliases for the associated `xxx_code` predicates and behave accordingly. This is safe to do since the reader for Version 3.3 of XSB supports only ASCII character codes, which are themselves single bytes.

6.1.5 Term I/O

`read(?Term)` ISO

A HiLog term is read from the current or designated input stream, and unified with `Term` according to the operator declarations in force. (See Section 4.1 for the definition and syntax of HiLog terms). The term must be delimited by a full stop (i.e. a "." followed by a carriage-return, space or tab). Predicate `read/1` does not return until a valid HiLog term is successfully read; that is, in the presence of syntax errors `read/1` does not fail but continues reading terms until a term with no syntax errors is encountered. If a call to `read(Term)` causes the end of the current input stream to be reached, variable `Term` is unified with the term `end_of_file`. In that case, further calls to `read/1` for the same input stream will cause an error failure.

In Version 3.3, `read/[1,2]` are non ISO-compliant in how they handle syntax errors or their behavior when encountering an end of file indicator.

`read(+Stream_or_alias, ?Term)` ISO

`read/2` has the same behavior as `read/1` but the input stream is explicitly designated by `Stream_or_alias`.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`

- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open stream
  - `existence_error(stream,Stream_or_alias)`

`read_canonical(-Term)`

Reads a term that is in canonical format from the current input stream and returns it in `Term`. On end-of-file, it returns the atom `end_of_file`. If it encounters an error, it prints an error message on STDERR and returns the atom `read_canonical_error`. This is significantly faster than `read/1`, but requires the input to be in canonical form.

`read_canonical(+Stream_or_alias),-Term)`

Behaves as `read_canonical/1`, but reads from `Stream_or_alias`.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open input stream
  - `existence_error(stream,Stream_or_alias)`

`read_term(?Term,?OptionsList)` ISO

A term is read from the current input stream as in `read/1`; but `OptionsList` is a (possibly empty) list of *read options* that specifies additional behavior. The read options include

- `variables(Vars)`: once a term has been read, `Vars` is a list of the variables in the term, in left-to-right order.
- `variable_names(VN_List)`: once a term has been read `VN_List` is a list of non-anonymous variables in the term. The elements of the list have the form `A = V` where `V` is a non-anonymous variable of the term, and `A` is the string used to denote the variable in the input stream.
- `singletons(VS_List)`: once a term has been read `VN_List` is a list of the non-anonymous `singleton` variables in the term. The elements of the list have the form `A = V` where `V` is a non-anonymous variable of the term, and `A` is the string used to denote the variable in the input stream.

Error Cases

- `OptionsList` is a variable, or is a list containing a variable element.
  - instantiation_error

- `OptionsList` contains a non-variable element `O` that is not a read option.
  - `domain_error(read_option,O)`

`read_term(+Stream_or_alias, ?Term,?OptionsList)` ISO

`read_term/3` has the same behavior as `read_term/2` but the input stream is explicitly designated using the first argument.

Error Cases are the same as `read_term/2`, but with the additional errors that may arise in stream checking.

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open stream
  - `existence_error(stream,Stream_or_alias)`

`write_term(?Term,+Options)` ISO

Outputs `+Term` to the current output stream. `Stream` (`write_term/3`) according to the list of write options, `Options`. The current set of write options which form a superset of the ISO-standard write options, are as follows:

- `quoted(+Bool)`. If `Bool = true`, then atoms and functors that can't be read back by `read/1` are quoted, if `Bool = false`, each atom and functor is written as its unquoted name. Default value is `false`.
- `ignore_ops(+Bool)`. If `Bool = true` each compound term is output in functional notation; curly brackets and list braces are ignored, as are all explicitly defined operators. If `Bool = false`, curly bracketed notation and list notation is enabled when outputting compound terms, and all other operator notation is enabled. Default value is `false`.
- `numbervars(+Bool)`. If `Bool = true`, a term of the form `'$VAR'(N)` where `N` is an integer, is output as a variable name consisting of a capital letter possibly followed by an integer. A term of the form `'$VAR'(Atom)` where `Atom` is an atom, is output as itself (without quotes). Finally, a term of the form `'$VAR'(String)` where `String` is a character string, is output as the atom corresponding to this character string. If `bool` is `false` this cases are not treated in any special way. Default value is `false`.
- `max_depth(+Depth)`. `Depth` is a positive integer or zero. If positive, it denotes the depth limit on printing compound terms. If `Depth` is zero, there is no limit. Default value is `0` (no limit).
- `priority(+Prio)` `Prio` is an integer between 1 and 1200. If the term to be printed has higher priority than `Prio`, it will be printed parenthesized. Default value is 1200 (no term parenthesized).

From the following examples it can be seen that `write_term/[2,3]` can duplicate the behavior of a number of other I/O predicates such as `write/[1,2]`, `writeq/[1,2]`, `write_canonical/[1,2]`, etc.

```
| ?- write_term(f(1+2,'A',"string",'$VAR'(3),'$VAR'('Temp'),(multifile foo)),[]).
f(1 + 2,A,"string",$VAR(3),$VAR(Temp),(multifile foo))
yes

| ?- write_term(f(1+2,'A',"string",'$VAR'(3),'$VAR'('Temp'),(multifile foo)),
                [quoted(true)]).
f(1 + 2,'A',"string",'$VAR'(3),'$VAR'('Temp'),(multifile foo))
yes

| ?- write_term(f(1+2,'A',"string",'$VAR'(3),'$VAR'('Temp'),(multifile foo)),
                [quoted(true),ignore_ops(true),numbervars(true)]).
f(+(1,2),'A','.'(115,'.'(116,'.'(114,'.'(105,'.'(110,'.'(103,[])))))),D,Temp,(multifile foo))
yes

| ?- write_term(f(1+2,'A',"string",'$VAR'(3),'$VAR'('Temp'),(multifile foo)),
                [quoted(true),ignore_ops(true),numbervars(true),priority(1000)]).
f(+(1,2),'A','.'(115,'.'(116,'.'(114,'.'(105,'.'(110,'.'(103,[])))))),D,Temp,multifile(foo))
yes
```

Error Cases

- `Options` is a variable
  - `instantiation_error`
- `Options` neither a variable nor a list
  - `type_error(list,Options)`
- `Options` contains a variable element, `O`
  - `instantiation_error`
- `Options` contains an element `O` that is neither a variable nor a write option.
  - `domain_error(write_option,O)`

ISO Compatability Note: In Version 3.3, `write_term/[2,3]` do not properly handle operators.

`write_term(+Stream_or_alias,?Term,+Options)` ISO

Behaves as `write_term/2`, but writes to `Stream_or_alias`.

Error Cases are the same as `write_term/2` but with these additions.

- `Stream_or_alias` is a variable
  - `instantiation_error`

- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open output stream
  - `existence_error(stream,Stream_or_alias)`

`write(?Term)` ISO

Semantically, `write/1` behaves as if `write_term/1` were invoked using `quoted(false)`, `ignore_ops(false)`, and `numbervars(false)`. Attributed variables are written according to the value of the Prolog flag `write_attributes` (cf. `current_prolog_flag/2`).

The HiLog term `Term` is written to the current output stream, according to the operator declarations in force. Any uninstantiated subterm of term `Term` is written as an anonymous variable (an underscore followed by a token).

All *proper HiLog terms* (HiLog terms which are not also Prolog terms) are not written in their internal Prolog representation. `write/1` always succeeds without producing an error.

HiLog (or Prolog) terms that are output by `write/1` cannot in general be read back using `read/1`. This happens for two reasons:

- The atoms appearing in term `Term` are not quoted. In that case the user must use `writeq/1` or `write_canonical/1` described below, which quote around atoms whenever necessary.
- The output of `write/1` is not terminated by a full-stop; therefore, if the user wants the term to be accepted as input to `read/1`, the terminating full-stop must be explicitly sent to the current output stream.

`write/1` treats terms of the form `'$VAR'(N)`, which may be generated by `numbervars/[1,3]` specially: it writes `'A'` if `N=0`, `'B'` if `N=1`, ..., `'Z'` if `N=25`, `'A1'` if `N=26`, etc. `'$VAR'(-1)` is written as the anonymous variable `'_'`.

`write(+Stream_or_alias, ?Term)` ISO

`write/2` has the same behavior as `write/1` but the output stream is explicitly designated using the first argument.

Error Cases are the same as `read_term/2`, but with the additional errors that may arise in stream checking.

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open output stream

– `existence_error(stream,Stream_or_alias)`

`writeq(?Term)` ISO

Acts as `write_term/1` when defined with the options `quoted(true)`, `numbervars(true)`, and `ignore_ops(false)`. In other words, atoms and functors are quoted whenever necessary to make the result acceptable as input to `read/1` `writeq/1` also treats terms of the form `'\VAR'(N)` specially, writing `A` if `N`= 0, etc., and output is in accordance with current operator definitions. `writeq/1` always succeeds without producing an error.

`writeq(+Stream_or_alias, ?Term)` ISO

`writeq/2` has the same behavior as `writeq/1` but the output stream is explicitly designated using the first argument.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open output stream
  - `existence_error(stream,Stream_or_alias)`

`write_canonical(?Term)` ISO

This predicate is provided so that the HiLog term `Term`, if written to a file, can be read back using `read_canonical/[1,2]` or `read/[1,2]` regardless of special characters appearing in `Term` or prevailing operator declarations. Like `write_prolog/1`, `write_canonical/1` writes all proper HiLog terms to the current output stream using the standard Prolog syntax (see Section 4.1 on the standard syntax of HiLog terms). `write_canonical/1` also quotes atoms and functors as `writeq/1` does, to make them acceptable as input of `read/1`. Except for list-notation (`[]`) and infix comma-list notation, operator declarations are not taken into consideration, so that apart from these exceptions compound terms are written in the form:

$$\langle predicate\ name\rangle(\langle arg_1\rangle, \ldots, \langle arg_n\rangle)$$

Unlike `writeq/1`, `write_canonical/1` does not treat terms of the form `'$VAR'(N)` specially. It writes square bracket lists using `'.'/2` and `[]` (that is, `[foo, bar]` is written as `'.'(foo,'.'(bar,[]))`).

Finally, `write canonical/2` writes attributed variables as simple variables.

ISO Compatability Note: In XSB, list notation and infix comma-list notation are considered canonical both for reading and writing. We find that this improves readability, and that these operators are so standard that there is little likelihood

that they will not be in effect by any Prolog reader. We therefore deviate from the ISO standard definition of canonical in these cases.

`write_canonical(+Stream_or_alias, ?Term)` ISO

`write_canonical/2` has the same behavior as `write_canonical/1` but the output stream is explicitly designated using the first argument.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open output stream
  - `existence_error(stream,Stream_or_alias)`

`writeln(?Term)`

`writeln(Term)` can be defined as `write(Term), nl`.

`writeln(+Stream,?Term)`

`writeln(Term)` can be defined as `write(Stream,Term), nl(Stream)`.

`write_prolog(?Term)` HiLog

`write_prolog(+Stream_or_alias,?Term)` HiLog

`write_prolog/1` acts as `write/1` except that any proper HiLog term `Term` is written using Prolog syntax – i.e. as a term whose outer functor is apply. `write_prolog/1` outputs `Term` according to the operator declarations in force. Because of this, it differs from `write_canonical/1` described above, despite the fact that both predicates write HiLog terms as Prolog terms.

`write_prolog/2` has the same behavior as `write_prolog/1` but the output stream is explicitly designated using the first argument. Error Cases for `write_prolog/2` are the same as for `write/2`.

Examples:

```
| ?- write_prolog(X(a,1+2)).
apply(_h120,a,1 + 2)

yes
| ?- write(X(a,1+2)).
_h120(a,1 + 2)

yes
| ?- write_canonical(X(a,1+2)).
apply(_h120,a,+(1,2))

yes
```

`numbervars(+Term, +FirstN,?LastN,+Options)` module: `num_vars`

This predicate provides a mechanism for grounding a (HiLog) term so that it may be analyzed. Each variable in the (HiLog) term `Term` is instantiated to a term of the form `'$VAR'(N)`, where `N` is an integer starting from `FirstN`. `FirstN` is used as the value of `N` for the first variable in `Term` (starting from the left). The second distinct variable in `Term` is given a value of `N` satisfying `"N is FirstN + 1"` and so on. The last variable in `Term` has the value `LastN-1`.

In `numbervars/4`, `Options` can be used to indicate the action to take upon encountering an attributed variable. Currently, `Options` must be either be the empty list, or the list `[attvar(Action)]` or the term `attvar(Action)`, where `Action` is

- `error` Throw a type error if an attributed variable is encountered.
- `bind` Bind attributed variables by unifying them with terms of the form `'$VAR'(N)`.
- `skip` Skip over attributed variables, performing no action on these variables.

Error Cases

- `Options` is a variable
  - `instantiation_error`
- `Options` is not an empty list, the list `[attvar(Action)]` or the term `attvar(Action)` where `Action` is one of `bind`, `error` or `skip`:
  - `domain_error`

`numbervars(+Term, +FirstN, ?LastN)` module: `num_vars`

Acts as `numbervars(+Term, +FirstN, ?LastN,attvar(error))`.

`numbervars(+Term)` module: `num_vars`

This predicate is defined as: `numbervars(Term, 0, _)`. It is included solely for convenience.

`unnumbervars(+Term, +FirstN, ?Copy)` module: `num_vars`

This predicate is a partial inverse of predicate `numbervars/3`. It creates a copy of Term in which all subterms of the form `'$VAR'(<int>)` where `<int>` is not less than `FirstN` are uniformly replaced by variables. `'$VAR''` subterms with the same integer are replaced by the same variable. Also a version `unnumbervars/2` is provided which calls `unnumbervars/3` with the second parameter set to 0.

Term Writing to Designated I/O Streams

While XSB has standard I/O streams for errors, warnings, messages, and feedback (cf. Section 6.1.1), the predicates above write to `STDOUT` which is the standard output for the process. Most of the time there is no issue with this as these streams are aliased to `STDOUT`.

However in a number of circumstances, `STDOUT` may be redirected: a user may have invoked `tell/1`, XSB may be invoked through C or interprolog, etc. In such cases, it may be useful to ensure that output goes to one of the other I/O streams.

`error_write(?Message)` module: `standard`
`error_writeln(?Message)` module: `standard`

These predicates output `Message` to XSB's `STDERR` stream, rather than to XSB's `STDOUT` stream, as does `write/1` and `writeln/1`. In addition, if `Message` is a list or comma list, the elements in the comma list are output as if they were concatenated together. Each of these predicates must be imported from the module `standard`.

`console_write(?Message)` module: `standard`
`console_writeln(?Message)` module: `standard`

As above, but writes to `STDFDBK`, the console feedback stream.

`warning(?Message)` module: `standard`

By default, this predicate outputs `Message` to XSB's `STDWARN` stream, rather than to XSB's `STDOUT` stream, as does `write/1` and `writeln/1`. In addition, if `Message` is a list or comma list, the elements in the comma list are output as if they were concatenated together. Each of these predicates must be imported from the module `standard`.

The default behavior for warnings can be altered by setting the value of the Prolog flag `warning_action` to either `silent_warning` which performs no action when `warning/1` is called. or `error_warning` which throws a miscellaneous exception when `warning/1` is called (WARNING: this includes compiler warnings). The default behavior can be restored by setting `warning_action` to `print_warning`.

`message(?Message)` module: `standard`
`messageln(?Message)` module: `standard`

As above, but writes to `STDMSG` the standard stream for messages.

6.1.6 Special I/O

`fmt_read(+Fmt,-Term,-Ret)`

`fmt_read(+Stream,+Fmt,-Term,-Ret)`

These predicates provides a routine for reading data from the current input file (which must have been already opened by using `see/1`) according to a C format, as used in the C function `scanf`. `Fmt` must be a string of characters (enclosed in `"`) representing the format that will be passed to the C call to `scanf`. See the C documentation for `scanf` for the meaning of this string. The usual alphabetical C escape characters (*e.g.*, $\backslash n$) are recognized, but not the octal or the hexadecimal ones. Another difference with C is that, unlike most C compilers, XSB insists that a single `%` in the format string signifies format conversion specification. (Some C compilers might output `%` if it is

not followed by a valid type conversion spec.) So, to output `%` you must type `%%`. Format can also be an atom enclosed in single quotes. However, in that case, escape sequences are not recognized and are printed as is.

`Term` is a term (*e.g.*, `args(X,Y,Z)`) whose arguments will be unified with the field values read in. (The functor symbol of `Term` is ignored.) Special syntactic sugar is provided for the case when the format string contains only one format specifier: If `Term` is a variable, `X`, then the predicate behaves as if `Term` were `arg(X)`.

If the number of arguments exceeds the number of format specifiers, a warning is produced and the extra arguments remain uninstantiated. If the number of format specifiers exceeds the number of arguments, then the remainder of the format string (after the last matching specifier) is ignored.

Note that floats do not unify with anything. `Ret` must be a variable and it will be assigned a return value by the predicate: a negative integer if end-of-file is encountered; otherwise the number of fields read (as returned by `scanf`.)

`fmt_read` cannot read strings (that correspond to the `%s` format specifier) that are longer than 16K. Attempting to read longer strings will cause buffer overflow. It is therefore recommended that one should use size modifiers in format strings (*e.g.*, `%2000s`), if such long strings might occur in the input.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open output stream
  - `existence_error(stream,Stream_or_alias)`

If the number of arguments in `Term` is greater than the number of conversion specifiers in `Fmt` no error is thrown, but a warning is issued.

`fmt_write(+Fmt,+Term)`
`fmt_write(+Stream_or_alias,+Fmt,+Term)`

These predicates provide routines for writing formatted data to a given output stream (`fmt_write/3`) or the current output stream (`fmt_write/2`).

`Fmt` should be a Prolog character list (string) or atom. A Prolog character list is preferred, as space can be more easily reclaimed for character lists than for atoms. `Term` is a Prolog term (*e.g.*, `args(X,Y,Z)`) whose arguments will be output. The number of arguments in `Term` should equal the number of conversion specifiers in `Fmt`. The functor symbol of `Term` is ignored [2].

[2] In the case where `Fmt` contains only a single conversion specifier, `Term` may be a string, integer or a float, and is considered to be equivalent to specifying `arg(Term)`.

Allowable syntaxes for `Fmt` reflect the syntax of the C function `printf()` on a given platform, with the following exceptions

- The usual alphabetical C escape characters (*e.g.*, $\backslash n$) are recognized, but not the octal or the hexadecimal ones.
- `%S` is supported, in addition to the usual C conversion specifiers. The corresponding argument can be any Prolog term. This provides an easy way to print the values of Prolog variables, etc.
- `%!` is supported and indicates that the corresponding argument is to be ignored and will generate nothing in the output.
- A single `%` in the format string must be followed by a conversion operator (e.g. `d`, `s`, etc.). (Some C compilers output `%` if the percentage character is not followed by a valid type conversion spec.) However, to output `%`, `fmt_write` must contain `%%`.

Example

```
| ?- fmt_write("%d %f %s %S \n",args(1,3.14159,ready,hello(world))).
1 3.141590 ready hello(world)

yes
```

XSB also offers an alternate version of formatted output in the `format` library described in volume 2. While not as efficient as `fmt_write/[2,3]`, the `format` library is more compatable with the formatted output found in other Prologs.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open output stream
  - `existence_error(stream,Stream_or_alias)`
- `Fmt` is uninstantiated or not a character string or atom
  - `type_error('character string or atom',Fmt)`
- A format specifier in `Fmt` and its corresponding argument in `Term` are of incompatable types.
  - `misc_error`
- `Term` contains fewer arguments than `Fmt` has format specifiers or `Term` is uninstantiated

- `misc_error`

If the number of arguments in `Term` is greater than the number of conversion specifiers in `Fmt` no error is thrown, but a warning is issued.

Caution for 64-bit Platforms As discussed, `fmt_write/[2,3]` calls `printf()` and inherits the flexibility of that function, but also its "features". One of these features is that in most 64-bit platforms, large integers that behave perfectly well otherwise are not printed out properly by `printf()` with the `%d` format – rather another format string needs to be used (such as `%ld` on Linux). `fmt_write/[1,2]` recognizes the `%ld` option and passes it onto `fprintf()`, but the proper format string for 64-bit integers may be different on other platforms.

`fmt_write_string(-String,+Fmt,+Term)`

This predicate works like the C function `sprintf`. It takes the format string and substitutes the values from the arguments of `Term` (*e.g.*, `args(X,Y,Z)`) for the formatting instructions %s, %d, etc. Additional syntactic sugar, as in `fmt_write`, is recognized. The result is available in `String`. `Fmt` is a string or an atom that represents the format, as in `fmt_write`.

If the number of format specifiers is greater than the number of arguments to be printed, an error is issued. If the number of arguments is greater, then a warning is issued.

`fmt_write_string` requires that the printed size of each argument (*e.g.*, X,Y,and Z above) must be less than 16K. Longer arguments are cut to that size, so some loss of information is possible. However, there is no limit on the total size of the output (apart from the maximum atom size imposed by XSB).

`file_read_line_list(-String)`

A line read from the current input stream is converted into a list of character codes. This predicate avoids interning an atom as does `file_read_line_atom/3`, and so is recommended when speed is important. This predicate fails on reaching the end of file.

`file_read_line_list(Stream_or_alias,-CharList)`

Acts as does `file_read_line_list`, but uses `Stream_or_atom`.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open input stream
  - `existence_error(stream,Stream_or_alias)`

`file_read_line_atom(-Atom)`

Reads a line from the current (textual) input stream, returning it as `Atom`. This predicate fails on reaching the end of file.

`file_read_line_atom(+Stream_or_alias,-Atom)`

Like `file_read_line_atom/1` but reads from `Stream_or_alias`. **Error Cases**

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open input stream
  - `existence_error(stream,Stream_or_alias)`

`file_write_line(+String, +Offset)` module: `file_io`
`file_write_line(+Stream_or_alias, +String, +Offset)` module: `file_io`

These predicates write `String` beginning with character `Offset` to the current output stream. `String` can be an atom or a list of ASCII character codes. This does *not* put the newline character at the end of the string (unless `String` already had this character). Note that escape sequences, like `\n`, are recognized if `String` is a character list, but are output as is if `String` is an atom.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open input stream
  - `existence_error(stream,Stream_or_alias)`
- `String` is neither a Prolog character list not an atom
  - `misc_error`

`file_getbuf_list(+Stream_or_alias, +BytesRequested, -CharList, -BytesRead)` module: `file_io`

Read `BytesRequested` bytes from file represented by `Stream_or_alias` (which must already be open for reading) into variable `String` as a list of character codes. This is analogous to `fread` in C. This predicate always succeeds. It does not distinguish between a file error and end of file. You can determine if either of these conditions has happened by verifying that `BytesRead` < `BytesRequested`.

`file_getbuf_list(+BytesRequested, -String, -BytesRead)` module: `file_io`

Like `file_getbuf_list/3`, but reads from the currently open input stream (*i.e.*, with `see/1`).

`file_getbuf_atom(+Stream_or_alias, +BytesRequested, -String, -BytesRead)` module: `file_io`

Read `BytesRequested` bytes from file represented by `Stream_or_alias` (which must already be open for reading) into variable `String`. This is analogous to `fread` in C. This predicate always succeeds. It does not distinguish between a file error and end of file. You can determine if either of these conditions has happened by verifying that `BytesRead` < `BytesRequested`.

Note: because XSB does not have an atom table garbage collector yet, this predicate should not be used to read large files. Use `read_getbuf_list` or another predicate in this case.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`
- `Stream_or_alias` is not associated with an open input stream
  - `existence_error(stream,Stream_or_alias)`

`file_getbuf_atom(+BytesRequested, -String, -BytesRead)` module: `file_io`

Like `file_getbuf_atom/4`, but reads from the currently open input stream.

`file_putbuf(+Stream_or_alias, +BytesRequested, +String, +Offset, -BytesWritten)` module: `file_io`

Write `BytesRequested` bytes into file represented by I/O port `Stream_or_alias` (which must already be open for writing) from variable `String` at position `Offset`. This is analogous to C `fwrite`. The value of `String` can be an atom or a list of ASCII characters.

Error Cases

- `Stream_or_alias` is a variable
  - `instantiation_error`
- `Stream_or_alias` is neither a variable nor a stream term nor an alias.
  - `domain_error(stream_or_alias,Stream_or_alias)`

- `Stream_or_alias` is not associated with an open input stream
  - `existence_error(stream,Stream_or_alias)`

`file_putbuf(+BytesRequested, +String, +Offset, -BytesWritten)` module: `file_io`

Like `file_putbuf/3`, but output goes to the currently open output stream.

6.2 Interactions with the Operating System

XSB provides a number of facilities for interacting with the UNIX and Windows operating systems. This section describes basic facilities for invoking shell commands and file manipulation. Chapter 1 of Volume 2 discusses more advanced commands for process spawning and control, along with interprocess communication.

`shell(+SystemCall)`

Calls the operating system with the atom `SystemCall` as argument, using the `libc` function `system()`. The predicate succeeds if `SystemCall` is executed successfully, otherwise it fails. As a notational convenience, the user can also supply `SystemCall` either as a list. In this case, elements of the list will be concatenated together to form the system call.

For example, the call:

```
| ?- shell('echo $HOME').
```

will output in the current output stream of XSB the name of the user's home directory; while the call:

```
| ?- File = 'test.c', shell(['cc -c ', File]).
```

will call the C compiler to compile the file `test.c`.

Note that in UNIX systems, since `system()` (and `shell/1`) executes by forking off a shell process. Thus it cannot be used, for example, to change the working directory of the program. For that reason the standard predicate `cd/1` described below should be used.

Error Cases

- `SystemCall` is a variable
  - `instantiation_error`
- `SystemCall` is neither an atom nor a list
  - `type_error(atom_or_list,SystemCall)`
- `SystemCall` is longer than the maximum command length allowed by `shell/1`
  - `resource_error(memory)`

`shell(+SystemCall, -Result)`

Calls the operating system with the atom `SystemCall` as argument, using the `libc` function `system()`. As a notational convenience, the user can also supply `SystemCall` as a list. In in this case, elements of the list will be concatenated together to form the system call. `shell/2` always succeeds instantiating `Result` to the exit code of `system()`. Thus `Result` will be 0 if SystemCall executed properly, and non-0 otherwise: the specific return values of `system()` may be platform-dependent.

Error Cases

- `SystemCall` is a variable
  - `instantiation_error`
- `SystemCall` is neither an atom nor a list
  - `type_error(atom_or_list,SystemCall)`
- `Result` is not a variable
  - `type_error(variable,Result)`
- `SystemCall` is longer than the maximum command length allowed by `shell/2`
  - `resource_error(memory)`

`shell_to_list(+SystemCall,-StdOut,-ErrOut,-Result)`

`shell_to_list(+SystemCall,-StdOut,-Result)`

Behaves as `shell/2` in its 1st and 4th arguments, and like `shell/2` always succeeds. Both `StdOut` and `ErrOut` are lists of lists: each element of the outer list corresponds to a line of output from `SystemCall`, while each element of an inner list corresponds to a token in that line. `shell_to_list/3` is thus a sort of Prolog analog of the shell command ‘`SystemCall`‘.

Examples:

```
?- shell_to_list(sw_vers,Stdout,Ret).

Stdout = [[ProductName:,Mac,OS,X],[ProductVersion:,10.4.9],[BuildVersion:,8P2137]]
Ret = 0

?- shell_to_lists('gcc -c nofile.c',StdOut,StdErr,Ret).

Stdout = []
StdErr = [[i686-apple-darwin8-gcc-4.0.1:,nofile.c:,No,such,file,or,directory]]
Ret = 256
```

Error cases are as with `shell/2`

`datime(?Date)` module: `standard`

Unifies `Date` to the current date, returned as a Prolog term, suitable for term comparison. Note that `datime/1` must be explicitly imported from the module `standard`.

Example:

```
> date
Mon Aug  9 16:19:44 EDT 2004
> nxsb1
XSB Version 2.6 (Duff) of June 24, 2003
[i686-pc-cygwin; mode: optimal; engine: slg-wam; gc: indirection; scheduling: local]

| ?- import datime/1 from standard

yes
| ?- datime(F).
F = datime(2004,8,9,20,20,23)

yes
```

6.2.1 The `path_sysop/2` interface

In addition, XSB provides the following unified interface to the operations on files. All these calls succeed iff the corresponding system call succeeds. These calls work on both Windows and Unixes unless otherwise noted.

`path_sysop(isplain, +Path)`

Succeeds, if `Path` is a plain file.

`path_sysop(isdir, +Path)`

Succeeds, if `Path` is a directory.

`path_sysop(rename, +OldPath, +NewPath)`

Renames `OldPath` into `NewPath`.

`path_sysop(copy, +FromPath, +ToPath)`

Copies `FromPath` into `ToPath`.

`path_sysop(rm, +Path)`

Removes the plain file `Path`.

`path_sysop(rmdir, +Path)`

Deletes the directory `Path`, succeeding only if the directory is empty.

`path_sysop(rmdir_rec, +Path)`

Deletes the directory `Path` along with any of its contents.

`path_sysop(link, +SrsPath, +DestPath)`
Creates a hard link from `SrsPath` to `DestPath`. UNIX only.

`path_sysop(cwd, -Path)`
Binds `Path` to the current working directory.

`path_sysop(chdir, +Path)`
Changes the current working directory to `Path`.

`path_sysop(mkdir, +Path)`
Creates a new directory, `Path`.

`path_sysop(exists, +Path)`
Succeeds if the file `Path` exists.

`path_sysop(readable, +Path)`
Succeeds if `Path` is a readable file.

`path_sysop(writable, +Path)`
Succeeds if `Path` is a writable file.

`path_sysop(executable, +Path)`
Succeeds if `Path` is an executable file.

`path_sysop(modtime, +Path, -Time)`
Returns a list that represents the last modification time of the file. Succeeds if file exists. In this case, `Time` is bound to a list `[high,low]` where `low` is the least significant 24 bits of the modification time and `high` is the most significant bits (25th) and up. `Time` represents the last modification time of the file. The actual value is thus $\texttt{high} * 2^{24} + \texttt{low}$, which represents the number of seconds elapsed since 00:00:00 on January 1, 1970, Coordinated Universal Time (UTC).

`path_sysop(newerthan, +Path1, +Path2)`
Succeeds is the last modification time of `Path1` is higher than that of `Path2`. Also succeeds if `Path1` exists but `Path2` does not.

`path_sysop(size, +Path, -Size)`
Returns a list that represents the byte size of `Path`. Succeeds if the file exists. In this case `Size` is bound to the list of the form `[high,low]` where `low` is the least significant 24 bits of the byte-size and `high` is the most significant bits (25th) and up. The actual value is thus $\texttt{high} * 2^{24} + \texttt{low}$.

`path_sysop(tmpfilename, -Name)`
Returns the name of a new temporary file. This is useful when the application needs to open a completely new temporary file.

`path_sysop(extension, +Name, -Ext)`
Returns file name extension.

`path_sysop(basename, +Name, -Base)`
Returns the base name of the file name (*i.e.*, the name sans the directory and the extension).

`path_sysop(dirname, +Name, -Dir)`
Returns the directory portion of the filename. The directory is slash or backslash terminated.

`path_sysop(isabsolute, +Name)`
Succeeds if `Name` is an absolute path name. File does not need to exist.

`path_sysop(expand, +Name, -ExpandedName)`
Binds `ExpandedName` to the expanded absolute path name of `Name`. The file does not need to exist. Duplicate slashes, references to the current and parent directories are factored out.

6.3 Evaluating Arithmetic Expressions through `is/2`

Before describing `is/2` and the expressions that it can evaluate, we note that in Version 3.3 of XSB, integers in XSB are represented using a single word of 32 or 64 bits, depending on the machine architecture. Floating point values are, by default, stored as word-sized references to double precision values, regardless of the target machine. Direct (non-referenced, tagged) single precision floats can be activated for speed purposes by passing the option –enable-fast-floats to the configure script at configuration time. This option is not recommended when any sort of precision is desired, as there may be as little as 28 bits available to represent a given number value under a tagged architecture.

All of the evaluable functors described below throw an instantiation error if one of their evaluated inputs is a variable, and an `evaluation(undefined)` error if one of their evaluated inputs is instantiated but non-numeric. With this in mind, we describe below only their behavior on correctly typed input.

ISO Compatability Note: In addition, evaluation of arithmetic expressions through `is/2` does not check for overflow or underflow. As a result, XSB's floating point operations do not conform to IEEE floating point standards, and deviates in this regard from the ISO Prolog standard (see [33] Section 9) We hope to fix these problems in a future release [3].

[3]We also note that the ISO Prolog evaluable functors`float_integer_part/1` (which can be obtained via `truncate/1`), `float_fractional_part/1` (which can be obtained via `X - truncate(X)`), and bitwise complement (which is implementation dependent in the ISO standard) are not implemented in Version 3.3.

`is(?Result,+Expression)` ISO

`is(Result,Expression)` is true iff the result of evaluating `Expression` as a sequence of evaluable functors unifies with `Result`. As mentioned in Section 3.10.5, `is/2` is an inline predicate, so calls to `is/2` within compiled code will not be visible during a trace of program execution.

6.3.1 Evaluable Functors for Arithmetic Expressions

`+(+Expr1,+Expr2)` Evaluable Functor (ISO)

If `+Expr1` evaluates to `Number1`, and `Expr2` evaluates to `Number2`, returns `Number1 + Number2`, performing any necessary type conversions.

`-(+Expr1,+Expr2)` Evaluable Functor (ISO)

If `+Expr1` evaluates to `Number1`, and `Expr2` evaluates to `Number2`, returns `Number1 - Number2`, performing any necessary type conversions.

`*(+Expr1,+Expr2)` Evaluable Functor (ISO)

If `+Expr1` evaluates to `Number1`, and `Expr2` evaluates to `Number2`, returns `Number1 * Number2` (i.e. multiplies them), performing any necessary type conversions.

`/(+Expr1,Expr2)` Evaluable Functor (ISO)

If `+Expr1` evaluates to `Number1`, and `Expr2` evaluates to `Number2`, returns `Number1 / Number2` (i.e. divides them), performing any necessary type conversions.

`div(+Expr1,Expr2)` ISO

`//(+Expr1,Expr2)` Evaluable Functor

If `+Expr1` evaluates to `Number1`, and `Expr2` evaluates to `Number2`, returns `Number1 // Number2` (i.e. integer division), performing any necessary type conversions, and rounding to 0 if necessary.

Example:

```
| ?- X is 3/2.

X = 1.5000

yes
| ?- X is 3 // 2.

X = 1

yes
| ?- X is -3 // 2.

X = -1

yes
```

`-(+Expr1)` Evaluable Functor (ISO)

If `+Expr` evaluates to `Number`, returns `-Number1`, performing any necessary type conversions.

`'∧'(+Expr1,+Expr2)` Evaluable Functor (ISO)

If `+Expr1` evaluates to `Number1`, and `Expr2` evaluates to `Number2`, returns the bitwise conjunction of `Number1` and `Number2`.

`'∨'(+Expr1,+Expr2)` Evaluable Functor (ISO)

If `+Expr1` evaluates to `Number1`, and `Expr2` evaluates to `Number2`, returns the bitwise disjunction `Number1` and `Number2`.

`'≫'(+Expr1,+Expr2)` Evaluable Functor (ISO)

If `+Expr1` evaluates to `Number1`, and `Expr2` evaluates to `Number2`, returns the logical shift right of `Number1`, `Number2` places.

`'≪'(+Expr1,+Expr2)` Evaluable Functor (ISO)

If `+Expr1` evaluates to `Number1`, and `Expr2` evaluates to `Number2`, returns the logical shift left of `Number1`, `Number2` places.

`xor(+Expr1,+Expr2)` ISO

`'><'(+Expr1,+Expr2)` Evaluable Functor

If `+Expr1` evaluates to `Number1`, and `Expr2` evaluates to `Number2`, returns the bitwise exclusive or of `Number1` and `Number2`.

`min(+Expr1,+Expr2)` Evaluable Functor (ISO)

If `+Expr1` evaluates to `Number1`, and `Expr2` evaluates to `Number2`, returns the minimum of the two.

`max(+Expr1,+Expr2)` Evaluable Functor (ISO)

If `+Expr1` evaluates to `Number1`, and `Expr2` evaluates to `Number2`, returns the maximum of the two.

`ceiling(+Expr)` Evaluable Functor (ISO)

If `+Expr` evaluates to `Number`, `ceiling(Number)` returns the integer ceiling of `Number` if `Number` is a float, and `Number` itself if `Number` is an integer.

`float(+Expr)` Evaluable Functor (ISO)

If `+Expr` evaluates to `Number`, `float(Number)` converts `Number` to a float if `Number` is an integer, and returns `Number` itself if `Number` is a float.

`floor(+Expr)` Evaluable Functor (ISO)

If `+Expr` evaluates to `Number`, `floor(Number)` returns the integer floor of `Number` if `Number` is a float, and `Number` itself if `Number` is an integer.

`mod(+Expr1,+Expr2)` Evaluable Functor (ISO)

If `+Expr1` evaluates to `Number1` and `Expr2` evaluates to `Number2` where `Number2` is not 0, `mod(Number1,Number2)` returns

$$Number1 - (\lfloor (Number1/Number2) \rfloor) \times Number2)$$

`rem(+Expr1,+Expr2)` Evaluable Functor (ISO)

If `+Expr1` evaluates to `Number1` and `Expr2` evaluates to `Number2` where `Number2` is not 0, `rem(Number1,Number2)` returns

$$Number1 - (Number1//Number2) \times Number2)$$

Example:

```
| ?- X is 5 mod 2.

X = 1

yes
| ?- X is 5 rem 2.

X = 1

yes
| ?- X is 5 mod -2.

X = -1

yes
| ?- X is 5 rem -2.

X = 1

yes
```

`round(+Expr)` Evaluable Functor (ISO)

If `+Expr` evaluates to `Number`, `round(Number)` returns the nearest integer to `Number` if `Number` is a float, and `Number` itself if `Number` is an integer.

`^/2` Evaluable Functor (ISO)

If `Expr1` and `Expr2` both evaluate to numbers, the infix function `^/2` raises `Expr1` to the `Expr2` power. If `Expr1` and `Expr2` both evaluate to integers, an integer is returned; otherwise a float is returned.

`'**'(+Expr1,+Expr2)` Evaluable Functor (ISO)

If `Expr1` and `Expr2` both evaluate to numbers, the infix function `**/2` raises `Expr1` to the `Expr2` power. A floating-point number is always returned.

`sqrt(+Expr)` Evaluable Functor (ISO)

If `+Expr` evaluates to `Number`, `sqrt(Number)` returns the square root of `Number`.

`truncate(+Expr)` Evaluable Functor (ISO)

If `+Expr` evaluates to `Number`, `truncate(Number)` truncates `Number` if `Number` is a float, and returns `Number` itself if `Number` is an integer.

`sign(+Expr)` Evaluable Functor (ISO)

If `+Expr` evaluates to `Number`, `sign(Number)` returns `1` if `Number` is greater than 0, `0` if `Number` is equal to 0, and `-1` if `Number` is less than 0.

`pi` Evaluable Functor (ISO)

Evaluates to π within an arithmetic expression.

`e` Evaluable Functor (ISO)

Evaluates to e, the base of the natural logarithm, within an arithmetic expression.

`epsilon` Evaluable Functor

Evaluates to *epsilon*, the difference between the float 1.0 and the first larger floating point number.

Mathematical Functions from `math.h`

XSB also allows as evaluable functors, many of the functions from the C library `math.h`. Functions included in XSB Version 3.3 are `cos/1`, `sin/1`, `tan/1`, `acos/1`, `asin/1`, `atan/1`, `log/1` (natural logarithm), `log10/1`, and `atan/2` (also available as `atan2/2`). For their semantics, see documentation to `math.h`.

6.4 Convenience

These predicates are standard and often self-explanatory, so they are described only briefly.

`true` ISO

Always succeeds.

`otherwise`

Same as `true/0`.

`fail` ISO

Always fails.

`false`

Same as `fail/0`.

6.5 Negation and Control

`'!'/0` ISO

Cut (discard) all choice points made since the parent goal started execution. Cuts across tabled predicates are not valid. The compiler checks for such cuts, although whether the scope of a cut includes a tabled predicate is undecidable in the presence of meta-predicates like `call/1`. Further discussion of conditions allowing cuts and of their actions can be found in Section 5.1.

`\+ +P` ISO

If the goal `P` has a solution, fails, otherwise it succeeds. Equivalently, it is true iff `call(P)` (see Section 6.11) is false. Argument `P` must be ground for sound negation as failure, although no runtime checks are made.

Error Cases

`instantiation_error` `P` is not instantiated.

`type_error(callable,P)` `P` is not callable.

`fail_if(+P)`

`not +P`

Like `\+/1` and provided for compatibility with legacy code. Compilation of `\+/1` and `fail_if/1` is optimized by XSB's compiler, while that of `not/1` is not – therefore the first two syntactical forms are preferred in terms of efficiency, while `\+/1` is preferred in terms of portability.

All error cases are the same as `call/1` (see Section 6.11).

`tnot(+P)` Tabling

The semantics of `tnot/1` allows for correct execution of programs with according to the well-founded semantics. `P` must be a tabled predicate, For a detailed description of the actions of tabled negation for in XSB Version 3.3 see [60, 62]. Chapter 5 contains further discussion of the functionality of `tnot/1`.

Error Cases

- `P` is not ground (floundering occurs)
  - `instantiation_error`
- `P` is not callable
  - `type_error(callable,P)`
- `P` is not a call to a tabled predicate
  - `table_error`

`sk_not(+P)` Tabling

If `+P` is a tabled predicate, `sk_not/1` acts as `tnot/1` but permits variables in its subgoal argument The semantics in the case of unbound variables is as follows:

```
... :- ..., sk_not(p(X)), ...
```

is equivalent to

```
... :- ..., tnot(pp), ...
pp :- p(X).
```

where `pp` is a new proposition. Thus, the unbound variable X is treated as `tnot`($\exists$`X`(`p`(`X`))).

If `+P` is a non-tabled predicate `sk_not/1` ensures that `+P` is ground and called via a tabled predicate so that `sk_not/1` can be used with non-tabled predicates as well, regardless of whether `+P` is ground or not.

`sk_not/1` uses an auxiliary tabled predicate, `tunnumcall/1` in its execution. Therefore to reclaim space at the predicate or call level (e.g. using `abolish_table_pred/1` or similar predicates), `tunnumcall/1` must be explicitly abolished.

Error Cases

- `P` is not instantiated
  - `instantiation_error`
- `P` is not callable
  - `type_error(callable,P)`

`u_not(+P)` module: `tables`

If `P` is ground (or cyclic), `u_not(P)` is equivalent to `tnot(P)`; but `u_not/1` provides a different semantics than `tnot/1` or `sk_not/1` if `P` is non-ground. In this latter case, `u_not(P)` applies SLG delay to the goal `P`, explicitly indicating that the default negation of `P` is floundered. This action is safe because any answer that relies on *not P* will be undefined, rather than true or false. A current limitation of `u_not/1` is that while floundering correctly causes a literal to be delayed, no simplification is ever performed if the delayed literal ever becomes ground (see the example below). `u_not/1` thus provides an informationally sound but incomplete semantics for floundering.

Thus, the use of `tnot/1`, `sk_not/1`, or `u_not/1` depends on two conditions. `sk_not/1` is the only one of these predicates that allows `P` to be a non-tabled predicate. However as mentioned, their main difference is in handling non-ground negative subgoals. If an error should be thrown for a non-ground negative subgoal, `tnot/1` should be used; if it is semantically correct to skolemize if `P` is not ground, `sk_not/1` should be used; if it is semantically correct to treat the truth value of the negative subgoal as undefined, `u_not/1` should be used. From the perspective of performance, `tnot/1` is fastest followed by `u_not/1` and then `sk_not/1`.

The following examples should clarify the behavior of `u_not/1`. For the program fragment:

```
:- table p/1,q/1.
p(1):- u_not(q(X)).
q(1).
```

the goal `p(V)` returns

```
V = 1 undefined
```

Examining this answer shows the following:

```
| ?- get_residual(p(1),Res).

Res = [floundered(q(_h258))].
```

The program fragment

```
:- table r/1,q/1.
r(1):- u_not(q(X)),s(X).
q(1).
s(1).
```

shows a limitation in the current implementation of `u_not/1`. The goal `r(V)` returns

```
V = 1 undefined
```

as before. However, examining the answer shows

```
| ?- get_residual(r(1),Res

Res = [floundered(q(1))]
```

Note that the binding *X=1* is propagated to the delayed literal after the resulution of `s(X)`. However, the call `tnot(q(1))` is not made once X is bound, so that the delayed literal does not fail.

Error Cases are the same as for `tnot/1`.

`P -> Q ; R` ISO

Analogous to if `P` then `Q` else `R`, i.e. defined as if by

```
(P -> Q ; R) :- P, !, Q.
(P -> Q ; R) :- R.
```

`P -> Q` ISO

When occurring other than as one of the alternatives of a disjunction, is equivalent to:

```
P -> Q ; fail.
```

`repeat`

Generates an infinite sequence of choice points (in other words it provides a very convenient way of executing a loop). It is defined by the clauses:

```
repeat.
repeat :- repeat.
```

`between(+L,+U,B)` module: `basics`

For `L` and `U` integers, with `L` less than or equal to `U`, successive calls to `between/3` unify `B` with all integers between `L` and `U` inclusively. If `L` is less than `U` the predicate fails.

Error Cases:

- `L` (or `U`) is a not a character
  - `type_error(integer,L)`

6.6 Unification and Comparison of Terms

The predicates described in this section allow unification and comparison of terms [4].

Like most Prologs, default unification in XSB does not perform a so-called *occurs check* — it does not handle situations where a variable `X` may be bound to a structure containing `X` as a proper subterm. For instance, in the goal

`X = f(X)` *% incorrect!*

`X` is bound to `f(X)` creating a term that is either cyclic or infinite, depending on one's point of view. Prologs in general perform unification without occurs check since without occurs check unification is linear in the size of the largest term to be unified, while unification with occurs check may be exponential in the size of the largest term to be unified. Most Prolog programmers will rarely, need to concern themselves with cyclic terms or unification with occurs check. However, unification with occurs check can be important for certain applications, in particular when Prolog is used to implement theorem provers or sophisticated constraint handlers. As a result XSB provides an ISO-style implementation

[4] Arithmetic comparison predicates that may evaluate terms before comparing them are described in Section 6.3.1.

of the predicate `unify_with_occurs_check/2` described below, as well as a Prolog flag `unify_with_occurs_check` that changes the behavior of unification in XSB's engine.

As opposed to unification predicates, term comparison predicates described below take into account a standard total ordering of terms, which has as follows:

variables @ < *floating point numbers* @ < *integers* @ < *atoms* @ < *compound terms*

Within each one of the categories, the ordering is as follows:

- ordering of variables is based on their address within the SLG-WAM — the order is *not* related to the names of variables. Thus note that two variables are identical only if they share the same address – only if they have been unified or are the same variable to begin with. As a corollary, note that two anonymous variables will not have the same address and so will not be considered identical terms. As with most WAM-based Prologs, the order of variables may change as variables become bound to one another. If the order is expected to be invariant across variable bindings, other mechanisms, such as attributed variables, should be used.
- floating point numbers and integers are put in numeric order, from $-\infty$ to $+\infty$. Note that a floating point number is always less than an integer, regardless of their numerical values. If comparison is needed, a conversion should be performed (e.g. through `float/1`).
- atoms are put in alphabetical (i.e. ASCII) order;
- compound terms are ordered first by arity, then by the name of their principal functor and then by their arguments (in a left-to-right order).
- lists are compared as ordinary compound terms having arity 2 and functor `'.'`.

For example, here is a list of terms sorted in increasing standard order:

```
[ X, 3.14, -9, fie, foe, fum(X), [X], X = Y, fie(0,2), fie(1,1) ]
```

The basic predicates for unification and comparison of arbitrary terms are:

`X = Y`
: Unifies `X` and `Y` without occur check.

`unify_with_occurs_check(One,Two)`
: Unifies `One` and `Two` using an occur check, and failing if `One` is a proper subterm of `Two` or if `Two` is a proper subterm of `One`.

Example:

```
| ?- unify_with_occurs_check(f(1,X),f(1,a(X))).

no
| ?- unify_with_occurs_check(f(1,X),f(1,a(Y))).

X = a(_h165)
Y = _h165

yes
| ?- unify_with_occurs_check(f(1,a(X)),f(1,a(X))).

X = _h165

yes
```

`T1 == T2`

Tests if the terms currently instantiating `T1` and `T2` are literally identical (in particular, variables in equivalent positions in the two terms must be identical). For example, the goal:

```
| ?- X == Y.
```

fails (answers no) because `X` and `Y` are distinct variables. However, the question

```
| ?- X = Y, X == Y.
```

succeeds because the first goal unifies the two variables.

`X \= Y` ISO

Succeeds if `X` and `Y` are not unifiable, fails if `X` and `Y` are unifiable. It is thus equivalent to `\+(X = Y)`.

`T1 \== T2` ISO

Succeeds if the terms currently instantiating `T1` and `T2` are not literally identical.

`Term1 ?= Term2`

Succeeds if the equality of `Term1` and `Term2` can be compared safely, i.e. whether the result of `Term1 = Term2` can change due to further instantiation of either term. It is defined as by `?=(A,B) :- (A==B ; A B̄), !.`

`unifiable(X, Y, -Unifier)` module: `constraintLib`

If `X` and `Y` can unify, succeeds unifying `Unifier` with a list of terms of the form `Var = Value` representing a most general unifier of `X` and `Y`. `unifiable/3` can handle cyclic terms. Attributed variables are handles as normal variables. Associated hooks are not executed [5].

[5] In Version 3.3, `unifiable/3` is written as a Prolog predicate and so is slower than many of the predicates in this section.

`T1 @< T2`
Succeeds if term `T1` is before term `T2` in the standard order.

`T1 @> T2`
Succeeds if term `T1` is after term `T2` in the standard order.

`T1 @=< T2`
Succeeds if term `T1` is not after term `T2` in the standard order.

`T1 @>= T2`
Succeeds if term `T1` is not before term `T2` in the standard order.

`T1 @= T2`
Succeeds if `T1` and `T2` are identical variables, or if the main structure symbols of `T1` and `T2` are identical.

`compare(?Op, +T1, +T2)`
Succeeds if the result of comparing terms `T1` and `T2` is `Op`, where the possible values for `Op` are:

'=' if `T1` is identical to `T2`,

'<' if `T1` is before `T2` in the standard order,

'>' if `T1` is after `T2` in the standard order.

Thus `compare(=, T1, T2)` is equivalent to `T1==T2`. Predicate `compare/3` has no associated error conditions.

`ground(+X)`
Succeeds if `X` is currently instantiated to a term that is completely bound (has no uninstantiated variables in it); otherwise it fails. While `ground/1` has no associated error conditions, it is not safe for cyclic terms: if cyclic terms may be an issue use `ground_or_cyclic/1`.

`ground_and_acyclic(+X)`

`ground_or_cyclic(+X)`
`ground_or_cyclic/1` succeeds if `X` is currently instantiated to a term that is completely bound (has no uninstantiated variables in it) *or* is a cyclic term; otherwise it fails. Alternately, `ground_and_acyclic/1` succeeds if `X` is currently instantiated to an acyclic term that is completely bound (has no uninstantiated variables in it). Neither predicate has no associated error conditions.

Both predicates are written to be as efficient as possible, and each requres a single traversal of a term, regardless of whether the term is ground, nonground or cyclic. However, due to the nature of checking for cyclicity, these predicates are somewhat slower than the unsafe `ground/1`.

`subsumes(?Term1, +Term2)` module: `subsumes`

Term subsumption is a sort of one-way unification. Term `Term1` and `Term2` unify if they have a common instance, and unification in Prolog instantiates both terms to that (most general) common instance. `Term1` subsumes `Term2` if `Term2` is already an instance of `Term1`. For our purposes, `Term2` is an instance of `Term1` if there is a substitution that leaves `Term2` unchanged and makes `Term1` identical to `Term2`. Predicate `subsumes/2` does not work as described if `Term1` and `Term2` share common variables.

`subsumes_chk(+Term1, +Term2)` module: `subsumes`
`subsumes_term(+Term1, +Term2)` ISO

The `subsumes_chk/2` predicate is true when `Term1` subsumes `Term2`; that is, when `Term2` is already an instance of `Term1`. This predicate simply checks for subsumption and does not bind any variables either in `Term1` or in `Term2`. `Term1` and `Term2` should not share any variables.

Examples:

```
| ?- subsumes_chk(a(X,f,Y,X),a(U,V,b,S)).

no
| ?- subsumes_chk(a(X,Y,X),a(b,b,b)).

X = _595884
Y = _595624
```

`variant(?Term1, ?Term2)` module: `subsumes`

This predicate is true when `Term1` and `Term2` are alphabetic variants. That is, you could imagine that `variant/2` as being defined like:

```
variant(Term1, Term2) :-
     subsumes_chk(Term1, Term2),
     subsumes_chk(Term2, Term1).
```

but the actual implementation of `variant/2` is considerably more efficient. However, in general, it does not work for terms that share variables; an assumption that holds for most (reasonable) uses of `variant/2`.

`check_variant(?Term1)` module: `tables`
`check_variant(+Term1,+DontCares)` module: `tables`

`check_variant/[1,2]` provide efficient means of checking whether the variant of a term has been asserted to a trie indexed predicate. A call `?- check_variant(Term)` thus succeeds if a variant of `Term` has been trie indexed and asseerted, and fails otherwise; the check performs no unification, and no backtracking is possible.

`check_variant/2` allows the user to specify that the last n arguments of `Term` are not to be checked for variance. This `check_variant(Term,N)` succeeds of there is a trie indexed term whose first $arity - n$ arguments are variants of those in term.

These predicates exploit the trie data structure to obtain their efficiency; as a result our implementation does not allow don't care arguments apart from the final n arguments. ***More importantly, for efficiency, no check is made to determine whether a predicate has been trie-indexed.*** If unsure, the user should call `current_index/2`.

Example 6.6.1 `?- import check_variant/1 from tables.`

```
yes
 ?- index(cmp/3, trie).

yes
| ?- assert(cmp(a,b,c)),assertcmp(d,e,f)).

yes
| ?- check_variant(cmp(a,b,c)).

yes
| ?- check_variant(cmp(a,b,1)).

no
| ?- check_variant(cmp(a,b,X)).

no
| ?- check_variant(cmp(a,b,X),1).

X = _h183
```

Error Cases

`type_error` Argument 1 of `check_variant/[1,2]` is not a callable structure.

`type_error` Argument 2 of `check_variant/[2]` is not an integer

6.6.1 Sorting of Terms

Sorting routines compare and order terms without instantiating them. Users should be careful when comparing the value of uninstantiated variables. The actual order of uninstantiated variables may change in the course of program evaluation due to variable aliasing, garbage collection, or other reasons.

`sort(+L1, ?L2)`

The elements of the list `L1` are sorted into the standard order, and any identical (i.e.

'==') elements are merged, yielding the list `L2`. The time to perform the sorting is $O(nlogn)$ where n is the length of list `L1`.

Examples:

```
| ?- sort([3.14,X,a(X),a,2,a,X,a], L).

L = [X,3.14,2,a,a(X)];

no
```

Exceptions:

`instantiation_error` Argument 1 of `sort/2` is a variable or is not a proper list.

`keysort(+L1, ?L2)`

The list `L1` must consist of elements of the form `Key-Value`. These elements are sorted into order according to the value of `Key`, yielding the list `L2`. The elements of list `L1` are scanned from left to right. Unlike `sort/2`, in `keysort/2` no merging of multiple occurring elements takes place. The time to perform the sorting is $\mathcal{O}(n \log n)$ where n is the length of list `L1`. Note that the elements of `L1` are sorted only according to the value of `Key`, not according to the value of `Value`. The sorting of elements in `L1` is not guaranteed to be stable in the presence of uninstantiated variables..

Example:

```
| ?- keysort([3-a,1-b,2-c,1-a,3-a], L).

L = [1-b,1-a,2-c,3-a,3-a]

yes
```

Error Cases:

`instantiation_error` `L1` `keysort/2` is a variable or is not a proper list.

`domain_error(key_value_pair,Element)` `L1` contains an element `Element` that is not of the form `Key-Value`.

`parsort(+L1, +SortSpec, +ElimDupl, ?L2)` module: `machine`

`parsort/4` is a very general sorting routine. The list `L1` may consist of elements of any form. `SortSpec` is the atom `asc`, the atom `desc`, or a list of terms of the form `asc(I)` or `desc(I)` where `I` is an integer indicating a sort argument position. The elements of list `L1` are sorted into order according to the sort specification. `asc` indicates ascending order based on the entire term; `desc` indicates descending order. For a sort specification that is a list, the individual elements indicate subfields of the source terms on which to sort. For example, a specification of `[asc(1)]` sorts the list

in ascending order on the first subfields of the terms in the list. `[desc(1),asc(2)]` sorts into descending order on the first subfield and within equal first subfields into ascending order on the second subfield. The order is determined by the standard predicate `compare`. If `ElimDupl` is nonzero, merging of multiple occurring elements takes place (i.e., duplicate (whole) terms are eliminated in the output). If `ElimDupl` is zero, then no merging takes place. A `SortSpec` of `[]` is equivalent to "asc". The time to perform the sorting is $O(nlogn)$ where n is the length of list `L1`. The sorting of elements in `L1` is not guaranteed to be stable. `parsort/4` must be imported from module `machine`.

Example:

```
| ?- parsort([f(3,1),f(3,2),f(2,1),f(2,2),f(1,3),f(1,4),f(3,1)],
     [asc(1),desc(2)],1,L).

L = [f(1,4),f(1,3),f(2,2),f(2,1),f(3,2),f(3,1)];

no
```

Error Cases:

`instantiation_error` `L1` is a variable or not a proper list.

6.7 Meta-Logical

To facilitate manipulation of terms as objects in themselves, XSB provides a number meta-logical predicates. These predicates include the standard meta-logical predicates of Prolog, along with their usual semantics. In addition are provided predicates which provide special operations on HiLog terms. For a full discussion of Prolog and HiLog terms see Section 4.1.

`var(?X)` ISO

Succeeds if `X` is currently uninstantiated (i.e. is still a variable); otherwise it fails.

Term `X` is uninstantiated if it has not been bound to anything, except possibly another uninstantiated variable. Note in particular, that the HiLog term X(Y,Z) is considered to be instantiated. There is no distinction between a Prolog and a HiLog variable.

Examples:

```
| ?- var(X).
yes
| ?- var([X]).
no
| ?- var(X(Y,Z)).
no
| ?- var((X)).
yes
```

```
| ?- var((X)(Y)).
no
```

`nonvar(?X)` ISO

Succeeds if `X` is currently instantiated to a non-variable term; otherwise it fails. This has exactly the opposite behaviour of `var/1`.

`atom(?X)` ISO

Succeeds only if the `X` is currently instantiated to an atom, that is to a Prolog or HiLog non-numeric constant.

Examples:

```
| ?- atom(HiLog).
no
| ?- atom(10).
no
| ?- atom('HiLog').
yes
| ?- atom(X(a,b)).
no
| ?- atom(h).
yes
| ?- atom(+).
yes
| ?- atom([]).
yes
```

`integer(?X)` ISO

Succeeds if `X` is currently instantiated to an integer; otherwise it fails.

`float(?X)` ISO

float/1 Same as `real/1`. Succeeds if `X` is currently instantiated to a floating point number; otherwise it fails.

`real(?X)`

Succeeds if `X` is currently instantiated to a floating point number; otherwise it fails. This predicate is included for compatibility with earlier versions of XSB.

`number(?X)` ISO

Succeeds if `X` is currently instantiated to either an integer or a floating point number (real); otherwise it fails.

`atomic(?X)` ISO

Succeeds if `X` is currently instantiated to an atom or a number; otherwise it fails.

Examples:

```
| ?- atomic(10).
yes
| ?- atomic(p).
yes
| ?- atomic(h).
yes
| ?- atomic(h(X)).
no
| ?- atomic("foo").
no
| ?- atomic('foo').
yes
| ?- atomic(X).
no
| ?- atomic(X((Y))).
no
```

`compound(?X)` ISO

Succeeds if `X` is currently instantiated to a compound term (with arity greater that zero), i.e. to a non-variable term that is not atomic; otherwise it fails.

Examples:

```
| ?- compound(1).
no
| ?- compound(foo(1,2,3)).
yes
| ?- compound([foo, bar]).
yes
| ?- compound("foo").
yes
| ?- compound('foo').
no
| ?- compound(X(a,b)).
yes
| ?- compound((a,b)).
yes
```

`structure(?X)`

Same as `compound/1`. Its existence is only for compatibility with previous versions.

`is_list(?X)`

Succeeds if `X` is a *proper list*. In other words if it is either the atom `[]` or `[H|T]` where H is any Prolog or HiLog term and T is a proper list; otherwise it fails.

Examples:

```
| ?- is_list([p(a,b,c), h(a,b)]).
yes
```

```
| ?- is_list([_,_]).
yes
| ?- is_list([a,b|X]).
no
| ?- is_list([a|b]).
no
```

`is_charlist(+X)`

Succeeds if `X` is a Prolog string, *i.e.*, a list of characters. Examples:

```
| ?- is_charlist("abc").
yes
| ?- is_charlist(abc).
no
```

`is_charlist(+X,-Size)`

Works as above, but also returns the length of that string in the second argument, which must be a variable.

`is_attv(+Term)`

Succeeds is `Term` is an attributed variable, and fails otherwise.

`is_most_general_term(?X)`

Succeeds if `X` is compound term with all distinct variables as arguments, or if `X` is an atom. (It fails if X is a cons node.)

```
| ?- is_most_general_term(f(_,_,_,_)).
yes
| ?- is_most_general_term(abc).
yes
| ?- is_most_general_term(f(X,Y,Z,X)).
no
| ?- is_most_general_term(f(X,Y,Z,a)).
no
| ?- is_most_general_term([_|_]).
no
```

`is_number_atom(?X)`

Succeeds if `X` is an atom (e.g. `'123'`) (as opposed to a number `123`) which can be converted to a numeric atom (integer or float) and fails otherwise. In particular, if `is_number_atom(X)` succeeds, then

```
| ?- atom_codes(X,Codes),number_codes(N,Codes).
```

will succeed.

`callable(?X)`

Succeeds if `X` is currently instantiated to a term that standard predicate `call/1` could take as an argument and not give an instantiation or type error. Note that it only checks for errors of predicate `call/1`. In other words it succeeds if `X` is an atom or a compound term; otherwise it fails. Predicate `callable/1` has no associated error conditions.

Examples:

```
| ?- callable(p).
yes
| ?- callable(p(1,2,3)).
yes
| ?- callable([_,_]).
yes
| ?- callable(_(a)).
yes
| ?- callable(3.14).
no
```

`proper_hilog(?X)` HiLog

Succeeds if `X` is a proper HiLog term – i.e. a HiLog term that is not a Prolog term; otherwise the predicate fails.

Examples: (In this example and the rest of the examples of this section we assume that `h` is the only parameter symbol that has been declared a HiLog symbol).

```
| ?- proper_hilog(X).
no
| ?- proper_hilog(foo(a,f(b),[A])).
no
| ?- proper_hilog(X(a,b,c)).
yes
| ?- proper_hilog(3.6(2,4)).
yes
| ?- proper_hilog(h).
no
| ?- proper_hilog([a, [d, e, X(a)], c]).
yes
| ?- proper_hilog(a(a(X(a)))).
yes
```

`functor(?Term, ?Functor, ?Arity)` ISO

Succeeds if the *functor* of the Prolog term `Term` is `Functor` and the *arity* (number of arguments) of `Term` is `Arity`. `Functor` can be used in either the following two ways:

1. If `Term` is initially instantiated, then

- If `Term` is a compound term, `Functor` and `Arity` are unified with the name and arity of its principal functor, respectively.
- If `Term` is an atom or a number, `Functor` is unified with `Term`, and `Arity` is unified with 0.

2. If `Term` is initially uninstantiated, then either both `Functor` and `Arity` must be instantiated, or `Functor` is instantiated to a number, and
   - If `Arity` is an integer in the range 1..255, then `Term` becomes instantiated to *the most general Prolog term* having the specified `Functor` and `Arity` as principal functor and number of arguments, respectively. The variables appearing as arguments of `Term` are all distinct.
   - If `Arity` is 0, then `Functor` must be either an atom or a number and it is unified with `Term`.
   - If `Arity` is anything else, then `functor/3` aborts.

Error Cases

`atom_or_variable` `Functor` is not an atom or variable.

`instantiation_error` Both `Term`, and either `Functor`, or `Arity` are uninstantiated.

Examples:

```
| ?- functor(p(f(a),b,t), F, A).
F = p
A = 3

| ?- functor(T, foo, 3).
T = foo(_595708,_595712,_595716)

| ?- functor(T, 1.3, A).
T = 1.3
A = 0

| ?- functor(foo, F, 0).
F = foo

| ?- functor("foo", F, A).
F = .
A = 2

| ?- functor([], [], A).
A = 0

| ?- functor([2,3,4], F, A).
F = .
A = 2

| ?- functor(a+b, F, A).
F = +
```

```
A = 2

| ?- functor(f(a,b,c), F, A).
F = f
A = 3

| ?- functor(X(a,b,c), F, A).
F = apply
A = 4

| ?- functor(map(P)(a,b), F, A).
F = apply
A = 3

| ?- functor(T, foo(a), 1).
++Error: Wrong type in argument 2 of functor/3
Aborting...

| ?- functor(T, F, 3).
++Error: Uninstantiated argument 2 of functor/3
Aborting...

| ?- functor(T, foo, A).
++Error: Uninstantiated argument 3 of functor/3
Aborting...
```

`hilog_functor(?Term, ?F, ?Arity)` HiLog

The XSB standard predicate `hilog_functor/3` succeeds

- when `Term` is a Prolog term and the principal function symbol (*functor*) of `Term` is `F` and the *arity* (number of arguments) of `Term` is `Arity`, or
- when `Term` is a HiLog term, having *name* `F` and the number of arguments `F` is applied to, in the HiLog term, is `Arity`.

The first of these cases corresponds to the "usual" behaviour of Prolog's `functor/3`, while the second is the extension of `functor/3` to handle HiLog terms. Like the Prolog's `functor/3` predicate, `hilog_functor/3` can be used in either of the following two ways:

1. If `Term` is initially instantiated, then
   - If `Term` is a Prolog compound term, `F` and `Arity` are unified with the name and arity of its principal functor, respectively.
   - If `Term` is an atom or a number, `F` is unified with `Term`, and `Arity` is unified with 0.
   - If `Term` is any other HiLog term, `F` and `Arity` are unified with the name and the number of arguments that `F` is applied to. Note that in this case `F` may still be uninstantiated.

2. If `Term` is initially uninstantiated, then at least `Arity` must be instantiated, and
   - If `Arity` is an integer in the range 1..255, then `Term` becomes instantiated to *the most general Prolog or HiLog term* having the specified `F` and `Arity` as name and number of arguments `F` is applied to, respectively. The variables appearing as arguments are all unique.
   - If `Arity` is 0, then `F` must be a Prolog or HiLog constant, and it is unified with `Term`. Note that in this case `F` cannot be a compound term.
   - If `Arity` is anything else, then `hilog_functor/3` aborts.

In other words, the standard predicate `hilog_functor/3` either decomposes a given HiLog term into its *name* and *arity*, or given an arity —and possibly a name— constructs the corresponding HiLog term creating new uninstantiated variables for its arguments. As happens with `functor/3` all constants can be their own principal function symbols.

Examples:

```
| ?- hilog_functor(f(a,b,c), F, A).
F = f
A = 3

| ?- hilog_functor(X(a,b,c), F, A).
X = _595836
F = _595836
A = 3

| ?- hilog_functor(map(P)(a,b), F, A).
P = _595828
F = map(_595828)
A = 2

| ?- hilog_functor(T, p, 2).
T = p(_595708,_595712)

| ?- hilog_functor(T, h, 2).
T = apply(h,_595712,_595716)

| ?- hilog_functor(T, X, 3).
T = apply(_595592,_595736,_595740,_595744)
X = _595592

| ?- hilog_functor(T, p(f(a)), 2).
T = apply(p(f(a)),_595792,_595796)

| ?- hilog_functor(T, h(p(a))(L1,L2), 1).
T = apply(apply(apply(h,p(a)),_595984,_595776),_596128)
L1 = _595984
L2 = _595776

| ?- hilog_functor(T, a+b, 3).
```

```
T = apply(a+b,_595820,_595824,_595828)
```

`arg(+Index, +Term, ?Argument)` ISO

Unifies `Argument` with the `Index`th argument of `Term`, where the index is taken to start at 1. In accordance with ISO semantics, `Index` must be instantiated to a non-negative integer, and `Term` to a compound term, otherwise an error is thrown as described below. If `Index` is `0` or a number greater than the arity of `Term`, the predicate quietly fails.

Examples:

```
| ?- arg(2, p(a,b), A).
A = b

| ?- arg(2, h(a,b), A).
A = a

| ?- arg(0, foo, A).
no

| ?- arg(2, [a,b,c], A).
A = [b,c]

| ?- arg(2, "HiLog", A).
A = [105,108,111,103]

| ?- arg(2, a+b+c, A).
A = c

| ?- arg(3, X(a,b,c), A).
X = _595820
A = b

| ?- arg(2, map(f)(a,b), A).
A = a

| ?- arg(1, map(f)(a,b), A).
A = map(f)

| ?- arg(1, (a+b)(foo,bar), A).
A = a+b
```

Error Cases

- `Index` is a variable
  - `instantiation_error`
- `Index` neither a variable nor an integer

  - `type_error(integer,Index)`
- `Index` is less than 0
  - `domain_error(not_less_than_zero,Index)`
- `Term` is a variable
  - `instantiation_error`
- `Term` neither a variable nor a compound term
  - `type_error(integer,Index)`

`arg0(+Index, +Term, ?Argument)`

Unifies `Argument` with the `Index`th argument of `Term` if `Index` > 0, or with the functor of `Term` if `Index` $= 0$.

`hilog_arg(+Index, +Term, ?Argument)` HiLog

If `Term` is a Prolog term, it has the same behaviour as `arg/3`, but if `Term` is a proper HiLog term, `hilog_arg/3` unifies `Argument` with the (`Index` $+ 1)^{th}$ argument of the Prolog representation of `Term`. Semantically, `Argument` is the `Index`th argument to which the *HiLog functor* of `Term` is applied. The arguments of the `Term` are numbered from 1 upwards. An atomic term is taken to have 0 arguments.

Initially, `Index` must be instantiated to a positive integer and `Term` to any non-variable Prolog or HiLog term. If the initial conditions are not satisfied or I is out of range, the call quietly fails. Note that like `arg/3` this predicate does not succeed for `Index`=0.

Examples:

```
| ?- hilog_arg(2, p(a,b), A).
A = b

| ?- hilog_arg(2, h(a,b), A).
A = b

| ?- hilog_arg(3, X(a,b,c), A).
X = _595820
A = c

| ?- hilog_arg(1, map(f)(a,b), A).
A = a

| ?- hilog_arg(2, map(f)(a,b), A).
A = b

| ?- hilog_arg(1, (a+b)(foo,bar), A).
A = foo

| ?- hilog_arg(1, apply(foo), A).
A = foo
```

```
| ?- hilog_arg(1, apply(foo,bar), A).
A = bar
```

Note the difference between the last two examples. The difference is due to the fact that `apply/1` is a Prolog term, while `apply/2` is a proper HiLog term.

`?Term =.. ?List` ISO

Given proper instantiation of the arguments, `=../2` (pronounced *univ*) succeeds when (1) `Term` unifies with a compound Prolog or HiLog term and `List` unifies with a list whose head is the functor of `Term` and whose tail is a list of the arguments of `Term`; or (2) when `Term` unifies with an atomic term and `List` unifies with a list whose only element is `Term`. More precisely,

- If initially `Term` is uninstantiated, then `List` must be instantiated either to a *proper list* (list of determinate length) whose head is an atom, or to a list of length 1 whose head is a number.
- If the arguments of `=../2` are both uninstantiated, or if either of them is not what is expected, `=../2` throws the appropriate error message.

Examples:

```
| ?- X - 1 =.. L.
X = _h112
L = [-,_h112,1]

| ?- p(a,b,c) =.. L.
L = [p,a,b,c]

| ?- h(a,b,c) =.. L.
L = [apply,h,a,b,c]

| ?- map(p)(a,b) =.. L.
L = [apply,map(p),a,b]

| ?- T =.. [foo].
T = foo

| ?- T =.. [apply,X,a,b].
T = apply(X,a,b)

| ?- T =.. [1,2].
++Error[XSB/Runtime/P]: [Type (1 in place of atomic)] in arg 2 of predicate =../2

| ?- T =.. [a+b,2].
++Error[XSB/Runtime/P]: [Type (a + b in place of atomic)] in arg 2 of predicate =../2

| ?- X =.. [foo|Y].
++Error[XSB/Runtime/P]: [Instantiation]  in arg 2 of predicate =../2
```

Error Cases

- `Term` is a variable and `List` is a variable, a partial list, a or a list whose head is a variable
  - `instantiation_error`
- `List` is neither a variable nor a non-empty list
  - `type_error(list, H)`
- `List` is a list whose head `H` is neither an atom nor a variable, and whose tail is not the empty list
  - `type_error(atomic, H)`
- `Term` is a variable and the tail of `List` has a length greater than XSB's maximum arity for terms (256)
  - `representation_error(max_arity)`

`?Term ^=.. [?F |?ArgList]`

HiLog When `Term` is a Prolog term, this predicate behaves exactly like the Prolog `=../2`. However when `Term` is a proper HiLog term, `^=../2` succeeds unifying `F` to its HiLog functor and `ArgList` to the list of the arguments to which this HiLog functor is applied. Like `=../2`, the use of `^=../2` can nearly always be avoided by using the more efficient predicates `hilog_functor/3` and `hilog_arg/3`. The behaviour of `^=../2`, on HiLog terms is as follows:

- If initially `Term` is uninstantiated, then the list in the second argument of `^=../2` must be instantiated to a *proper list* (list of determinate length) whose head can be any Prolog or HiLog term.
- If the arguments of `^=../2` are both uninstantiated, or if the second of them is not what is expected, `^=../2` aborts, producing an appropriate error message.

Examples:

```
| ?- p(a,b,c) ^=.. L.
L = [p,a,b,c]

| ?- h(a,b,c) ^=.. L.
L = [h,a,b,c]

| ?- map(p)(a,b) ^=.. L.
L = [map(p),a,b]

| ?- T ^=.. [X,a,b].
T = apply(X,a,b)

| ?- T ^=.. [2,2].
T = apply(2,2)
```

```
| ?- T ^=.. [a+b,2].
T = apply(a+b,2)

| ?- T ^=.. [3|X].
++Error: Argument 2 of ^=../2 is not a proper list
Aborting...
```

Error Cases

`instantiation_error` Argument 2 of `^=../2` is not a proper list.

`copy_term(+Term, -Copy)` ISO

Makes a `Copy` of `Term` in which all variables have been replaced by brand new variables which occur nowhere else. It can be very handy when writing (meta-)interpreters for logic-based languages. The version of `copy_term/2` provided is *space efficient* in the sense that it never copies ground terms. Predicate `copy_term/2` has no associated errors or exceptions.

Examples:

```
| ?- copy_term(X, Y).

X = _598948
Y = _598904
```

rr

```
  | ?- copy_term(f(a,X), Y).

X = _598892
Y = f(a,_599112)
```

`term_depth(+Term, -Depth)`

`term_depth/2` provides an efficient way to find the maximal depth of a term. Term depth is defined recursively as follows:

- The depth of a structure is defined as 1 + the maximal depth of any argument of that structure.
- The depth of an attributed variable is the depth of the attribute structure associated with that variable.
- The depth of a list `[H|T]` is defined as 1 + the maximal depth of `H` and `T`.
- The depth of any other element is 1.

Note that according to this definition, the depth of the list `[a,b]` is 3, since the list is equivalent to the structure `.(a,.(b,[]))` whose depth is 3.

`term_depth/2` does not check for cyclic structures, so it must be ensured that `Term` is acyclic.

`term_size(+Term, -Size)`

`term_size/2` provides an efficient way to find the total number of constituents of a term. Term size is defined recursively as follows:

- The size of an attributed variable is 1 (the variable size) + the size of the attribute structure.
- The size of a non-compound term is 1.
- The size of a compound term is defined as 1 + the sum of the sizes of all arguments of that term.
- The size of a list `[H|T]` is defined as the size of the term `'.'(H,T)`.

`term_size/2` does not check for cyclic structures, so it must be ensured that `Term` is acyclic.

6.8 Cyclic Terms

6.8.1 Unification with and without Occurs Check

Cyclic terms are created when Prolog unifies two terms whose variables have not been standardized apart: for instance

$$X = f(X)$$

will produce the cyclic term f(f(f(f(f(f(...))))))) – in other words, a term with an "infinite" depth. Note that according to the mathematical definition of unification, `X` should not unify with a term containing itself. There are two reasons why XSB (along with virtually all other Prologs) has this *default* behavior.

- The default unification algorithm, when it unifies a variable V with a term T, does not check for the occurrence of V in `T`, in other words it does not perform an *occurs check*. Unification without an occurs check is linear in the sizes of the terms to be unified, while unification with an occurs check is exponential in the sizes of the terms. This complexity is not just theoretical: it can slow down programs that perform unification of large non-ground terms – sometimes drastically.
- Some programs purposefully construct cyclic terms: this occurs with various constraint libraries such as CHR. These libraries do not perform as expected when a mathematically correct unification algorithm is used.

XSB provides two mechanisms for overriding this default behavior for unification.

- First, there is a Prolog flag `unify_with_occurs_check` which when set to `on` ensures that all unification is mathematically correct. Care should be taken when using this flag, for the above two reasons.

- For more detailed usages, the ISO predicate `unify_with_occurs_check/2` can be used syntactically rather than Prolog's default unification operator `=/2`.

6.8.2 Cyclic Terms

Fortunately, the creation of cyclic terms is uncommon for most types of programming; even when cyclic terms arise they can often be avoided by the proper use of `copy_term/2` or other predicates. Nevertheless cyclic terms do arise when XSB is used for meta-programming or if XSB is used as the basis of a high-level knowledge representation language such as Flora-2 or Silk. It is important that XSB's behavior be *cycle-safe* in the sense that the creation of cyclic terms per se will not create infinite loops in XSB's tabling or XSB's builtins. Like some other Prologs, XSB supports unification of cyclic terms. In addition, most predicates like `functor/3`, or `=../2` that either take non-compound terms or that do not require term traversal are cycle-safe. A few builtins that require term-traversal are "safe" for cyclic terms. For instance writing in XSB is subject to a depth check, which terminates for cyclic terms. Most importantly, the XSB heap garbage collector is guarenteed to be safe for cyclic terms.

Variant tabling can also handle cyclic terms if the proper flags are set. These flags are `max_table_subgoal_depth` which determines the maximal "reasonable" depth of a subgoal; and `max_table_answer_depth`, `max_table_answer_list_depth` which determine the maximal "reasonable" depth for non-list terms or lists (respectively) in answers. These last two flags also determine a "reasonable" depth for interned tries. Each of these depth flags have an associated answer flag: `max_table_subgoal_action`, `max_table_answer_action` and `max_table_answer_list_action` respectively. The actions can be of three types: `error` which throws an error if a term with a certain depth is encountered as a tabled subgoal or answer (regardless of whether that term is tabled); `failure` which causes failure for these cases; and `fail_on_cycles` which fails on cyclic terms, and otherwise throws an error for a term of a certain depth [6].

While the above operations cycle-safe, cyclic terms can cause problems in XSB for builtins or predicates that require term traversal. For instance the library predicates `length/2` and `append/2` currently go into infinite loops with cyclic terms; unless otherwise specified it is the user's responsibility to check library predicates (as opposed to standard builtins) for acyclicity using `is_acyclic/1` or `is_cyclic/1`. In addition the following XSB builtins are `not` cycle-safe:

- `bagof/3`, `copy_term/2`, `ground/1` `numbervars/[1,3,4]`, `setof/3`, `subsumes/2`, `subsumes_chk/2`, `term_depth/2`, `term_size/2`, term_to_atom/[2,3], `term_to_codes/[2,3]`, `term_variables/2`, `unifiable/2` and `variant/2` [7].

[6] We hope to efficiently integrate cycle checking into XSB's subsumptive tabling in the reasonably near future.

[7] The predicate `ground_or_cyclic/1` is safe for cyclic terms.

- Various table inspection builtins based on `get_call/2` or similar routines (including `get_residual/2`).

Arguably, programs should not intentionally create cyclic terms, and the above flags, as well as the following predicates, can help debug when cyclic terms are created.

`is_cyclic(?X)`
Succeeds if `X` is a cyclic term.

`is_acyclic(?X)`
`acyclic_term(?X)` ISO
Succeeds if `X` is not a cyclic term.

6.9 Manipulation of Atomic Terms

This section lists some of XSB's standard predicates for manipulating atomic terms. See also in Volume 2, Section 1.5 for other library predicates. Section 7 for wildcard matching, and Section 8 for an interfae to the PCRE library.

`atom_codes(?Atom, ?CharCodeList)` ISO
The standard predicate `atom_codes/2` performs the conversion between an atom and its character list representation. If `Atom` is supplied (and is an atom), `CharList` is unified with a list of ASCII codes representing the *"name"* of that atom. In that case, `CharList` is exactly the list of ASCII character codes that appear in the printed representation of `Atom`. If on the other hand `Atom` is a variable, then `CharList` must be a proper list of ASCII character codes. In that case, `Atom` is instantiated to an atom containing exactly those characters, even if the characters look like the printed representation of a number.
Examples:

```
| ?- atom_codes('Foo', L).
L = [70,111,111]

| ?- atom_codes([], L).
L = [91,93]

| ?- atom_codes(X, [102,111,111]).
X = foo

| ?- atom_codes(X, []).
X = ''
```

```
| ?- atom_codes(X, "Foo").
X = 'Foo'

| ?- atom_codes(X, [52,51,49]).
X = '431'

| ?- atom_codes(X, [52,51,49]), integer(X).
no

| ?- atom_codes(X, [52,Y,49]).
++Error[XSB/Runtime/P]: [Instantiation]  in arg 2 of predicate atom_codes/2
Forward Continuation...

| ?- atom_codes(431, L).
++Error[XSB/Runtime/P]: [Type (431 in place of atom)] in arg 1 of predicate
atom_codes/2
Forward Continuation...

| ?- atom_codes(X, [52,300,49]).
[Representation (300 is not character code)] in arg 2 of predicate
atom_codes/2
Forward Continuation...
```

Error Cases

- `Atom` is a variable and `CharCodeList` is a partial list or a list with an element which is a variable
  - `instantiation_error`
- `Atom` is neither a variable nor an atom
  - `type_error(atom, Atom)`
- `Atom` is a variable and `CharCodeList` is neither a list nor a partial list
  - `type_error(list, CharCodeList)`
- `Atom` is a variable and an element `E` of `CharCodeList` is neither a variable nor a character code
  - `representation_error(character_code, E)`

`number_codes(?Number, ?CharCodeList)` ISO

The standard predicate `number_codes/2` performs the conversion between a number and its character list representation. If `Number` is supplied (and is a number), `CharList` is unified with a list of ASCII codes comprising the printed representation of that `Number`. If on the other hand `Number` is a variable, then `CharList` must be a proper list of ASCII character codes that corresponds to the correct syntax of a number (either integer or float) In that case, `Number` is instantiated to that number, otherwise `number_codes/2` will simply fail.

Examples:

```
| ?- number_codes(123, L).
L = [49,50,51];

| ?- number_codes(N, [49,50,51]), integer(N).
N = 123

| ?- number_codes(31.4e+10, L).
L = [51,46,49,51,57,57,57,55,69,43,49,48]

| ?- number_codes(N, "314e+8").
N = 3.14e+10

| ?- number_codes(foo, L).
++Error[XSB/Runtime/P]: [Type (foo in place of
  number)] in arg 1 of predicate
number_codes
Forward Continuation...
```

Error Cases

- `Number` is a variable and `CharCodeList` is a partial list or a list with an element which is a variable
  - `instantiation_error`
- `Number` is neither a variable nor a number
  - `type_error(number, Number)`
- `Number` is a variable and `CharCodeList` is neither a list nor a partial list
  - `type_error(list, CharCodeList)`
- `Number` is a variable and an element `E` of `CharCodeList` is neither a variable nor a character code
  - `representation_error(character_code, E)`

`name(?Constant, ?CharList)`

The standard predicate `name/2` performs the conversion between a constant and its character list representation. If `Constant` is supplied (and is any atom or number), `CharList` is unified with a list of ASCII codes representing the *"name"* of the constant. In that case, `CharList` is exactly the list of ASCII character codes that appear in the printed representation of `Constant`. If on the other hand `Constant` is a variable, then `CharList` must be a proper list of ASCII character codes. In that case, `name/2` will convert a list of ASCII characters that can represent a number to a number rather than to a character string. As a consequence of this, there are some atoms (for example `'18'`) which cannot be constructed by using `name/2`. If conversion to an atom is preferred in these cases, the standard predicate `atom_codes/2` should be used instead. The syntax for numbers that is accepted by `name/2` is exactly the one which `read/1` accepts.

Examples:

```
| ?- name('Foo', L).
L = [70,111,111]

| ?- name([], L).
L = [91,93]

| ?- name(431, L).
L = [52,51,49]

| ?- name(X, [102,111,111]).
X = foo

| ?- name(X, []).
X = ''

| ?- name(X, "Foo").
X = 'Foo'

| ?- name(X, [52,51,49]).
X = 431

| ?- name(X, [45,48,50,49,51]), integer(X).
X = -213

| ?- name(3.14, L).
++Error[XSB/Runtime/P]: [Miscellaneous] Predicate name/2 for reals is not implemented yet
Aborting...
```

- `Constant` is a variable and `CharCodeList` is a partial list or a list with an element which is a variable
  - `instantiation_error`
- `Constant` is neither a variable nor atomic
  - `type_error(atomic, Constant)`
- `Constant` is a variable and `CharCodeList` is neither a list nor a partial list
  - `type_error(list, CharCodeList)`
- `Constant` is a variable and an element `E` of `CharCodeList` is neither a variable nor a character code
  - `representation_error(character_code, E)`

`atom_chars(?Number, ?CharList)` ISO

Like `atom_codes/2`, but the list returned (or input) is a list of characters *as atoms* rather than ASCII codes. For instance, `atom_chars(abc,X)` binds `X` to the list `[a,b,c]` Instead of `[97,98,99]`.

Error Cases

- `Atom` is a variable and `CharList` is a partial list or a list with an element which is a variable
  - `instantiation_error`
- `Atom` is neither a variable nor an atom
  - `type_error(atom, Atom)`
- `Atom` is a variable and `CharList` is neither a list nor a partial list
  - `type_error(list, CharList)`
- An element `E` of `CharList` is not a single-character atom
  - `type_error(character, E)`
- `Atom` is a variable and an element `E` of `CharCodeList` is not a single-character atom
  - `representation_error(character, E)`

`number_chars(?Number, ?CharList)` ISO

Like `number_codes/2`, but the list returned (or input) is a list of characters *as atoms* rather than ASCII codes. For instance, `number_chars(123,X)` binds `X` to the list `['1','2','3']` instead of `[49,50,51]`.

Error Cases

- `Number` is a variable and `CharList` is a partial list or a list with an element which is a variable
  - `instantiation_error`
- `Number` is neither a variable nor a number
  - `type_error(number, Number)`
- `Number` is a variable and `CharList` is neither a list nor a partial list
  - `type_error(list, CharList)`
- An element `E` of `CharList` is not a single-character atom
  - `type_error(character, E)`
- `CharList` is a list of single-character atoms but is not parsable as a number (by XSB)
  - `syntax_error(CharList)`

`number_digits(?Number, ?DigitList)`

Like `number_codes/2`, but the list returned (or input) is a list of digits *as numbers* rather than ASCII codes (for floats, the atom '.', '+' or '-', and 'e' will also be present in the list). For instance, `number_digits(123,X)` binds `X` to the list `[1,2,3]` instead of `['1','2','3']`, and `number_digits(123.45,X)` binds `X` to `[1,.,2,3,4,5,0,0,e,+,0,2]`.

Error cases are the same as `number_chars/2`.

`char_code(?Character, ?Code)` ISO

The standard predicate `char_code/2` is true if `Code` is the current code for `Character`. In XSB it is defined as `atom_codes(Character,[Code])`.

`atom_length(+Atom1,?Length)` ISO

This standard predicate succeeds if `Length` unifies with the length of (the name of) `Atom`.

Example

```
|?- atom_length(trilobyte,L).

L = 9
```

Error Cases

- `Atom` is a variable
  - `instantiation_error`
- `Atom` is neither a variable nor an atom
  - `type_error(atom,Atom)`
- `Length` is neither a variable nor an integer
  - `type_error(integer,Length)`

`concat_atom(+AtomList,?Atom)` module: `string`

`AtomList` must be a list structure containing atoms, integers and/or floats. This predicate flattens `AtomList` and concatenates the atoms and integers into a single atom, returned in `Atom`. Integers and floats are converted to character strings using `number_codes/2`.

This is a somewhat more general predicate than the ISO `atom_concat/2` described below, and can be more efficient if numerous atoms are to be concatenated together.

`concat_atom(+AtomList,+Sep,?Atom)` module: `string`

`AtomList` must be a list containing atoms, integers and/or floats, and `Sep` must be an atom. This predicate concatenates the atoms and integers into a single atom, separating each by `Sep`, return the resulting atom in `Atom`. Integers and floats are converted to character strings using `number_codes/2`.

This is a somewhat more general predicate than the ISO `atom_concat/2` described below, and can be more efficient if numerous atoms are to be concatenated together.

`atom_concat(Atom1,Atom2,Atom3)` ISO

- **Usage:** `atom_concat(?Atom,?Atom,+Atom)`

- **Usage:** `atom_concat(+Atom,+Atom,-Atom)`

Succeeds if `Atom12` is the concatenation of `Atom1` and `Atom2`.

Examples

```
| ?- atom_concat(hello,world,F).

F = hello world

| ?- atom_concat(X,Y,'hello world').

X =
Y = hello world;

X = h
Y = ello world
```

The last query will re-succeed for all combinations of atoms that produce `hello world`.

Error Cases

- `Atom1` and `Atom3` are both variables
  - `instantiation_error`
- `Atom2` and `Atom3` are both variables
  - `instantiation_error`
- `Atom1` is neither a variable nor an atom
  - `type_error(atom,Atom1)`
- `Atom2` is neither a variable nor an atom
  - `type_error(atom,Atom2)`
- `Atom3` is neither a variable nor an atom
  - `type_error(atom,Atom3)`

`sub_atom(+Atom,?LeftLength,?CenterLength,?RightLength,?CenterAtom` ISO

Succeeds if `Atom` can be broken into three pieces: A left atom of length `LeftLength`, a center atom `CenterAtom` of length `CenterLength` and a right atom of length `RightLength`. If sufficient arguments are uninstantiated to produce `CenterAtom` in non-deterministic starting positions, the predicate will backtrack through all center atoms for which the left atom length is the smallest , up to those whose left atom length is greatest (see examples below).

Examples

```
| ?- sub_atom(trilobyte,5,4,RL,CA).

RL = 0
CA = byte
| ?- sub_atom(trilobyte,1,CL,2,CA).

CL = 6
CA = riloby
| ?- sub_atom(trilobyte,LL,6,RL,riloby).

LL = 1
RL = 2
| ?- sub_atom(trilobyte,RL,4,LL,CA).

RL = 0
LL = 5
CA = tril;

RL = 1
LL = 4
CA = rilo;

RL = 2
CL = 3
CA = ilob
| ?- sub_atom(trilobyte,LL,CL,RL,CA).

LL = 0
CL = 0
RL = 9
CA = ;

LL = 0
CL = 1
RL = 8
CA = t;

LL = 0
CL = 2
RL = 7
CA = tr;

: /* after more backtracking */

LL = 0
CL = 9
RL = 0
CA = trilobyte;
```

```
LL = 1
CL = 0
RL = 8
CA = ;

Ll = 1
CL = 1
RL = 7
CA = r;
```

Error Cases

- `Atom` is a variable
  - `instantiation_error`
- `Atom` is neither a variable nor an atom
  - `type_error(atom, Atom)`
- `CenterAtom` is neither a variable nor an atom
  - `type_error(atom, CenterAtom)`
- `LeftLength` is neither a variable nor an integer
  - `type_error(integer, LeftLength)`
- `CenterLength` is neither a variable nor an integer
  - `type_error(integer, CenterLength)`
- `RightLength` is neither a variable nor an integer
  - `type_error(integer, RightLength)`
- `LeftLength` is an integer that is less than zero
  - `domain_error(not_less_than_zero, LeftLength)`
- `CenterLength` is an integer that is less than zero
  - `domain_error(not_less_than_zero, CenterLength)`
- `RightLength` is an integer that is less than zero
  - `domain_error(not_less_than_zero, RightLength)`

`string_substitute(+InpStr, +SubstrList, +SubstitutionList, -OutStr)` module: `string`

`InputStr` can an atom or a list of characters. `SubstrList` must be a list of terms of the form `s(BegOffset, EndOffset)`, where the name of the functor is immaterial. The meaning of the offsets is the same as for `substring/4`. (In particular, negative offsets represent offsets from the first character past the end of `String`.) Each such

term specifies a substring (between `BegOffset` and `EndOffset`; negative `EndOffset` stands for the end of string) to be replaced. `SubstitutionList` must be a list of atoms or character lists.

Offsets start from 0, as in C/Java.

This predicate replaces the substrings specified in `SubstrList` with the corresponding strings from `SubstitutionList`. The result is returned in `OutStr`. `OutStr` is a list of characters, if so is `InputStr`; otherwise, it is an atom.

If `SubstitutionList` is shorter than `SubstrList` then the last string in `SubstitutionList` is used for substituting the extra substrings specified in `SubstitutionList`. As a special case, this makes it possible to replace all specified substrings with a single string.

As in the case of `re_substring/4`, if `OutStr` is an atom, it is not interned. The user should either intern this string or convert it into a list, as explained previously.

The `string_substitute/4` predicate always succeeds.

Here are some examples:

```
| ?- string_substitute('qaddf', [s(2,4)], ['123'] ,L).

L = qa123f

| ?- string_substitute('qaddf', [s(2,-1)], ['123'] ,L).

L = qa123

| ?- string_substitute("abcdefg", [s(4,-1)], ["123"],L).

L = [97,98,99,100,49,50,51]

| ?- string_substitute('1234567890123', [f(1,5),f(5,7),f(9,-2)], ["pppp", lll],X).

X = 1ppppll189lll

| ?- string_substitute('1234567890123', [f(1,5),f(6,7),f(9,-2)], ['---'],X).

X = 1---6---89---
```

`term_to_atom(+Term,-Atom,+Options)` module: `string`

Converts `+Term` to an atomic form according to a list of write options, `Options`, that are similar to those used by `write_term/[2,3]`. The various options of `term_to_atom/[2,3]` are especially useful for the interface from C to XSB (see *Calling XSB from C* in Volume 2 of this manual).

- `quoted(+Bool)`. If `Bool = true`, then atoms and functors that can't be read back by `read/1` are quoted, if `Bool = false`, each atom and functor is written as its unquoted name. Default value is `false`.
- `ignore_ops(+Bool)`. If `Bool = true` each compound term is output in functional notation; list braces are ignored, as are all explicitly defined operators. If `Bool = canonical`, bracketed list notation is used. Default value is `canonical`. The corresponding value of `false`, that would enable operator precedence, is not yet implemented.
- `numbervars(+Bool)`. If `Bool = true`, a term of the form `'$VAR'(N)` where `N` is an integer, is output as a variable name consisting of a capital letter possibly followed by an integer. A term of the form `'$VAR'(Atom)` where `Atom` is an atom, is output as itself (without quotes). Finally, a term of the form `'$VAR'(String)` where `String` is a character string, is output as the atom corresponding to this character string. If `bool` is `false` this cases are not treated in any special way. Default value is `false`.

Error Cases

- `Options` is a variable
  - `instantiation_error`
- `Options` neither a variable nor a list
  - `type_error(list,Options)`
- `Options` contains a variable element, `O`
  - `instantiation_error`
- `Options` contains an element `O` that is neither a variable nor a write option.
  - `domain_error(write_option,O)`

Examples:

```
| ?- term_to_atom(f(a,1,X,['3cpio',d(3),'$VAR'("Foo")]),F,[]).

X = _h131
F = f(a,1,_h0,[3cpio,d(3),$VAR([70,111,111])])

yes
| ?- term_to_atom(f(a,1,X,['3cpio',d(3),'$VAR'("Foo")]),F,[numbervars(true)]).

X = _h131
F = f(a,1,_h0,[3cpio,d(3),Foo])

yes
| ?- term_to_atom(f(a,1,X,['3cpio',d(3),'$VAR'("Foo")]),F,[numbervars(true),quoted(true)]).

X = _h131
```

```
F = f(a,1,_h0,['3cpio',d(3),Foo])

yes
| ?- term_to_atom(f(a,1,X,['3cpio',d(3),'$VAR'("Foo")]),F,[numbervars(true),quoted(true),ignore_ops(true)]).

X = _h131
F = f(a,1,_h0,'.'('3cpio','.'(d(3),'.'(Foo,[]))))

yes
```

`term_to_atom(+Term,-Atom)` module: `string`

This predicate converts an arbitrary Prolog term `Term` into an atom, putting the result in `Atom`. It is defined using the default options for `term_to_atom/3`, e.g. `ignore_ops(canonical)`, `quoted(false)`, and `numbervars(false)`.

`term_to_codes(+Term,-CodeList,+OptionList)` module: `string`

This predicate is used in the definition of `term_to_atom/3` but only converts a term into a list of ASCII codes, and does not intern the list as an atom. Allowed values for `OptionList` and error cases are the same as in `term_to_atm/3`.

`term_to_codes(+Term,-CodeList)` module: `string`

This predicate converts a term to a list of ASCII codes. It is defined using the default options for `term_to_atom/3`, e.g. `ignore_ops(canonical)`, `quoted(false)`, and `numbervars(false)`.

`gc_atoms`

Explicitly invokes the garbage collector for atoms that are created, but no longer needed. By default, `gc_atoms/1` is called automatically, unless the Prolog_flag `atom_garbage_collection` is set to `false`, or if more than one thread is active. However there are reasons why a user may need to invoke atom table garbage collection. First, in Version 3.3, if atom table garbage collection is invoked automatically, it occurs periodically on heap garbage collection, or if numerous asserts and retracts have taken place. These heuristics overlook certain cases where numerous atoms may be created without invoking the garbage collector – e.g. through repeated uses of `format_write_string/3`. In addition if user-defined C code contains pointers to XSB's atom table, atom table garbage collection will be unsafe, as Version 3.3 of XSB does not detect such pointers in external code. In such cases, atom table garbage collection should be turned off via the Prolog flag `atom_garbage_collection`, and reinvoked at a point where the external pointers are no longer used.

6.10 All Solutions and Aggregate Predicates

Often there are many solutions to a problem and it is necessary somehow to compare these solutions with one another. The most general way of doing this is to collect all the

solutions into a list, which may then be processed in any way desired. So XSB provides ISO-standard predicates such as `setof/3`, `bagof/3`, and `findall/3` to collect solutions into lists. Sometimes however, one wants simply to perform some aggregate operation over the set of solutions, for example to find the maximum or minimum of the set of solutions. XSB uses answer subsumption to produce a powerful aggregation facility as discussed in Section 5.4

`setof(?Template, +Goal, ?Set)` ISO

This predicate may be read as "`Set` is the set of all instances of `Template` such that `Goal` is provable". If `Goal` is not provable, `setof/3` fails. The term `Goal` specifies a goal or goals as in `call(Goal)`. `Set` is a set of terms represented as a list of those terms, without duplicates, in the standard order for terms (see Section 6.6). If there are uninstantiated variables in `Goal` which do not also appear in `Template`, then a call to this evaluable predicate may backtrack, generating alternative values for `Set` corresponding to different instantiations of the free variables of `Goal`. Variables occurring in `Goal` will not be treated as free if they are explicitly bound within `Goal` by an existential quantifier. An existential quantification can be specified as:

```
Y ^ G
```

meaning there exists a `Y` such that `G` is true, where `Y` is some Prolog term (usually, a variable).

Error cases are the same as predicate `call/1` (see Section 6.11).

Example: Consider the following predicate:

```
p(red,high,1).
p(green,low,2).
p(blue,high,3).
p(black,low,4).
p(black,high,5).
```

The goal `?- setof(Color,Height^Val^p(Color,Height,Val),List)` returns a single solution:

```
Color = _h73
Height = _h87
Val = _h101
L = [black,blue,green,red]
```

If `Height` is removed from the sequence of existential variables, so that the goal becomes:

```
?- setof(Color,Val^p(Color,Height,Val),List)
```

the first solution is:

```
Color = _h73
Val = _h87
Height = high
L = [black,blue,red];
```

upon backtracking, a second solution is produced:

```
Color = _h73
Val = _h87
Height = low
L = [black,green]
```

`bagof(?Template, +Goal, ?Bag)` ISO

This predicate has the same semantics as `setof/3` except that the third argument returns an unsorted list that may contain duplicates.

Error Cases are the same as predicate `call/1` (see Section 6.11).

Example: For the predicate `p/3` in the example for `setof/3`, the goal `?- bagof(Color,Height^Val^p(Color,Height,Val),L)` returns the single solution:

```
Color = _h73
Height = _h87
Val = _h101
L = [red,green,blue,black,black];
```

If `Height` is removed from the sequence of existential variables, so that the goal becomes: `?- bagof(Color,Val^p(Color,Height,Val),List)`, the first solution is:

```
Color = _h73
Val = _h87
Height = high
L = [red,blue,black];
```

upon backtracking, a second solution is produced:

```
Color = _h73
Val = _h87
Height = low
L = [green,black];
```

`findall(?Template, +Goal, ?List)` ISO

Similar to predicate `bagof/3`, except that variables in `Goal` that do not occur in `Template` are treated as existential, and alternative lists are not returned for different bindings of such variables. Note that this means that `Goal` should not contain existential variables. This makes `findall/3` deterministic (non-backtrackable). Unlike `setof/3` and `bagof/3`, if `Goal` is unsatisfiable, `findall/3` succeeds binding `List` to the empty list.

Error cases are the same as `call/1` (see Section 6.11).

Example: For the predicate `p/3` in the example for `setof/3`, the goal `findall(Color,p(Color,Height,Val),L)` returns a single solution:

```
Color = _h73
Height = _h107
Val = _h121
F = [red,green,blue,black,black]
```

`findall(?Template, +Goal, ?List,?Tail)`

Acts as `findall/3`, but returns the result as the difference-list `Bag-Tail`. In fact, the 3-argument version is defined in terms of the 4-argument version:

```
findall(Templ, Goal, Bag) :- findall(Templ, Goal, Bag, [])
```

Error cases are the same as `findall/3` (or `call/1`).

`tfindall(?Template, +Goal, ?List)` Tabling

Like `findall/3`, `tfindall/3` treats all variables in `Goal` that do not occur in `Template` as existential. However, in `tfindall/3`, the `Goal` must be a call to a single tabled predicate.

`tfindall/3` allows `findall` functionality to be used safely with tabling by throwing an error if it is called recursively. Its use can be seen by considering the following series of programs.

```
p1(X):- findall(Y,p1(Y),X).
```

When executing the goal `p(X)`, XSB will throw an error when it reaches the maximum number of recursive invocations of findall.

Next, consider the program

```
:- table t/1.
t(X):- findall(Y,t(Y),X).
t(a).
```

The query `t(X)` will terminate without error, but will return two answers: `X = []` and `X = a`. These answers are hard to defend semantically, since there is an implicit domain closure axiom in findall-like predicates. On the other hand, for the program

```
:- table t2/1.
t2(X):- tfindall(Y,t2(Y),X).
t2(a).
```

the query `t2(X)` will throw a table error, indicating that a call to `tfindall/3` is apparently non-stratified footnoteDetection of non-stratification is based on the approximate detection of dependencies among subgoals maintained by XSB. This approximation is quite close for local evaluation, but is less close for batched evaluation.. Other behavior for tabled aggregation is provided by answer subsumption as discussed in Section 5.4

Other differences between predicates `findall/3` and `tfindall/3` can be seen from the following example:

```
| ?- [user].
[Compiling user]
:- table p/1.
p(a).
p(b).
[user compiled, cpu time used: 0.639 seconds]
[user loaded]

yes
| ?- p(X), findall(Y, p(Y), L).

X = a
Y = _922928
L = [a];

X = b
Y = _922820
L = [a,b];

no
| ?- abolish_all_tables.

yes
| ?- p(X), tfindall(Y, p(Y), L).

X = b
Y = _922820
L = [b,a];

X = a
Y = _922820
```

```
L = [b,a];

no
```

Error cases include those of `findall/3` (see above), along with

`table_error` Upon execution `Goal` is not a subgoal of a tabled predicate.

`table_error` A call to `tfindall/3` is apparently non-stratified

`X ^ Goal` ISO

Within `setof/3`, `bagof/3` and the like, the `^ /2` operator means there exists an `X` such that `Goal` is true.

`excess_vars(+Term, +ExistVarTerm, +AddVarList, -VarList)` module: `setof`

Returns in `VarList` the list of (free) variables found in `Term` concatenated to the end of `AddVarList`. (In normal usage `AddVarList` is passed in as an empty list.) `ExistVarTerm` is a term containing variables assumed to be quantified in `Term` so none of these variables are returned in the resulting list (unless they are in `AddVarList`.) Subterms of `Term` of the form `(VarTerm ^ SubTerm)` are treated specially: all variables in `VarTerm` are assumed to be quantified in `SubTerm`, and so no occurrence of these variables in `SubTerm` is collected into the resulting list.

Error Cases

`type_error` `AddVarList` is not a list of variables

`memory` Not enough memory to collect the variables.

`find_n(+N,?Template, +Goal, ?List)` module: `setof`

Acts as `findall/3` but returns only the first `N` bindings of `Template` to `List`.

6.11 Meta-Predicates

`call(#X)` ISO

If `X` is a non-variable term in the program text, then it is executed exactly as if `X` appeared in the program text instead of `call(X)`, e.g.

```
..., p(a), call( (q(X), r(Y)) ), s(X), ...
```

is equivalent to

```
..., p(a), q(X), r(Y), s(X), ...
```

However, if `X` is a variable in the program text, then if at runtime `X` is instantiated to a term which would be acceptable as the body of a clause, the goal `call(X)` is executed as if that term appeared textually in place of the `call(X)`, *except that* any cut ('!') occurring in `X` will remove only those choice points in `X`. If `X` is not instantiated as described above, an error message is printed and `call/1` fails.

Error Cases

`instantiation_error X` is a variable

`type_error(callable,X) X` is not callable.

`#X`

(where `X` is a variable) executes exactly the same as `call(X)`. However, the explicit use of `call/1` is considered better programming practice. The use of a top level variable subgoal elicits a warning from the compiler.

`call(Goal,Arg,...)` ISO

`call(Goal,Arg)` where `Goal` is an N-ary callable term first constructs a new N+1-ary term `NewGoal` with the same functor and first N arguments as `Goal` and with `Arg` as its N+1th argument, and then calls `NewGoal`. As an example,

```
call(member(X),[a,b,c])
```

is equivalent to `call(member(X,[a,b,c]))`. `Goal` must be a callable term, but can be prepended by a module name using the `:/2` symbol. `call(Goal,Arg1,Arg2,...)` will act similarly. Note that `Goal` should usually be atomic – if the outer functor of `Goal` is, say, `,/2`, `call/[2-10]` will try to add the extra argument(s) to the comma functor, which is generally not the intended behavior.

While meta calls are generally fast in XSB, the extra term manipulation of `call/[2-10]` makes it somewhat slower than `call/1`.

`call_tv(#Goal,-TV)` Tabling

Calls `Goal` just as with `call/1`, and if `Goal` does not fail, instantiates `TV` with either `true` or `undefined`, depending on the value of `Goal` in the well-founded semantics. `Goal` need not be tabled itself.

Error cases are the same as `call/1`.

`timed_call(#Goal,+Interval,#Handler,+Option)`

`timed_call(#Goal,+Interval,#Handler)`

This predicate calls `Goal` and, if `Goal` is still being evaluated after `Interval` milliseconds, `Goal` will be interrupted and `Handler` executed. In the case where `Handler` succeeds or fails, the execution of `Goal` will be continued; if `Handler` throws an uncaught exception the execution of `Goal` may be aborted. In this way `timed_call/3` can be used enforce a time-out on `Goal`.

`Interval` can be either a positive integer or the term `repeating(Int)` where `Int` is a non-negative integer. In this latter case, `Goal` is interrupted every `Int` milliseconds until it terminates (whether by normal termination or by `Handler` throwing an exception). In the case of repeated interrupts, the time taken to execute `Handler` is not counted as part of `Interval` milliseconds.

Nested calls to `timed_call/3` are not allowed unless `Option` is set to `nested`.

- If `Option` is not equal to `nested`, or if `timed_call/3` is used, then a nested call to `timed_call/4` will throw a permission error.
- If `Option` is equal to `nested` then the nested timed call is simply treated as a call to `Goal`: in other words the interval and handler for the nested call is ignored.

As an implementation note, `timed_call/[3,4]` is based on XSB's internal interrupt mechanism, used for attributed variable handlers and thread signalling. As such, the ability to execute complex actions upon interrupt and to resume is very robust. However, checks for interrupts are only made whenever XSB's SLG-WAM engine is executing. Because of this, if XSB is suspended on I/O, calling a C or java function, in a C-implemented builtin, or otherwise outside of its virtual machine, the interrupt will not be executed until computation is back within XSB's virtual machine.

`timed_call/3` is not yet implemented for the multi-threaded engine but its functionality is easily duplicated using thread signalling (Section‘7.5).

Examples Consider the simple (and non-tabled) program fragment

```
loop :- loop.
```

which goes into an infinite loop on the query `?- loop.` However, the query

```
timed_call(loop,repeating(500),abort).
```

will interrupt `loop` and abort its computation after 500 milliseconds. Alternately, the query

```
timed_call(loop,500,statistics).
```

will interrupt the computation after 500 seconds, print out statistics, and resume the computation where it left off.

```
timed_call(loop,repeating(500),statistics).
```

will interrupt the computation every 500 milliconds tp print statistics. More sophisticated interrupt handlers could introspect a computation (e.g., using `statistics/2` or `table_dump/[1,3]`) and possibly modify parameters of the computation when possible (e.g., by changing one form of tabling to another, when permitted).

Error Cases Error cases are the same as in `call/1` for the first and third arguments of `timed_call/3`, along with these other errors.

`Interval` is not an integer

- `type_error(integer,Interval)`

`Interval` is not a positive integer

- `domain_error(positive_integer,Interval)`

A call `C` to `timed_call/3` is made within the scope of some other call to `timed_call/3`

- `permission_error(nested_call,predicate,Goal)`

`timed_call/3` is called from the multi-threaded engine

- `misc_error`

`bounded_call(#Goal,+MaxMemory,+MaxCPU,#Handler)` module: `standard`
`bounded_call(#Goal,+MaxMemory,+MaxCPU)` module: `standard`

These predicates call `Goal` and check once per second whether the total CPU time to execute `Goal` is greater than `MaxCPU` seconds, and whether the total memory taken by XSB is greater than `MaxMemory` bytes. Under `bounded_call/4` if either of these conditions arise, `Handler` is called; under `bounded_call/3` a resource exception is thrown for memory or CPU time.

These predicates are implemented directly using `timed_call/3` and inherit the advantages and limitations of that predicate. As an advantage, the ability to execute complex actions upon interrupt and to resume is very robust. However, checks for interrupts are only made whenever XSB's SLG-WAM engine is executing. Because of this, if XSB is suspended on I/O, calling a C or java function, in a C-implemented builtin, or otherwise outside of its virtual machine, the interrupt will not be executed until computation is back within XSB's virtual machine.

`Handler` cannot cause `timed_call/3` to be executed as a subgoal; but otherwise `Handler` has no restrictions.

`bounded_call/[3,4]` is not yet implemented for the multi-threaded engine but its functionality is easily duplicated using thread signalling (Section‘7.5).

Error Cases Error cases are the same as in `call/1` for the first argument of `bounded_call/3`, and are the same as that of `timed_call` for `Handler`.

`MaxCPU` or `MaxMemory` is not an integer

- `type_error(integer)`

`MaxCPU` or `MaxMemory` is not a positive integer

- `domain_error(positive_integer)`

`once(#X)` ISO

`once/1` is defined as `once(X):- call(X),!.` `once/1` should be used with care in tabled programs. The compiler can not determine whether a tabled predicate is called in the scope of `once/1`, and such a call may lead to runtime errors. If a tabled predicate may occur in the scope of `once/1`, use `table_once/1` instead.

Error cases are the same as `call/1`.

`forall(Generate,Test)`

`forall(Generate, Test)` is true iff for all possible bindings of `Generate`, the goal `Test` is true. Procedurally, abstracting error checking, the predicate shall behave as being defined by `\+ (call(Generator), \+ call(Test))`.

Error cases are the same as `call/1`.

`table_once(#X)` Tabling

`table_once/1` is a weaker form of `once/1`, suitable for situations in which a single solution is desired for a subcomputation that may involve a call to a tabled predicate. `table_once(?Pred)` succeeds only once even if there are many solutions to the subgoal `Pred`. However, it does not "cut over" the subcomputation started by the subgoal `Pred`, thereby ensuring the correct evaluation of tabled subgoals.

`call_cleanup(#Goal,#Handler)` ISO

`call_cleanup(Goal, Cleanup)` calls `Goal` just as if it were called via `call/1`, but it is ensures that `Handler` will be called after `Goal` finishes execution. `call_cleanup/2` is thus useful when `Goal` uses a resource, (such as a stream, mutex, database cursor, etc.) that should be released when `Goal` finishes execution.

More precisely, `Goal` finishes execution either 1) by failure, 2) by determining that the success of `Goal` is deterministic, 3) when an error is thrown and not handled by `Goal` or one of its subgoals; or 4) when `Goal` is cut over. In all of these cases, `Handler` will be called and will succeed non-deterministically. We illustrate these cases through examples.

- Failure of `Goal`:

  ```
  ?- call_cleanup(fail,writeln(failed(Goal))).
  ```

  In this case, `Goal` has no solutions, and the handler is invoked when the engine backtracks out of `Goal`.

- Deterministic success of `Goal`. Assume that `p(1)` and `p(2)` have been asserted. Then

  ```
  ?- call_cleanup((p(X),writeln(got(p(X)))),writeln(handled(p(X)))).
  got(p(1))

  X = 1;
  got(p(2))
  handled(p(2))

  X = 2;

  no
  ```

Note that `Handler` is called only after the last solution of the goal `p(X)` has been obtained. XSB decides to call `Handler` only when it can be determined that the success of `Goal` has left no choice points. In such a case, the final solution has been obtained for `Goal`. Of course, it may be that a solution S to `Goal` leaves a choice point but the choice point will produce no further solutions for `Goal`. XSB will not call `Handler` in this case, rather it will wait until there are no choice points left for `Goal`.

- An uncaught error E is thrown out of `Goal`. In this case, `Handler` will be called, and then, if E is uncaught, E will be rethrown. This is illustrated in the following example (Error handling is discussed further in Section 12.3.2):

```
?- catch(call_cleanup(throw(my_error),writeln(invoking_handler)),Ball,write(Ball))
invoking_handler
my_error
yes
```

  Of course, `Handler` itself can be wrapped in a `catch/3` so that any errors will be caught by `call_cleanup/2`.

- Choice points for `Goal` are removed via a cut. Consider an example in which `p/1` has the same extension as above (`p(1),p(2)`:

```
call_cleanup(p(X),writeln(handled_1)),!.
handled_1

X = 1

yes
```

  The handler is invoked immediately when the choice point laid down by `p(X)` is cut over – before returning to the command line. If a cut cuts over more than goal to be cleaned, more than one handler will be executed:

```
?-call_cleanup(p(X),writeln(handled_4_1)),
    call_cleanup(p(Y),writeln(handled_4_2)),
    call_cleanup(p(Z),writeln(handled_4_3)),
    !.
handled_4_3
handled_4_2
handled_4_1

X = 1
Y = 1
Z = 1
```

`call_cleanup/2` is thus an extremely powerful and flexible mechanism when used in a simple manner. While `Handler` is "guaranteed" to be invoked whenever `Goal` finishes

execution [8], it may be difficult to predict when `Handler` will be invoked, as `Handler` may be invoked because of deeply non-local cuts over `Goal`, and even when such cuts are not present, the invocation depends on XSB determining when the last solution for `Goal` has been obtained. Baroque usages, such as invoking `call_cleanup/2` and cuts in the handler are supported, but may lead to code that is difficult to debug, since handlers may be invoked based on the state of XSB's choice point stack.

Error Cases

`Goal` is a variable

- `instantiation error`

`Goal` is neither a variable nor a callable term

- `type error(callable, Goal)`

`Handler` is a variable

- `instantiation error`

`Handler` is neither a variable nor a callable term

- `type error(callable, Handler)`

6.12 Information about the System State

Various aspects of the state of an instance of XSB — information about what predicates, modules, or dynamic clauses have been loaded, their object files, along with other information can be inspected in ways similar to many Prolog systems. However, because the atom-based module system of XSB may associate structures with particular modules, predicates are provided to inspect these elements as well. The following descriptions of *state* predicates use the terms *predicate indicator*, *term indicator* and *current module* to mean the following:

- By *predicate indicator* we mean a *compound term* of the form `M:F/A` or simply `F/A`. When the predicate indicator is fully instantiated, `M` and `F` are atoms representing the *module name* and the *functor* of the predicate respectively and `A` is a non negative integer representing its *arity*.

  Example: `usermod:append/3`

- By *term indicator* we mean a predicate or function symbol of arity N followed by a sequence of N variables (enclosed in parentheses if N is greater than zero). A term indicator may optionally be prefixed by the module name, thus it can be of the form `M:Term`.

  Example: `usermod:append(_,_,_)`

[8] In fact we don't guarantee anything, see XSB's license.

- A module `M` becomes a *current (i.e. "known") module* as soon as it is loaded in the system or when another module that is loaded in the system imports some predicates from module `M`.

  Note that due to the dynamic loading of XSB, a module can be current even if it has not been loaded, and that some predicates of that module may not be defined. In fact, a module can be current even if it does not exist. This situation occurs when a predicate is improperly imported from a non-existent module. Despite this, a module can never lose the property of being *current*.

`current_input(?Stream)` ISO

Succeeds iff stream `Stream` is the current input stream, or procedurally unifies `Stream` with the current input stream.

Error Cases

- `Stream` is neither a variable nor a stream identifier
  - `domain_error(stream_or_variable,Stream))`

`current_output(?Stream)` ISO

current_output/1 Succeeds iff stream `Stream` is the current output stream, or procedurally unifies `Stream` with the current output stream.

Error Cases

- `Stream` is neither a variable nor a stream identifier
  - `domain_error(stream_or_variable,Stream))`

ISO Compatability Note: In XSB `current_input/1` does not throw an error if `Stream` is not a current input stream, but quietly fails instead.

`current_prolog_flag(?Flag_Name, ?Value)` ISO

`current_prolog_flag/2` allows the user to examine both dynamic aspects of XSB along with certain non-changeable ISO flags and non-changeable Prolog-commons flags. Calls to `current_prolog_flag/2` will unify against ISO, Prolog-commons, and XSB-specific flags.

ISO and Prolog-commons flags are as follows:

- `bounded` Indicates whether integers in XSB are bounded. This flag always has the value `true`
- `min_integer, max_integer` The minimum integer available in the current XSB configuration (differs between 32- and 64-bits).
- `max_arity` Indicates the maximum arity of terms in XSB. This flag always has the value `255`
- `integer_rounding_function` This flag always has the value `toward_zero`

- `debug` Indicates whether trace or debugging is turned `on` or `off`
- `unknown` Indicates the behavior taken when calling an unknown predicate. Values can be set to `fail`, `warning`, or `error`, indincating that calls to unknown predicates fail, produce a warning message to `user_warning` or throw an existence error. The default setting is `error`.
- `double_quotes` Indicates that double-quoted terms in XSB represent lists of character codes. Value is `codes`
- `dialect` indicates the implementation of Prolog that is running. Using this flag, applications intended to run on more than one Prolog can take actions that conditional on the executing Prolog. The value is `xsb`.
- `version_data` indicates the version of XSB that is running. Using this flag, applications intended to run on more than one Prolog can take actions that conditional on the executing Prolog. The value is `xsb`.

ISO Compatability Note: The ISO flags `char_conversion` is not available – XSB does not use character conversion. XSB reads double quoted strings as lists of character codes, so that the value of the flag `double_quotes` is always `codes`, and this flag is not settable.

Non-standard flag names may be specific to XSB or may be common to XSB and certain other Prolog. These flag names are:

- `backtrace_on_error` `on` iff system-handled errors automatically print out the trace of the execution stack where the error arose, `off` otherwise. Default is `on`. In the multi-threaded engine, this flag is thread-specific and controls whether the backtrace for a current execution will be printed to `STDERR`.
- `dcg_style` the DCG style currently used; `xsb` or `standard` (standard is used in Quintus, SICSTUS, etc.). See Section 11.4 for more details. Default is `xsb`. This flag affects all threads in the process.
- `heap_garbage_collection` `indirection`, `none`, `sliding`, or `copying` depending on the heap garbage collection strategy that is currently being employed (see also Section 3.7). Default is `indirection`. This flag is private to each thread.
- `heap_margin` Specifies the size *in bytes* of the margin used to determine whether to perform heap garbage collection or reallocation of the environment stack. The default is 8192 (8K) bytes for 32-bit platforms 16384 (16K) for 64-bit platforms. Setting this field to a large value (e.g. in the megabyte range) can cause XSB to be more aggressive in terms of expanding heap and local stack and to do fewer heap garbage collections than with the default value. However `heap_margin` should not be set *lower* than its default, as this may prevent XSB from properly creating large terms on the heap.
- `clause_garbage_collection` `on` if garbage collection for retracted clauses is allowed, and off otherwise. Default is `on`. This flag is private to each thread.

- `atom_garbage_collection on` if garbage collection for atomic constants is allowed, and off otherwise. Default is `on`. This flag is global for all threads (currently, string garbage collection will only be invoked if there is a single active thread.)
- `table_gc_action abolish_tables_transitively` if predicates or subgoals that depend on a conditional answer of an abolished table are to be abolished automatically, and `abolish_tables_singly` if not. Default is `abolish_tables_transitively`. This flag affects all threads in the process.
- `goal` the goal passed to XSB on command line with the '-e' switch; '`true.`' if nothing is passed. This flag may be examined, but not set.
- `tracing on` iff trace mode is on; `off` otherwise. This flag affects all threads in the process.
- `write_depth` The depth to which a term is written by `write`-like predicates. Default is 64. This flag affects all threads in the process.
- `warning_action` The action to take on warnings: the default value `print_warning` prints a warning message to the XSB `STDWARN` stream when `warning/1` is called; `silent_warning` silently succeeds when `warning/1` is called; and `error_warning/1` throws a miscellaneous exception.
- `write_attributes` Determines the action to take by `write/1` when it writes an attributed variable. By default *write/1* portrays attributed variables using module-specific routines (cf. Volume 2 of this manual) as $Variable\{Module : PA_Output\}$ where PA_Output is the output of the `portray_attrubutes/2` clause for $Module$. However the value `ignore` causes an attributed variable to be written simply as a variable; and `dots` causes $Variable\{< module_name >: ...\}$ to be written. Finally, the value `write` causes a variables attribute to be written as a term [9]. The default behavior is set to the value `portray`.
- `max_table_subgoal_action` The action to take when a tabled subgoal of maximum depth is encountered. To understand the use of this flag, consider that if a predicate such as

  ```
  p(X):- p(f(X)).
  ```

  is tabled, it can (semantically) create subgoals of infinite depth. When the maximum subgoal depth is reached, XSB can either throw a miscellaneous error (the default action); or XSB can fail – an action that may be valid for certain programs. The action is set to fail by the value `failure` while the action of throwing an error can be (re-)set using the value `error`.
- `max_table_subgoal_depth` The maximum depth of a subgoal argument that can be added to a table: when the depth is reached, an action is taken as indicated for the previous flag. The default value is `maximum_integer`.

[9] When writing an attribute, any attributed variables in the attribute itself are written just as variables with their attributes ignored.

- `max_table_answer_action` The action to take when a tabled answer of maximum depth is encountered. To understand the use of this flag, consider the program fragment:

  ```
  :- table p/1.
  p(f(X)):- p(X).          p(a).
  ```

  is tabled, the model for the goal `?- p(X)` is infinite, so that this program will not terminate. When the maximum answer depth is reached, XSB can either

  1. Throw a miscellaneous error, set using the value `error`. This is the default action.
  2. Apply bounded rationality by abstracting the answer with a truth value of *undefined*; settable using the value `bounded_rationality`.
  3. Issue a warning, settable using the value `warning`.
  4. Fail the answer addition, an action that may be valid for certian programs, settable using the value `fail`.

  Note that this flag affects only structures that are not lists (since large lists are more common than other large structures).

- `max_table_answer_depth` The maximum depth of an answer argument that can be added to a table: when the depth is reached, an action is taken as indicated for the previous flag. The default value is `maximum_integer`.

  Note that this flag affects only structures that are not lists (since large lists are more common than other large structures).

- `max_table_answer_list_action` The action to take when a tabled answer of maximum list depth is encountered. To understand the use of this flag, consider the program fragment:

  ```
  :- table l/1.
  l([a|X]):- l(X).          l([a]).
  ```

  is tabled, the model for the goal `?- l(X)` is infinite, so that this program will not terminate. When the maximum answer list depth is reached, XSB can either throw a miscellaneous error (the default action); emit a warning; or XSB can fail – an action that may be valid for certain programs [10]. The action is set to fail by the value `failure` while the action of throwing an error can be (re-)set using the value `error`, and the action of warning is set by the value `warning`.

- `max_table_answer_list_depth` The maximum list depth of an answer argument that can be added to a table: when the depth is reached, an action is taken as indicated for the previous flag. The default value is `maximum_integer`.

  Note that this flag affects only structures that are lists (since large lists are more common than other large structures).

[10] Failure in this case can be seen as an implicit form of answer abstraction.

- `max_memory` The maximum amount of memory *in kilobytes* that an XSB thread (in the single-threaded engine) or all XSB threads (in the multi threaded engine) can use for their combined execution stacks, program space, tables, or any other purpose. If a query exceeds this amount, XSB will abort the query with a resource exception and then try to reclaim space used by the query. As with other flags, this flag can be set during an XSB session. The value of 0 effectively disables the flag, allowing XSB to allocate as much memory as the underlying OS will grant. The default value is 0, so that the flag is disabled.
- `unify_with_occurs_check` If set to `on`, perform all unification using an occurs check, which makes unification mathematically correct, but computationally complex. Without the occurs check, the unification

  $$X = f(X)$$

  will produce a cyclic term `X = f(f(f(f(...))))`; with the occurs check this unification will fail. Setting the flag to `on` may slow down programs, perhaps drastically, and may be incompatable with some constraint libraries such as CHR. An alternate to this flag is the ISO predicate `unify_with_occurs_check/2`: see Section 6.8 for further discussion. The default for this flag is `off`.
- `exception_pre_action` If set to `print_incomplete_tables`, the predicate `print_incomplete_tables/` is called *before* throwing an exception, and this information can be used to help understand the context in which the exception arose. Only exceptions that are thrown over at least one incomplete table will cause the file to be created. (Figure out about file). The default for this flag is `off`.
- `max_tab_usage` If set to `on`, maintains the maximal table usage (in bytes) for display in `statistics/[0,1]`. This information can be useful if a program performs various types of table abolishes. Setting this flag to `on` may slightly slow down computation. Defailt is `off`.

The following flags affect only the multi-threaded engine.

- `thread_glsize` In the multi-threaded engine, the initial size, in kbytes, of the global and local stack area of a newly created thread if no such option is explicitly passed. By default this is 768 (or 1536 for 64-bit configurations), or whatever was passed in if the command-line option `-m` was used, but that value may be modified at any time by resetting the flag. This flag affects a thread created by any thread in the process.
- `thread_tcpsize` In the multi-threaded engine, the initial size, in kbytes, of the trail and choice point area of a newly created thread if no such option is explicitly passed. By default this is 768 (or 1536 for 64-bit configurations), or whatever was passed in if the command-line option `-c` was used, but that value may be modified at any time by resetting the flag. This flag affects a thread created by any thread in the process.

- `thread_complsize` In the multi-threaded engine, the initial size, in kbytes, of the completion stack area of a newly created thread if no such option is explicitly passed. By default this is 64 (or 128 for 64-bit configurations), or whatever was passed in if the command-line option `-O` was used, but that value may be modified at any time by resetting the flag. This flag affects a thread created by any thread in the process.
- `thread_pdlsize` In the multi-threaded engine, the initial size, in kbytes, of the unification stack area of a newly created thread if no such option is explicitly passed. By default this is 64 (or 128 for 64-bit configurations), or whatever was passed in if the command-line option `-m` was used, but that value may be modified at any time by resetting the flag. This flag affects a thread created by any thread in the process.
- `thread_detached` In the multi-threaded engine, this specifies whether threads are to be created as detached or joinable if no explicit option is passed. A value of `true` indicates that threads are to be created as detached, and `false` as joinable. If this flag is not set, its default is `false`.
- `max_threads` In the multi-threaded engine, the maximum number of valid threads. By default this is 1024 and this value may not be reset at runtime, but it may be set by the command-line option `-max_threads`. This option is settable only by a command-line argument, and has no effect in the single-threaded engine.
- `max_queue_size` In the multi-threaded engine, the default maximum number of terms a message queue contains before writes to the message queue block. By default this is 1000. If set to 0, queues by default will be unbounded. This option has no effect in the single-threaded engine.
- `shared_predicates` In the multi-threaded engine, indicates whether predicates are considered thread-shared by default – that is, whether tables or dynamic predicates are shared among threads. By default this is false, and predicates are considered thread-private by default. This option is settable only by a command-line argument, and has no effect in the single-threaded engine.

Note that the non-standard flags are used only for dynamic XSB settings, *i.e.*, settings that might change between sessions (via command line arguments) or within the same session (via modifiable flags). For static configuration information, the predicate `xsb_configuration/2` is used. xsb_configuration/2.

Error Cases

- `Flag_Name` is neither a variable nor an atom.
  - `domain_error(atom_or_variable,Flag_Name)`

`set_prolog_flag(?Flag_Name, ?Value)` ISO

`set_prolog_flag/2` allows the user to change settable prolog flags. Currently the

only settable ISO flag is the `unknown` flag. Setting the flag `unknown` to `fail` results in calls to undefined predicates to quietly fail. Setting it to `warning` causes calls to undefined predicates to generate a warning (to `STDWARN`) and then fail. Setting it to `error` (the default) causes calls to undefined predicates to throw an existence error.

Dynamic XSB settings can also be changed, as described in `current_prolog_flag/2`.

Error Cases

- `Flag_Name` or `Value` is a variable.
  - `instantiation_error`
- `Flag_Name` is not the name of a recognized Prolog flag.
  - `domain_error(prolog_flag,Flag_Name)`

`current_predicate(?Predicate_Indicator)` ISO

`current_predicate/1` can be used to backtrack through indicators for loaded user or system predicates. If `Predicate_Indicator` unifies with `Module:F/A` all loaded predicates unifying with this indicator is returned. If `Predicate_indicator` is `F/A`, `current_predicate/1` behaves as if it were called with the form `usermod:F/A`. Unlike `current_functor/1` `current_predicate/1` does not return indicators for predicates that have been imported but not actually loaded into code space. For more detailed analysis of predicate properties, the predicate `predicate_property/2` can be used.

As an example to backtrack through all of the predicates defined and loaded in module `blah`, regardless of whether `blah` is a system or a user defined module, use:

```
| ?- current_predicate(blah:Predicate).
```

In this case `Predicate` will have the form: `Functor/Arity`.

To backtrack through all predicates defined and loaded in any current module, use:

```
| ?- current_predicate(Module:Functor/Arity).
```

This succeeds once for every predicate that is loaded in XSB's database.

To find the predicates having arity 3 that are loaded in `usermod`, use:

```
| ?- current_predicate(usermod:Functor/3).
```

while to find all predicates loaded in the global modules of the system regardless of their arity, use:

```
| ?- current_predicate(usermod:Predicate).
```

Error Cases

- `Predicate_indicator` is neither a variable nor a predicate indicator
  - `type_error(predicate_indicator,Predicate_indicator))`

ISO Compatability Note: In XSB, `current_predicate` will backtrack through system predicates as well as user predicates.

`current_module(?Module)`

The standard predicate `current_module/1` allows the user to check whether a given module is *current* or to generate (through backtracking) all currently known modules. Succeeds iff `Module` is one of the modules in the database. This includes both user modules and system modules. For more detailed analysis of module properties, the predicate `module_property/2` can be used.

Note that predicate `current_module/1` succeeds for a given module even if that module does not export any predicates. There are no error conditions associated with this predicate; if its argument does not unify with one of the current modules, `current_module/1` simply fails.

`current_module(?Module, ?ObjectFile)`

Predicate `current_module/2` gives the relationship between the modules and their associated object file names. The file name `ObjectFile` must be absolute and end with the object file extension for the system (by default, `.xwam`). It is possible for a current module to have no associated file name (as is the case for `"usermod"`), or for the system to be unable to determine the file name of a current module. In both cases, predicate `current_module/1` will succeed for this module, while `current_module/2` will fail. The system is unable to determine the file name of a given module if that module is not in one of the directories of the search path (see Section 3.6). Once again, there are no error conditions associated with this predicate; if the arguments of `current_module/2` are not correct, or `Module` has no associated `File`, the predicate will simply fail.

`current_functor(?Predicate_Indicator)`

`current_predicate/1` can be used to backtrack through indicators for all non-atomic terms occurring in loaded modules. If `Predicate_Indicator` unifies with `Module:F/A` all term indicators unifying with `F/A` in a module unifying with `Module` are returned. If `Predicate_indicator` is `F/A`, `current_predicate/1` behaves as if it were called with the form `usermod:F/A`. Unlike `current_predicate/1` `current_functor/1` returns not only structures occurring in predicates but predicates that are imported into loaded modules but are not yet themselves loaded.

As an example, to backtrack through all of the functors of positive arity (function and predicate symbols) that appear in the global modules of the system regardless of whether they are system or a user defined, use:

```
| ?- current_functor(Functor/Arity), Arity > 0.
```

There are no error conditions associated with this predicate; if its argument is not a predicate indicator the predicate simply fails.

`current_index(Functor/Arity,IndexSpec)`

XSB has a variety of ways to index dynamic predicate including alternate argument indexing, multiple argument indexing, star-indexing, and tries, as discussed in Section 6.14. In addition XSB allows a choice of which argument to index for compiled

predicates as well. `current_index/2` returns the index specification for each functor/arity pair unifying with `Functor/Arity` and visible from the calling context of `current_index/2`.

`current_atom(?Atom_Indicator)`
Generates (through backtracking) all currently known atoms, and unifies each in turn with `Atom_Indicator`.

`predicate_property(?Term_Indicator, ?Property)`
The standard predicate `predicate_property/2` can be used to find the properties of any predicate that is visible to a particular module. Succeeds iff `Term_Indicator` is a term indicator for a current predicate whose principal functor is a predicate having `Property` as one of its properties. Or procedurally, `Property` is unified with the currently known properties of the predicate having `Term_Indicator` as its skeletal specification.

A brief description of `predicate_property/2` is as follows:

- If `Term_Indicator` is not a variable, and is a structure or atom, then `Property` is successively unified with the various properties associated with `Term_Indicator`. If `Term_Indicator` is not a known to the system, the call succeeds with `Property` successively unified to `exported` and `unclassified`. These properties can be considered as a default for any structure or atom.
- If `Property` is bound to a valid predicate property, then `predicate_property/2` successively unifies `Term_Indicator` with the skeletal specifications of all predicates known to the system having the specified `Property`.
- If `Term_Indicator` is a variable, then it is unified (successively through backtracking) with the most general term for a predicate whose known properties are unified with `Property`.
- If `Term_Indicator` is not a term indicator, or if `Property` is not a valid predicate property, the call fails.

For example, all the loaded predicate skeletal specifications in module `"usermod"` may be enumerated using:

```
| ?- predicate_property(Pred, loaded).
```

Also the following query finds all predicate skeletal specifications that are exported by module `blah`:

```
| ?- predicate_property(blah:Pred, exported).
```

Currently, the following properties are associated with predicates either implicitly or by declaration. Double lines show property categories, and a predicate can have at most one property of each category.

- *Execition Type* which is one of

  - unclassified The predicate symbol is not yet classified according to this category. This property has various meanings. Usually for exported predicate symbols in system or user defined modules it means that the predicate is yet unloaded (because it has not been used). In `usermod` it usually means that the predicate is either a function symbol, or an unloaded predicate symbol (including constants).
  - dynamic The predicate is dynamic.
  - `loaded` The predicate (including internal predicates) is a Prolog predicate loaded into the module in question; this is always the case for predicates in `usermod`.
  - `unloaded` The predicate is yet unloaded into the module in question.
  - `foreign` The predicate is a foreign predicate. This implies that the predicate is already loaded in the system, because currently there is no way for XSB to know that a predicate is a foreign predicate until it is loaded in the system.
- *Visibility Type* which can be one of
  - `exported` The predicate symbol is exported by the module in question; in other words the predicate symbol is visible to any other module in the system.
  - `local` The predicate symbol is local to the module in question.
  - `imported_from(Mod)` The predicate symbol is imported into the module in question from module `Mod`.
- *Tabling Call Behavior* which can be one of
  - `tabled(variant)` The predicate has been declared tabled and to use call variance.
  - `tabled(subsumptive)` The predicate has been declared tabled and to use call subsumption
  - `tabled(default)` The predicate has been declared tabled and to use the default tabling strategy of the session, which can be either call variance or call subsumption.
- *Incremental Tabling Behavior* which can be one of
  - `incremental` The predicate was declared as either incremental dynamic or as incremental tabled; or
  - `opaque` The predicate was declared as opaque to incremental updates.
- `spied` The predicate symbol has been declared spied (either conditionally or unconditionally).
- `shared` The predicate has been declared shared in the multi-threaded engine. This means that any dynamic code or tables for this predicate will be shared among threads, but it does not affect static, non-tabled code.
- `built_in` The predicate symbol has the same Functor and Arity as one of XSB's standard predicates, and is available tothe user without needing to load a file or import th epredicate from a module.

- `meta_predicate(Template)` The predicate is a meta-predicate. This property provides compatibility with other Prolog compilers and with forthcoming ISO Prolog standards.

Finally, since `dynamic` is usually declared as an operator with precedence greater than 999, writing the following:

```
| ?- predicate_property(X, dynamic).
```

will cause a syntax error. The way to achieve the desired result is to parenthesize the operator like in:

```
| ?- predicate_property(X, (dynamic)).
```

`module_property(?Module, ?Property)`

The standard predicate `module_property/2` can be used to find the properties of any current module. Succeeds iff `Module` is the name of a current module having `Property` as one of its properties. Or procedurally, `Property` is unified with the currently known properties of the module having `Module` as its name.

Currently, the following properties are associated with modules implicitly

Property	*Explanation*
`unloaded`	The module (including system modules) though it is current, is yet unloaded in the system.
`loaded`	The module (including system modules) is loaded in the system; this is always the case for `usermod`.

`listing`

Lists in the current output stream the clauses for all dynamic predicates found in module `usermod`. Note that `listing/0` does not list any compiled predicates unless they have the `dynamic` property (see `predicate_property/2`). A predicate gets the `dynamic` property when it is explicitly declared as `dynamic`, or automatically acquires it when some clauses for that predicate are asserted in the database. In cases where a predicate was compiled but converted to `dynamic` by asserting additional clauses for that predicate, `listing/0` will just display an indication that there exist compiled clauses for that predicate and only the dynamically created clauses of the predicate will be listed. For example:

```
| ?- [user].
[Compiling user]
a(X) :- b(X).
a(1).
[user compiled, cpu time used:  0.3 seconds]
[user loaded]

yes
| ?- assert(a(3)).

yes
| ?- listing.

a(A) :-
      $compiled.
a(3).

yes
```

Predicate `listing/0` always succeeds. The query:

```
| ?- listing.
```

is just a notational shorthand for the query:

```
| ?- listing(X).
```

`listing(+Predicate_Indicator)`

If `Predicate_Indicator` is a variable then `listing/1` is equivalent to `listing/0`. If `Predicate_Indicator` is an atom, then `listing/1` lists the dynamic clauses for all predicates of that name found in module `usermod` of the database. The argument `Predicate_Indicator` can also be a predicate indicator of the form `Name/Arity` in which case only the clauses for the specified predicate are listed. Finally, it is possible for `Predicate_Indicator` to be a list of predicate indicators and/or atoms; e.g.

```
| ?- listing([foo/2, bar, blah/4]).
```

If `Predicate_Indicator` is not a variable, an atom or a predicate indicator (or list of predicate indicators) of the form `Name/Arity`, predicate `listing/1` will simply fail.

In future releases of XSB, we intend to allow the user to specify a predicate indicator of the form `Module:Name/Arity` as argument of `listing/1`.

`xsb_configuration(Feature_Name, ?Value)`

Succeeds iff the current value of the XSB feature `Feature_Name` is `Value`.

This predicate provides information on a wide variety of features related to how XSB was built, including the compiler used, the compiler and loader flags, the machine

and OS on which XSB was built, the release number, the various directories that XSB uses to find its libraries, etc.

To find all features and their values, ask the following query:

```
| ?- xsb_configuration(FeatureName, Value), fail.
```

Here is how `xsb_configuration` might look like:

```
xsb_configuration(architecture, 'i386-apple-darwin8.9.1').
%% configuration is usualy the same as architecture, but it can also
%% contain special tags, {\it e.g.}, i386-apple-darwin8.9.1-dbg, for a verion
%% built with debugging enabled.
xsb_configuration(configuration, 'i386-apple-darwin8.9.1-dbg').
xsb_configuration(host_os, 'darwin8.9.1').
xsb_configuration(os_version, '8.9.1').
xsb_configuration(os_type, 'darwin').
xsb_configuration(host_vendor, 'apple').
xsb_configuration(host_cpu,  'i386').
xsb_configuration(compiler, 'gcc').
xsb_configuration(compiler_flags, '-faltivec -fPOC -Wall -pipe -g').
xsb_configuration(loader_flags, '-g -lm ').
xsb_configuration(compile_mode, 'debug').
%% The type of XSB engine configured.
xsb_configuration(scheduling_strategy, '(local)').
xsb_configuration(engine_mode, 'slg-wam').
xsb_configuration(word_size, '32').
%% The following is XSB release information
xsb_configuration(major_version, '3').
xsb_configuration(minor_version, '3').
xsb_configuration(patch_version, '1').
xsb_configuration(beta_version, '').
xsb_configuration(version, '3.3.1').
xsb_configuration(codename, 'Pignoletto').
xsb_configuration(release_date, date(2011, 04, 12)).
%% Support for other languages
xsb_configuration(perl_support, 'yes').v
xsb_configuration(perl_archlib, '/usr/lib/perl5/i386-linux/5.00404').
xsb_configuration(perl_cc_compiler, 'cc').
xsb_configuration(perl_ccflags, '-Dbool=char -DHAS_BOOL -I/usr/local/include').
xsb_configuration(perl_libs, '-lnsl -lndbm -lgdbm -ldb -ldl -lm -lc -lposix -lcrypt').
xsb_configuration(javac, '/usr/bin/javac').
/* Tells where XSB is currently residing; can be moved */
xsb_configuration(install_dir, InstallDir) :- ...
/* User home directory. Usually HOME. If that is null, then it would
   be the directory where XSB is currently residing.
   This is where we expect to find the .xsb directory */
xsb_configuration(user_home, Home) :- ...
/* Where XSB invocation script is residing */
```

```
xsb_configuration(scriptdir, ScriptDir) :- ...
/* where are cmplib, syslib, lib, packages, etc live */
xsb_configuration(cmplibdir, CmplibDir) :- ...
xsb_configuration(libdir, LibDir) :- ...
xsb_configuration(syslibdir, SyslibDir) :- ...
xsb_configuration(packagesdir, PackDir) :-  ...
xsb_configuration(etcdir, EtcDir) :- ...
/* architecture and configuration specific directories */
xsb_configuration(config_dir, ConfigDir) :- ...
xsb_configuration(config_libdir, ConfigLibdir) :- ...
/* site-specific directories */
xsb_configuration(site_dir, '/usr/local/XSB/site').
xsb_configuration(site_libdir, SiteLibdir) :- ...
/* site and configuration-specific directories */
xsb_configuration(site_config_dir, SiteConfigDir) :- ...
xsb_configuration(site_config_libdir, SiteConfigLibdir) :- ...
/* Where user's arch-specific libraries are found by default. */
xsb_configuration(user_config_libdir, UserConfigLibdir) :- ...
```

`hilog_symbol(?Symbol)`

Succeeds iff `Symbol` has been declared as a HiLog symbol, or procedurally unifies `Symbol` with one of the currently known (because of a prior declaration) HiLog symbols. The HiLog symbols are always atoms, but if the argument of `hilog_symbol`, though instantiated, is not an atom the predicate simply fails. So, one can enumerate all the HiLog symbols by using the following query:

```
| ?- hilog_symbol(X).
```

`current_op(?Precedence, ?Specifier, ?Name)` ISO

This predicate is used to examine the set of operators currently in force. It succeeds when the atom `Name` is currently an operator of type `Specifier` and precedence `Precedence`. None of the arguments of `current_op/3` need to be instantiated at the time of the call, but if they are, they must be of the following types:

`Precedence` must be an integer in the range from 1 to 1200.

`Specifier` must be one of the atoms:

```
xfx xfy yfx fx fy hx hy xf yf
```

`Name` it must be an atom.

Error Cases

- `Precedence` is neither a variable nor an integer in the range from 1 to 1200.
  - `domain_error(operator_priority,Precedence)`
- `Specifier` is neither a variable nor an operator specifier of the types above.

  - `domain_error(operator_specifier,Specifier)`
- `Name` is neither a variable nor an atom.
  - `domain_error(atom_or_variable,Name)`

`hilog_op(?Precedence, ?Type, ?Name)`

This predicate has exactly the same behaviour as `current_op/3` with the only difference that `Type` can only have the values `hx` and `hy`.

6.13 Execution State

`break`

Causes the current execution to be suspended at the beginning of the next call. The interpreter then enters break level 1 and is ready to accept input as if it were at top level. If another call to `break/0` is encountered, it moves up to break level 2, and so on. While execution is done at break level $n > 0$ the prompt changes to n: `?-`.

To close a break level and resume the suspended execution, the user can type the the atom `end_of_file` or the end-of-file character applicable on the system (usually `CTRL-d` on UNIX systems). Predicate `break/0` then succeeds (note in the following example that the calls to `break/0` do not succeed), and the execution of the interrupted program is resumed. Alternatively, the suspended execution can be abandoned by calling the standard predicate `abort/0`, which causes a return to the top level.

An example of `break/0` 's use is the following:

```
| ?- break.
[ Break (level 1) ]
1:  ?- break.
[ Break (level 2) ]
2:  ?- end_of_file.
[ End break (level 2) ]

yes
1:  ?-
```

Entering a break closes all incomplete tables (those which may not have a complete set of answers). Closed tables are unaffected, even if the tables were created during the computation for which the break was entered.

`halt` ISO

halt/0 Exits the XSB session regardless of the break level. On exiting the system cpu and elapsed time information is displayed.

`halt(Code)` ISO

halt/1 Exits the XSB session regardless of the break level, sending the integer `Code`

to the parent process. Normally `0` is considered to indicate normal termination, while other exit codes are used to report various degrees of abnormality.

Error Cases

- `Code` is not an integer
  - `type_error(Integer,Code)`

`prompt(+NewPrompt, ?OldPrompt)`

Sets the prompt of the top level interpreter to `NewPrompt` and returns the old prompt in `OldPrompt`.

An example of `prompt/2` 's use is the following:

```
| ?- prompt('Yes master > ', P).

P = | ?- ;

no
Yes master > fail.

no
Yes master >
```

`trimcore` module: `machine`

A call to `trimcore/0` reallocates an XSB thread's execution stacks (and some tabling stacks) to their initial allocation size, the action affecting only the memory areas for the calling thread. When XSB is called in standalone or server mode, `trimcore/0` is automatically called when the top interpreter level is reached. When XSB is embedded in a process, `trimcore/0` is called at the top interpreter level for any thread created through xsb_ccall_thread_create() (see Volume 2, Chapter 3 *Embedding XSB in a Process*).

`gc_heap`

Explicitly invokes the garbage collector for a thread's heap. By default, heap garbage collection is called automatically for each thread upon stack expansion, unless the Prolog flag `heap_garbage_collection` is set to `none`. Automatic heap garbage collection should rarely need to be turned off, and should rarely need to be invoked manually.

`statistics`

Displays usage information on the current output stream, including:

- Process-level information about allocated memory excluding execution stacks but including:
  - `atoms` Space used to maintain global information about predicates and structures.

  - `string` Space used to maintain information about atomic constants in XSB.
  - `asserted` Space allocated for dynamic code.
  - `asserted` Space allocated for static code.
  - `foreign` Space allocated for foreign predicates.
  - `table` Space allocated for XSB's tables.
  - `findall` Space allocated for buffers to support `findall/3` and similar predicates.
  - `mt-private` Private space used by threads.
  - `profiling` Space used to maintain profiling information, if XSB is called with profiling on.
  - `gc temp` Temporary space for used for heap garbage collector.
  - `interprolog` space allocated for the Interprolog XSB/Java interface.
  - `thread` space allocated for the thread table
  - the space occupied by subgoal and answer tables (in the form of tries) [57, 18, 36]. In the multi-threaded configuration process level table space includes shared tables but not private tables.

- Thread-specific information about allocation of memory for the calling thread including the
  - Global stack (heap) and local (environment) stack (see e.g. [1]) for the calling thread. Memory for these two WAM stacks is allocated as a single unit so that each stack grows together; information is provided on the current allocation for the stacks as well as on the stack sizes themselves. (See Section 3.7 for the memory re-allocation algorithm).
  - Trail and choice point stack (see e.g. [1]) for the calling thread. Memory for these two WAM stacks is allocated as a single unit so that each stack grows together; information is provided on the current allocation for the stacks as well as on the stack sizes themselves. The (re-)allocation follows the algorithm sketched in Section 3.7). (See Section 3.7 for the memory re-allocation algorithm).
  - SLG unification stack for the calling thread This stack is used as a space to copy terms from the execution stacks into table space, or back out. This stack will not be reallocated unless extremely large terms are tabled.
  - SLG completion stack for the calling thread. The completion stack is used to perform incremental completion for sets of mutually dependent tabled subgoals. One completion stack frame is allocated per tabled subgoal [60] but the size of these frames is version-dependent.
  - the space occupied by private subgoal and answer tables for the calling thread.

  In XSB's single-threaded configuration, maximum space used by each of will be output if the `'-s'` command-line option is used

- Information about the number of tabling operations performed in the session by any thread. Note that the statistics are divided up between calls to predicates that use variant tabling and those that use (call) subsumptive tabling (see Section 5.2.1 and [36]).
  - Call Subsumption Subgoal Operations. For predicates that use subsumptive tabling, the total number of subsumptive subgoal calls is given, as is the number of new calls (`producers`) and the number of repeated calls to non-completed tables (`variants`). Furthermore, the number of properly subsumed calls to incomplete tables is given, along with the number of subsumed calls to completed tables. Finally, the total number of subsumptive table entries overall is given, including all producer and consumer calls.
  - Call Subsumption Answer Operations. In call subsumptive tabling, answer lists are copied from producer subgoals to subsumed consumer subgoals (this operation is not required in variant tabling). The number of `answer ident` operations represents the number of times this copy is done. In addition, the number of consumptions performed by all consuming subsumptive table entries is also given.
  - Call Variance Subgoal Operations. For call variance the number of subgoal check/insert operations is given along with the unique number of subgoals encountered (`generator`) and the number of redundant consumer encountered (`consumer`).
  - Total Answer Operations. For both variant and subsumptive tables, the number of answer check insert operations is given along with the number of answers actually inserted into the table and the number of redundant answers derived.
- Garbage Collection Information. Time spent garbage collecting by the calling thread and number of heap cells collected.
- Information about process CPU and clock time, as well as the number of active threads.

As mentioned above, if XSB is configured with the single-threaded engine and is invoked with the `'-s'` option (see Section 3.7), additional information is printed out about maximum use of each execution stack and table space. However, the `'-s'` option can substantially slow down the emulator so benchmarks of time should be performed separately from benchmarks of space.

Example: The following printout shows how the `statistics/0` output looks if it is invoked with the `'-s'` option (without it the `Maximum stack used`, and `Maximum table space used` lines are not shown). Information about the allocation size is provided since the sizes can be changed through emulator options (see Section 3.7).

```
| ?- statistics.
```

```
Memory (total)         2429504 bytes:       726696 in use,      1702808 free
  permanent space       645520 bytes:       645520 in use,            0 free
    atom                                    120328
    string                                  156872
    asserted                                  3184
    compiled                                358216
    other                                     6920
  glob/loc space        786432 bytes:          652 in use,       785780 free
    global                                     456 bytes
    local                                      196 bytes
  trail/cp space        786432 bytes:          476 in use,       785956 free
    trail                                       88 bytes
    choice point                               388 bytes
  SLG unific. space      65536 bytes:            0 in use,        65536 free
  SLG completion         65536 bytes:            0 in use,        65536 free
  SLG table space        80048 bytes:        80048 in use,            0 free

  Maximum stack used: global 436724, local 14780, trail 27304, cp 20292,
                      SLG completion 0 (0 subgoals)
  Maximum table space used:  0 bytes

Tabling Operations
  0 subsumptive call check/insert ops: 0 producers, 0 variants,
  0 properly subsumed (0 table entries), 0 used completed table.
  0 relevant answer ident ops.  0 consumptions via answer list.
  0 variant call check/insert ops: 0 producers, 0 variants.
  0 answer check/insert ops: 0 unique inserts, 0 redundant.


   0 heap (  0 string) garbage collections by copying: collected 0 cells in 0.000000 secs

Time: 0.190 sec. cputime,  13.921 sec. elapsetime
```

`statistics(+Key)`

`statistics/1` allows the user to output detailed statistical information about the atom and symbol tables, as well as about table space. The following calls to `statistics/1` are supported:

- `statistics(reset)` Resets the CPU time as well as counts for various tabling operations.
- `statistics(atom)` Outputs statistics about both the atom and symbol tables. An example is:

```
| ?- statistics(atom).

Symbol table statistics:
------------------------
Table Size: 8191
Total Symbols: 1188
            used buckets:              1088  (range: [0, 8174])
            unused buckets:            7103
```

```
            maximum bucket size:       3  (#: 18)

String table statistics:
------------------------
Table Size: 16381
Total Strings: 1702
            used buckets:              1598  (range: [0, 16373])
            unused buckets:            14783
            maximum bucket size:       3  (#: 2318)
```

- `statistics(table)` Outputs *very* detailed statistics about table space, including breakdowns into variant and subsumptive call- and answer- trie nodes and hash tables; answer return list nodes, and structures for conditional answers (cf. [60, 57, 36, 17]). In the multi-threaded engine, these data structures are reported both for shared tables and for private tables of the calling thread.

  While this option is intended primarily for developers, it can also provide valuable information for the serious user of tabling.

Error Cases

- `Key` not a valid atom for input to `statistics/1`
  - `domain_error(statisticsInputDomain,Key))`

`statistics(?Key,-Result)`

`statistics/2` allows a user to determine information about resources used by XSB. Currently `statistics/2` unifies `Key` with

- `runtime`, which instantiates `Result` to the structure `[TotalCPU,IncrCPU]` where `TotalCPU` is the total (process-level) CPU time at the time of call, and `IncrCPU` is the CPU time taken since the last call to `statistics/2`. Times are measured in seconds. The process-level CPU time includes time taken for system calls, as well as time taken for garbage collection and stack-shifting. Note that in the multi-threaded engine, `statistics/2` measures the time for all threads.
- `walltime`, which instantiates `Result` to the list `[TotalTime,IncrTime]` where `TotalTime` is the total elapsed time at the time of call, and `IncrTime` is the elapsed time taken since the last call to `statistics/2`. Times are measured in seconds.
- `tablespace` which instantiates `Result` to the list `[Alloc,Used]`. In the single-threaded engine, `Alloc` is the total table space allocated and `Used` is the total table space used, both in bytes. In the multi-threaded engine, both refer to table space *private* to the calling thread.
- `shared_tablespace` which instantiates `Result` to the list `[Alloc,Used]`. In the multi-threaded engine, `Alloc` is the total space allocated for *shared* tables and `Used` is the total table space used, both in bytes. An error is thrown if this option is called by the single-threaded engine.

- `gl` which instantiates `Result` to the list `[Alloc,Used]`, where `Alloc` is the total number of bytes allocated for XSB's combined heap and local (environment) stack, while `Used` is the approximate number of bytes used by both of these stacks. In the multi-threaded engine, these numbers refer only to the stacks of the calling thread.
- `tc` which instantiates `Result` to the list `[Alloc,Used]`, where `Alloc` is the total number of bytes allocated for XSB's combined trail and choice point stack while `Used` is the number of bytes used by both of these stacks. In the multi-threaded engine, these numbers refer only to the stacks of the calling thread.
- `heap` which instantiates `Result` to the total number of bytes used by XSB's heap. In the multi-threaded engine, the number refers only to the heap of the calling thread.
- `local` which instantiates `Result` to the total number of bytes used by XSB's local (environment) stack. In the multi-threaded engine, the number refers only to the local stack of the calling thread.
- `trail` which instantiates `Result` to the total number of bytes used by XSB's trail stack. In the multi-threaded engine, the number refers only to the trail stack of the calling thread.
- `choice_point` which instantiates `Result` to the total number of bytes used by XSB's choice point stack. In the multi-threaded engine, the number refers only to the choice point stack of the calling thread.
- `open_tables` which instantiates `Result` to the number of uncompleted tables in XSB's completion stack. In the multi-threaded engine, this number refers to the completion stack of the calling thread, which may contain both thread-private and thread-shared tables.
- `atoms` which instantiates `Result` to the number of bytes taken by atoms in the atom table.

Example An example of using `statistics/2` to check CPU time is as follows:

```
?- statistics(runtime,[BeforeCumu,BeforeIncr]),spin(100000000),
   statistics(runtime,[AfterCumu,AfterIncr]).

BeforeCumu = 5.0167
BeforeIncr = 5.0167
AfterCumu = 9.6498
AfterIncr = 4.6331
```

Note that `statistics/2` can provide either cumulative or incremental times; here

$$AfterCumu - BeforeCumu = AfterIncr$$

Checking wall time is done similarly.

```
?- statistics(walltime,Before),sleep(1),statistics(walltime,After).

Before = [35.0651,35.0651]
After = [36.0652,1.0001]
```

Error Cases

- `Key` not a valid atom for input to `statistics/1`
  - `domain_error(statisticsInputDomain,Key))`

`time(+Goal)`

Prints both the CPU time and wall time taken by the execution of `Goal`. Any choicepoints of `Goal` are discarded. The definition of predicate is based on the SWI-Prolog definition (minus reporting the number of inferences, which XSB does not currently support). This predicate is also found on other Prolog compilers such as YAP.

6.14 Asserting, Retracting, and Other Database Modifications

XSB provides an array of features for modifying the dynamic database. As a default, using `assert/1`, clauses can be asserted using first-argument indexing in a manner that is now standard to Prolog implementations. However, a variety of other behaviors can be specified using the (executable) directives `index/3` and `index/2`. For instance, dynamic clauses can be declared to have multiple or joint indexes, and this indexing can be either hash-based as is typical in Prolog systems or based on *tries*. No matter what kind of indexing is used, space is dynamically allocated when a new clause is asserted and, unless specified otherwise, released after it is retracted. Furthermore, the size of any index table expands dynamically as clauses are asserted.

All dynamic predicates are compiled into SLG-WAM code, however the manner of their compilation may differ, and the differences in compilation affect the semantics for the predicate. If a dynamic predicate P/n is given an indexing directive of `trie`, clauses for P/n will be compiled using trie instructions; otherwise clauses for P/n will be compiled into SLG-WAM instructions along the lines of static predicates.

Consider first dynamic predicates that use any indexing other than `trie` – including multiple or joint indices and star indexing. XSB asserts WAM code for such clauses so that that the execution time of dynamic code is similar to compiled code for unit and binary clauses. Furthermore, tabling can be used by explicitly declaring a predicate to be both dynamic and tabled. In Version 3.3, when the clause of a dynamic predicate is asserted as WAM code, the *"immediate semantics"* rather than the ISO Semantics of assert/retract [45]. The immediate semantics allows assert and retract to be fast and spatially efficient, but

requires that significant care must be taken when modifying the definition of a predicate which is currently being executed.

If a dynamic predicate is given an indexing directive of `trie`, clauses of the predicate are compiled (upon a call `assert/1`) using trie instructions as described in [57]. Creation of trie-based dynamic code is significantly faster than creation of other dynamic code, and execution time may also be faster. However, trie-based predicates can only be used for unit clauses where a relation is viewed as a set, and where the order of the facts is not important.

XSB does not at this time fully support dynamic predicates defined within compiled code. The only way to generate dynamic code is by explicitly asserting it, or by using the standard predicate `load_dyn/1` to read clauses from a file and assert them (see the section *Asserting Dynamic Code* in Volume 2). There is a `dynamic/1` predicate (see page 235) that declares a predicate within the system so that if the predicate is called when no clauses are presently defining it, the call will quietly fail instead of issuing an "Undefined predicate" error message.

`asserta(+Clause)` ISO

If the index specification for the predicate is not `trie`, this predicate adds a dynamic clause, `Clause`, to the database *before* any other clauses for the same predicate currently in the database. If the index specification for the predicate is `trie`, the clause is asserted arbitrarily within the trie, and a warning message sent to `stderr`.

Note that because of the precedence of `:-/2`, asserting a clause containing this operator requires an extra set of parentheses: `assert((Head :- Body))`.

Error Cases

- `Clause` is not instantiated
  - `instantiation_error`
- `Clause` is not a callable clause.
  - `domain_error(callable,Clause)`
- `Clause` has a head that is a static built-in
  - `permission_error(modify,builtin,Clause)`
- `Clause` has a head that is a static user predicate
  - `permission_error(modify,static,Clause)`

`assertz(+Clause)` ISO

If the index specification for the predicate is not `trie`, this predicate adds a dynamic clause, `Clause`, to the database *after* any other clauses for the same predicate currently in the database. If the index specification for the predicate is `trie`, the clause is asserted arbitrarily within the trie, and a warning message sent to `stderr`. Error cases are as with `asserta/1`.

Note that because of the precedence of `:-/2`, asserting a clause containing this operator requires an extra set of parentheses: `assert((Head :- Body))`.

`assert(+Clause)` ISO

If the index specification for the predicate is not `trie`, this predicate adds a dynamic clause, `Clause`, to the database *after* any other clauses for the same predicate currently in the database (acting as `assertz/1`). If the index specification for the predicate is `trie`, the clause is asserted arbitrarily within the trie. Error cases are as with `assertz/1`.

Note that because of the precedence of `:-/2`, asserting a clause containing this operator requires an extra set of parentheses: `assert((Head :- Body))`.

`assert(+Clause,+AorZandVar,+Index)`

This is a lower-level interface to (non-trie-indexed) assert. It is normally not needed except in one particular situation, when assert aborts because it needs too many registers. In this case, this lower-level assert may allow the offending clause to be correctly asserted.

The default implementation of non-trie-indexed assert generates code with a single pass through the asserted term. Because of this, it cannot know when it has encountered the final occurrence of a variable, and thus it can never release (and thus re-use) registers that are used to refer to variables. Since there is a limit of 255 registers in the XSB virtual machine, asserting a clause with more than this many distinct variables results in an error. There is an alternative implementation of assert that initially traverses the clause to determine the number of occurrences of each variable and thus allows better use of registers during code generation.

`Clause` is the clause to assert. `AorZandVar` is an integer whose lower 2 bits are used: The low-order bit is 0 if the clause is to be added as the first clause, and 1 if it is to be added as the last clause. If the second bit (2) is on, then the clause is traversed to count variable occurrences and so improve register allocation for variables; if it is 0, the default one-pass code-generation is done. So, for example, if `AorZandVar` is 3, then the clause will be asserted as the last one in the predicate and the better register allocation will be used. `Index` indicates the argument(s) on which to index.

`retract(+Clause)` ISO

Removes through backtracking all clauses in the database that match with `Clause`. `Clause` must be of one of the forms: `Head` or `Head :- Body`. Note, that because of the precedence of `:-/2`, using the second form requires an extra set of parentheses: `retract((Head :- Body))`.

The technical details on space reclamation are as follows. When retract is called, a check is made to determine whether it is safe to reclaim space for that clause. Safety is ensured when:

- A check is made of the choice point stack indicating that no choice point will backtrack into space that is being reclaimed; AND
  - The predicate is thread-private; OR
  - there is a single active thread
- AND if the predicate is tabled, there is no incomplete table for that predicate.

If it is safe to reclaim space for the clause, space is reclaimed immediately. Otherwise the clause is marked so that its space may later be reclaimed through garbage collection. (See `gc_dynamic/1`).

Error Cases

- `Clause` is not instantiated
  - `instantiation_error`
- `Clause` is not a callable clause.
  - `domain_error(callable,Clause)`
- `Clause` has a head that is a static built-in
  - `permission_error(modify,builtin,Clause)`
- `Clause` has a head that is a static user predicate
  - `permission_error(modify,static,Clause)`

`retractall(+Head)`

removes every clause in the database whose head matches with `Head`. The predicate whose clauses have been retracted retains the `dynamic` property (contrast this behavior with that of predicates `abolish/[1,2]` below). Predicate `retractall/1` is determinate and always succeeds. The term `Head` is not further instantiated by this call. Conditions for space reclamation and error cases are as with `retract/1`.

`abolish(+PredSpec)` ISO

Removes all information about the specified predicate. `PredSpec` is of the form `Pred/Arity`. Everything about the abolished predicate is completely forgotten by the system (including the `dynamic or static` property, whether the predicate is tabled, and whether the predicate is thread-shared or thread-private) [11]. Any completed tables for the predicate are also removed.

It is an error to abolish a predicate when there is more than 1 active thread, regardless of whether the predicate is thread-private or thread-shared. The reason for this is that, even if `PredInd` denotes a thread-private predicate, one thread may be making use of `PredInd` as another thread abolishes it. `abolish/1` throws an error in such a case to prevent such a semantic inconsistency. Similarly, if there is a non-completed table for `PredInd`, an error is thrown to prevent incompleteness in the tabled computation.

[11] For compatibility with older Prologs, there is also an `abolish/2` which takes `Pred` and `Arity` as its two arguments.

ISO Compatability Note: Version 3.3 of XSB allows static predicates to be abolished and their space reclaimed. Such space is reclaimed immediately, and unlike the case for abolished static code, no check is made to ensure that XSB's choice point stack is free of choice points for the abolished static predicate. Abolishing static code is thus dangerous and should be avoided unless a user is certain it is safe to use.

Error Cases

- `PredInd`, `Pred` or `Arity` is not instantiated
  - `instantiation_error`
- `Arity` is not in the range 0..255 (`max_arity`)
  - `domain_error(arity_indicator,Arity)`
- `PredInd` indicates a static built-in
  - `permission_error(modify,builtin,Predind)`
- `abolish/1` is called when there is more than 1 active thread.
  - `misc_error`
- `PredInd` has a non-completed table in the current thread.
  - `table_error`
- There are active backtrack points to a (dynamic) clause for `PredInd` [12].
  - `misc_error`

`clause(+Head,?Body)` ISO

Returns through backtracking all dynamic clauses in the database whose head matches `Head` and Body matches `Body`. For facts the `Body` is `true`. `clause/2` works properly for all dynamically *asserted* clauses, even if they are trie-indexed; however `clause/2` does not access trie-inserted terms. In the multi-threaded engine, when a thread T calls `clause/2` it accesses both thread-shared dynamic code and thread-private dynamic code for T.

Error Cases

- `Head` is not instantiated
  - `instantiation_error`
- `Head` (or `Body`) is not a callable clause.
  - `domain_error(callable,Head)`
- `Head` is a static built-in
  - `permission_error(access,builtin,Head)`

[12] XSB throws an error in this case because garbage collection for abolished predicates has not been implemented (unlike for retract(all) and various table abolishes). Besides, you shouldn't be abolishing a predicate that you could backtrack into. What were you thinking?

- `Head` is a static user predicate
  - `permission_error(access,static,Clause)`

`gc_dynamic(-N)`

Invokes the garbage collector for dynamic clauses that have been retracted, or whose predicate has been abolished. When called with more than 1 active thread, `gc_dynamic/1` will always perform garbage collection for that thread's private retracted clauses; however in Version 3.3, it will only perform garbage collection for retracted thread-shared clauses if there is a single active thread. `N` is the number or shared and/or private frames left to be collected – if `N` is unified to 0, then all possible garbage collecting has been performed. `N` is unified to -1 garbage collection was not attempted (due to multiple active threads).

By default, `gc_dynamic/1` is called automatically at the top level of the XSB interpreter, when abolishing a predicate, and when calling retractall for an "open" term containing no variable bindings.

`index(+PredSpec, +IndexSpec)`

In `index(PredSpec, IndexSpec)`, `PredSpec` is a predicate indicator or term indicator, and `IndexSpec` is a form of index specification as described below.

In general, XSB supports hash-based indexing on various arguments of clauses, on combinations of arguments, as well as within the arguments of a clause. The availability of various kinds of indexing depends on whether code is static (e.g. compiled) or dynamic (e.g. asserted, loaded with `load_dyn/1` and so on). Index directives can be given to the compiler as part of source code or executed during program execution (analogously to `op/3`). When executed during program execution, `index/2` does *not* re-index an already existing predicate; however for dynamic predicates `index/2` does affect the index for clauses asserted after the directive has been given.

- *Hash-based Indexing*
  - *Static Predicates* In this case `IndexSpec` must be a non-negative integer which indicates the argument on which an index is to be constructed. If `IndexSpec` is 0, then no index is kept (possibly an efficient strategy for predicates with only one or two clauses.)
  - *Dynamic Predicates* For a dynamic predicate, (to which no clauses have yet been asserted), a wide variety of indexing techniques are possible. We discuss their syntax first, and then their semantics. For dynamic predicates then, `IndexSpec` can be either an *indexing element* or a list of indexing elements. Each indexing element defines a separate index and specifies an argument or group of arguments that make up the search key of that index. Thus an indexing element consists of one or more *argument indicators* joined together by `+/2`. An argument indicator is may be an integer (`ArgNo`) indicating an

argument number (starting from 1) to use in the index, or it may have the form `*(ArgNo)`.

If `ArgNo` is an integer, only the main functor symbol of argument `ArgNo` will participate in the index. When annotated with the asterisk, the first 5 fields of argument `ArgNo` (in a depth-first traversal of the term) will be used in the index. If there are fewer than 5, they all will be used. If any of the first 5 is a variable, then the index cannot be used.

An index is usually on a single argument, in which case the indexing element consists of a single argument indicator. If an indexing element contains more than one argument specifier, then a joint index is specified i.e. an index will be constructed so that the values of each argument indicator are to be concatenated to create the search key of the index.

Examples help clarify this. `index(p/3,[2,1])` indicates that clauses asserted for the predicate `p/3` should be indexed on both the second and the first argument. A query Q to `p/3` will first use the second argument index to `p/3` if the second argument of Q is non-variable, and will use the main functor of the second argument. Otherwise, if the second argument of Q is a variable, but not the first argument, the first argument index of `p/3` will be used. If both arguments in Q are variables, no index will be used and Q will backtrack through all clauses for `p/3`.

`index(p/3,[*(2),1])` would result in similar behavior as the previous example, but the first index to be tried (on the second argument) would be built using more of the term value in that second argument position (not just the main functor symbol.)

As another example, one could specify: `index(p/5,[1+2,1,4])`. After clauses are asserted to it, a call to `p/5` would first check to see if both the first and second arguments are non-variable and if so, use an index based on both those values. Otherwise, it would see if the first argument is non-variable and if so, use an index based on it. Otherwise, it would see if the fourth argument is non-variable and if so use an index based on it. As a last resort, it would use no index but backtrack through all the clauses in the predicate. In each of these cases, the indexes are built using only the main functor symbol in the indicated argument position. (Notice that it may well make sense to include an argument that appears in a joint specification later alone, as 1 in this example, but it never makes sense forcing the single argument to appear earlier. In that case the joint index would never be used.)

If we want to use similar indexing on `p/5` of the previous example, except say argument 1 takes on complex term values and we want to index on more of those terms, we might specify the index as `index(p/5,[*(1)+2,*(1),4])`.

- *Trie-based Indexing* If `Predspec` is dynamic, the executable directive `index(Predspec,trie)` causes clauses for `Predspec` to be asserted using tries (see [57], which is available

through the XSB web page). The name trie indexing is something of a misnomer since the trie itself both indexes the term and represents it. In XSB, a trie index is formed using a left-to-right traversal of the unit clauses. These indexes can be very effective if discriminating information lies deep within a term, and if there is sharing of left-prefixes of a term, trie indexing can reduce the space needed to represent terms. Furthermore, asserting a unit clause as a trie is much faster than asserting it using default WAM code. Despite these advantages, representing terms as tries leads to semantic differences from asserted code, of which the user should be aware. First, the order of clauses within a trie is arbitrary: using `asserta/1` or `assertz` for a predicate currently using trie indexing will give the same behavior as using `assert`. Also, the current version of XSB only allows trie indexing for unit clauses.

If in doubt what indexing is being used for a predicate, a call to `current_index/2` can be made.

Error Cases

- `PredSpec` or `IndexSpec` is a variable
  - `instantiation_error`
- `PredSpec` is neither a variable, a predicate indicator, nor a callable term.
  - `type_error(predicate_indicator_or_callable,PredSpec)`
- `IndexSpec` is not ground
  - `instantiation_error`
- `IndexSpec` is neither a properly formed indexing element nor a list of indexing elements
  - `domain_error(indexing_element,IndexSpec)`
- `IndexSpec` is a list containing an element `IndexElt` that not a properly formed indexing element
  - `domain_error(indexing_element,IndexElt)`
- `PredSpec` represents a predicate that has been previously defined to be static
  - `permission_error(modify,static_predicate)`

`dynamic(+Operations)` ISO

`dynamic/1` can be used either as a compiler declaration or as an executable directive. Used as a compiler declaration, it indicates that all clauses for each predicate denoted by the command are dynamic – clauses for these predicates can be asserted or retracted. Without this declaration compiled clauses will be treated as static. Executed as a directive in a state of execution where no clauses exist for each denoted predicate `dynamic/1` ensures clauses for the affected predicates are to be treated as dynamic. If `PredSpec` contains a predicate that is defined as static or as foreign code, a permission error will be thrown. `Operations` can take one of two forms:

1. `Operations` is a predicate indicator, a callable term, or a comma-list of predicate indicators or callable terms.
2. `Operations` has the form `Predspec as Options` where
   - `PredSpec` is a predicate indicator, a callable term, or comma-list of predicate indicators or callable terms.
   - `Options` is either a dynamic_option or a list of dynamic_options. These dynamic options control the attributes of a dyamic predicate. In Version 3.3, the following dynamic options are supported
     - `tabled` which causes the dynamic predicate to be tabled. The declaration/directive `dynamic p/n as tabled` has the same effect as `table p/n as dynamic`.
     - `variant` which causes the table evaluation method of the predicate(s) to use call variance.
     - `incremental` which allows (incremental) tables that are based on the dynamic predicate to be automatically updated when clauses are asserted or retracted.
     - `opaque`. This option is essencially the same as non-incremental dynamic code, *except* that `opaque` predicates can be made `incremental` by a later `dynamic/1` directive, and `incremental` predicates can be made `opaque` by a `dynamic/1` directuve.
     - `private` which causes the predicate(s) to be treated as thread private.
     - `shared` which causes the predicate(s) to be treated as thread shared.

If the directive

`dynamic` p/n`.`

is executed, its behavior is as follows:

- If p/n is already dynamic, the directive has no effect, regardless of wither p/n is tabled, incremental or opaque, private or shared.
- If p/n has *not* already been defined, the directive makes p/n non-tabled, non-incremental, and to use the default thread sharing strategy (`private` unless XSB is called with `-shared_predicates`).

If the directive

`dynamic` *PredList* `as` *Options*`.`

is executed, various checks are performed on *Options*. These checks are (mostly) performed before any predicates are declared as dynamic or options changed, and reduce the possibility of leaving some p/n in *PredList* with inconsistent attributes.

- If a dynamic predicate in `Predlist` is declared as `incremental` it may be changed to `opaque` at any time; similarly, a dynamic predicate that is `opaque` may be changed to `incremental`

- Otherwise, an attempt to change an attribute of p/n in *PredList* – i.e. whether p/n is tabled or not, incremental/opaque or not, and thread-private or thread-shared – will throw a permission error.

In addition, regardless of the state of predicates in *PredList*, if options contains an inconstent set of declarations, a domain error will be thrown. `Options` is inconsistent in the following cases:

- `Options` contains `tabled` or `variant` and `opaque` or `incremental`. Tabled dynamic incremental code is not yet supported in XSB.
- `Options` contains both `private` and `shared`
- `Options` contains both `incremental` and `opaque`

Error Cases

Error cases are summarized as follows. Let `Operations` be of the form `PredSpec` or `PredSpec` as `Options`. Then if

- `PredSpec` or is a variable or a comma list containing a variable
  - `instantiation_error`
- An element of `PredSpec` is neither a variable nor a comma list
  - `type_error(callable,PredSpec)`
- A predicate in `PredSpec` has been previously defined to be static or foreign
  - `permission_error(modify,static_predicate)`
- `Options` is a variable or a list containing a variable
  - `instantiation_error`
- `Options` contains an element `Option` that isn't a dynamic option (as described above)
  - `domain_error(dynamic_option,Option)`
- `Options` contains inconsistnet elements (as described above)
  - `table_error`
- An option in `Options` would modify a predicate in predspec in a manner that is not allowed (as described above)
  - `permission_error`

In addition, if a predicate `p/n` was declared to be dynamic and a file containing clauses for `p/n` is later consulted, a permission error will be thrown.

6.14.1 Reading Dynamic Code from Files

Several built-in predicates are available that can assert the contents of a file into XSB's database. These predicates are useful when code needs to be dynamic, or when the they contain a large number of clauses or facts. Configured properly, files containing millions of facts can be read and asserted into memory in under a minute, making XSB suitable for certain kinds of in-memory database operations [13].

Each of the predicates in this section allow loading from files with proper prolog extensions, and makes use of the XSB library paths. See Sections 3.6 and 3.3 for details.

`load_dyn(+FileName)`

Asserts the contents of file `FileName` into the database. All existing clauses of the predicates in the file that already appear in the database, are retracted, unless there is a `multifile/1` declaration for them. An indexing declaration of a predicate `p/n` in `FileName` will be observed as long as the declarations occur before the first clause of `p/n`. file will be observed as Clauses in `FileName` must be in a format that `read/1` will process. So, for example, operators are permitted. As usual, clauses of predicates are not retracted if they are compiled instead of dynamically asserted. All predicates are loaded into `usermod`. Module declarations such as `:- export` are ignored and a warning is issued.

Dynamically loaded files can be filtered through the XSB preprocessor. To do this, put the following in the source file:

```
:- compiler_options([xpp_on]).
```

Of course, the name `compiler_options` might seem like a misnomer here (since the file is not being compiled), but it is convenient to use the same directive both for compiling and loading, in case the same source file is used both ways.

Error Cases

- `FileName` is a variable
  - `instantiation_error`
- `FileName` is not an atom.
  - `type_error(atom,Filename)`
- `FileName` has been loaded previously in the session *and* there is more than one active thread.
  - `misc_error`

[13] In Version 3.3, loading code dynamically can also be useful when the clauses contain atoms whose length is more than 255 that cannot be handled by the XSB compiler.

`load_dyn(+FileName,+Dir)`

Asserts the contents of file `FileName` into the database. `Dir` indicates whether `assertz` or `asserta` is to be used. If `Dir` is `z`, then `assertz` is used and the behavior of `load_dyn(FileName)` is obtained. If `Dir` is `a`, then `asserta` is used to add the clauses to the database, and clauses will be in the reverse order of their appearance in the input file. `asserta` is faster than `assertz` for predicates such that their indexing and data result in many hash collisions. `Dir` is ignored for facts in `FileName` that are trie-indexed.

Error Cases

- `FileName` is a variable
  - `instantiation_error`
- `FileName` is not an atom:
  - `type_error(atom,FileName)`
- `Dir` is not equal to `a` or `z` [14]:
  - `domain_error(a_or_z,Dir)`
- `FileName` has been loaded previously in the session *and* there is more than one active thread.
  - `misc_error`

`load_dync(+FileName)`

Acts as `load_dyn/1`, but assumes that facts are in "canonical" format and is much faster as a result. In XSB, a term is in canonical format if it does not use any operators other than list notation and comma-list notation. This is the format produced by the predicate `write_canonical/1`. (See `cvt_canonical/2` to convert a file from the usual `read/1` format to `read_canonical` format.) As usual, clauses of predicates are not retracted if they are compiled instead of dynamically asserted. All predicates are loaded into `usermod`. `:- export` declarations are ignored and a warning is issued.

Notice that this predicate can be used to load files of Datalog facts (since they will be in canonical format). This predicate is significantly faster than `load_dyn/1` and should be used when speed is important. (See `load_dync/2` below for further efficiency considerations.) A file that is to be dynamically loaded often but not often modified by hand should be loaded with this predicate.

As with `load_dyn/1`, the source file can be filtered through the C preprocessor. However, since all clauses in such a file must be in canonical form, the `compiler_options/1` directive should look as follows:

```
:-(compiler_options('.'(xpp_on,[]))).
```

[14] For backward compatibility, `0` and `1` are also allowed.

Error Cases

- `FileName` is a variable
  - `instantiation_error`
- `FileName` is not an atom.
  - `type_error(atom,FileName)`
- `FileName` has been loaded previously in the session *and* there is more than one active thread.
  - `misc_error`

`load_dync(+FileName,+Dir)`

Acts as `load_dyn/2`, but assumes that facts are in "canonical" format. `Dir` is ignored for trie-asserted code, but otherwise indicates whether `assertz` or `asserta` is to be used. If `Dir` is `z`, then `assertz` is used and the exact behavior of `load_dync(FileName)` is obtained. If `Dir` is `a`, then `asserta` is used to add the clauses to the database, and clauses will end up in the reverse order of their appearance in the input file.

Setting `Dir` to `a` for non trie-asserted code can sometimes be *much* faster than the default of `z`. The reason has to do with how indexes on dynamic code are represented. Indexes use hash tables with bucket chains. No pointers are kept to the ends of bucket chains, so when adding a new clause to the end of a bucket (as in `assertz`), the entire chain must be run. Notice that in the limiting case of only one populated bucket (e.g., when all clauses have the same index term), this makes assertz-ing a sequence of clauses quadratic. However, when using `asserta`, the new clause is added to the beginning of its hash bucket, and this can be done in constant time, resulting in linear behavior for asserta-ing a sequence of clauses.

Error Cases

- `FileName` is a variable
  - `instantiation_error`
- `FileName` is not an atom:
  - `type_error(atom,FileName)`
- `Dir` is not instantiated to `a` or `z` [15]:
  - `domain_error(a_or_z,Dir)`
- `FileName` has been loaded previously in the session *and* there is more than one active thread.
  - `misc_error`

[15] For backward compatibility, `0` and `1` are also allowed.

`ensure_loaded(+FileName,+Action)`

This predicate does nothing if `FileName` has been loaded or consulted into XSB, and has not changed since it was loaded or consulted. Otherwise

- If `Action` is instantiated to `dyn` the behavior is as `load_dyn/1` (or `load_dyn(FileName,z)`).
- If `Action` is instantiated to `dyna` the behavior is as `load_dyn(FileName,a)`.
- If `Action` is instantiated to `dync` the behavior is as `load_dync/1` (or `load_dync(FileName,z)`).
- If `Action` is instantiated to `dynca` the behavior is as `load_dync(FileName,a)`.
- If `Action` is instantiated to `consult`, `FileName` is consulted (action is the same as `ensure_loaded/1`).

Error Cases

- `FileName` is not instantiated:
  - `instantiation_error`
- `FileName` is not an atom:
  - `type_error(atom,FileName)`
- `Action` is not a valid load action as described above
  - `domain_error(loadAction,Action)`

`cvt_canonical(+FileName1,+FileName2)` module: `consult`

Converts a file from standard term format to "canonical" format. The input file name is `FileName1`; the converted file is put in `FileName2`. This predicate can be used to convert a file in standard Prolog format to one loadable by `load_dync/1`.

6.14.2 The `storage` Module: Associative Arrays and Backtrackable Updates

XSB provides a high-level interface that allows the creation of "objects" that efficiently manage the storage of facts or of associations between keys and values. Of course, facts and associative arrays can be easily managed in Prolog itself, but the `storage` module is highly efficient and supports the semantics of backtrackable updates as defined by Transaction logic [6] in addition to immediate updates. The semantics of backtrackable updates means that an update made by the storage module may is provisional until the update is committed. Otherwise, if a subgoal calling the update fails, the change is undone. The commit itself may be made either by the predicate `storage_commit/1`, or less cleanly by cutting over the update itself.

A storage object O is referred to by a name, which must be a Prolog atom. O can be associated either with a set of facts or a set of *key-value pairs*. Within a given storage object each key is associated with a unique value: however since keys and values can be

arbitrary Prolog terms, this constraint need not be a practical restriction. A storage object O is created on demand, simply by calling (a backtrackable or non-backtrackable) update predicate that refers to O. However to reclaim O's space within a running thread, the predicate `storage_reclaim_space/1` must be called. Both backtackable and non-backtrackable updates can be made to the same storage object, although doing so may not always be a good programming practice.

If multiple threads are used, each storage object is private to a thread, and space for a storage object is reclaimed upon a thread's exit. Thread-shared storage objects may be supported in future versions.

All the predicates described in this section must be imported from module `storage`.

Non-backtrackable Storage

`storage_insert_keypair(+StorageName,+Key, +Value, ?Inserted)`

Insert the given Key-Value pair into `StorageName`. If the pair is new, then `Inserted` unifies with `1`. If the pair is already in `StorageName`, then `Inserted` unifies with `0`. If `StorageName` already contains a pair with the given key that is associated with a *different* value, then `Inserted` unifies with `-1`. The first argument, `StorageName`, must be an atom naming the storage to be used. Different names denote different storages. In all cases the predicate succeeds.

`storage_delete_keypair(+StorageName, +Key, ?Deleted)`

Delete the key-value pair with the given key from `StorageName`. If the pair was in `StorageName` then `Deleted` unifies with `1`. If it was *not* in `StorageNames` then `Deleted` unifies with `0`. The first argument, `StorageName`, must be an atom naming the storage object to be used. Different names denote different storages. In both cases the predicate succeeds.

`storage_find_keypair(+StorageName, +Key, ?Value)`

If `StorageName` has a key pair with the given key, then `Value` unifies with the value stored in `StorageName`. If no such pair exists in the database, then the goal fails.

Note that this predicate works with non-backtrackable associative arrays described above as well as with the backtrackable ones, described below.

`storage_insert_fact(+StorageName, +Fact, ?Inserted)`

Similar to keypair insertion, but this primitive inserts facts rather than key pairs.

`storage_delete_fact(+StorageName, +Fact, ?Inserted)`

Similar to key-pair deletion, but this primitive deletes facts rather than key pairs.

`storage_find_fact(+StorageName, +Fact)`

Similar to key-pair finding, but this primitive finds facts facts rather than key pairs.

Backtrackable Updates

`storage_insert_keypair_bt(+StorageName, +Key, +Value, ?Inserted)`

A call to this predicate inserts a key pair into `StorageName` as does `storage_insert_keypair/4`, and the key-value pair may be queried via `storage_find_keypair/3`, just as with the non-backtrackable updates described above. In addition, the key-value pair can be removed from `StorageName` by explicit deletion. However, the key pair will be removed from `StorageName` upon failing over the insertion goal *unless* a commit is made to `StorageName` through the goal `storage_commit(StorageName)`. The exact semantics is defined by Transaction Logic [6].

Note it is the update itself that is backtrackable, not the key-value pair. Hence, a key-pair may be (provisionally) inserted by a backtrackable update and deleted by a non-backtrackable update, or inserted by a non-backtrackable update and (provisionally) deleted by a backtrackable update. Of course, whether such a mixture makes sense would depend on a given application.

`storage_delete_keypair_bt(+StorageName, +Key, ?Deleted)`

Like `storage_delete_keypair/3`, but backtrackable as described for `storage_insert_keypair_bt/4`.

`storage_insert_fact_bt(+StorageName, +Goal)`

Like `storage_insert_fact/2`, but backtrackable.

`storage_delete_fact_bt(+StorageName, +Goal)`

This is a backtrackable version of `storage_delete_fact/2`.

`storage_commit(+StorageName)`

Commits to `StorageName` any backtrackable updates since the last commit, or since initialization if no commit has been made to `StorageName`. If `StorageName` does not exist, the predicate silently fails.

Reclaiming Space

`storage_reclaim_space(+StorageName)`

This is similar to `reclaim_space/1` for `assert` and `retract`, but it is used for storage managed by the primitives defined in the `storage` module. As with `reclaim_space/1`, this goal is typically called just before returning to the top level.

6.15 Tabling Declarations and Builtins

In XSB, tables are designed so that they can be used transparently by computations. However, it is necessary to first inform the system of which predicates should be evaluated using

tabled resolution (Section 3.10.2), and whether variant or subsumptive tabling should be used (Chapter 5). Further, it is often useful to be able to explicitly inspect a table, or to alter its state. The predicates described in this section are provided for these purposes. In order to ground the discussion of these predicates, we continue our overview of tables and table creation from Chapter 5. For a detailed description of the implementation of table access routines in XSB, the reader is referred to [57, 36, 18] and other papers listed in the bibliography.

Tables and Table Entries

Abstractly, a table can be seen as a set of entry triples $\langle S, \mathcal{A}, Status\rangle$ where S is a subgoal, $\mathcal{A}$ is its associated answer set, and *Status* its status — whether it is `complete` or `incomplete`. In terms of implementation, "the table" is actually a set of mini-tables, each one containing entries for a particular predicate. Hence, we may refer to the table containing entries for some predicate `p/n` as "the table for `p/n`." Further recall that a particular predicate may be evaluated according to either a variant or subsumptive strategy as chosen by the user. Invocation of a call during an evaluation leads to the classification of the call, as well as its possible insertion into the table. Each call can be classified as either (a) a *generator*, or *producer*, of an answer set, or (b) a *consumer* of the answer set of some subgoal in the table. Creation of a table entry thus relies not only on the call and on the subgoals already present in the table, but also upon whether call-variance or call-subsumption is used (cf. [36]).

Answers, Returns, and Templates

Given a table entry $(S, \mathcal{A}, Status)$, the set of variables in S is sometimes called the *substitution factor* of S. The order of arguments in the substitution factor corresponds to the order of distinct variables in a left-to-right traversal of S. Each answer in $\mathcal{A}$ substitutes values for the variables in the substitution factor of S; this substitution is sometimes called an answer substitution. The table inspection predicates allow access to substitution factors and answer substitutions through a family of terms whose principle functors are `ret/n`, where `n` is the size of the substitution factor.

Example 6.15.1 *Let $S =$* `p(X,f(Y))` *be a producer subgoal (or simply, a subgoal if call-variance is used). Using the* `ret/n`*notation, the substitution factor can be depicted as* `ret(X,Y)`*, while the answer substitution* `{X=a,Y=b}` *is depicted as* `ret(a,b)`*. Note that the application of the answer substitution to the producer subgoal yields the answer* `p(a,f(b))`*.*

To take a slightly more complex example, consider the subgoal `q(X)` *where* `X` *is an attributed variable whose attribute is* `f(Z,Y,Y)`*. In this case the substitution factor is* `ret(X,Z,Y)`*.* □

In a similar manner, XSB maintains substitutions between producer subgoals and consuming subgoals when subsumption-based tabling is used. The *return template* for a consuming call is a substitution mapping variables of its producer to subterms of the call. This template can then be used to select returns from the producer which satisfy the consuming call. Note, then, that a return template of a *subsumed* subgoal may show partial instantiations. Return templates are also represented as `ret/n` terms in the manner described above.

Example 6.15.2 *Let* `p/2` *of the previous example be evaluated using subsumption and let* S *be present in its table. Further, let* S_1*:* `p(A,f(B))` *and* S_2*:* `p(g(Z),f(b))` *be two consuming subgoals of* S*. Then the* return template *of* S_1 *is* `ret(A,B)` *and that of* S_2 *is* `ret(g(Z),b)`*.* S_1*, being a variant of* S*, selects all returns of* S *such that* `{X=A,Y=B}`*.* S_2*, on the other hand, selects only* relevant *answers of* S*, those where the returns satisfy* `{X=g(Z),Y=b}`*.* □

Skeletons and Predicate Specifications

A *skeleton* for a functor `f/n` is a structure of the form `f(`Arg_1`,...,`Arg_n`)` where each Arg_i is a distinct variable. Similarly the skeleton of a term is the skeleton formed from the principal functor of the term, so that skeletons from the terms `f(1,2)` and `f(A,B)` are the same. A *return skeleton* is a specific application of this notion to answer returns. From it, one may discern the size of the template for a given subgoal. Finally, we assume that a predicate specification for a predicate `p` and arity `n`, represented as `PredSpec` below, can be given either using the notation `p/n` or as a skeleton, `p(`t_1`,...,`t_n`)`.

6.15.1 Declaring and Modifying Tabled Predicates

`table(+Operations)` Tabling

`table/1` can be used either as a compiler declaration or as an executable directive. Used as a compiler declaration, it indicates that each predicate denoted by the command is to be compiled using (a particular form of) tabling, and may indicate that the predicate itself is dynamic or thread-shared or thread-private. Executed as a directive in a state of execution where no clauses exist for each denoted predicate `table/1` ensures that any clauses asserted for each predicate use tabling and may indicate the mode of tabling to be used. The parameter `Operations` can take one of three forms:

1. `Operations` is a predicate indicator, a callable term, or a comma-list or list of predicate indicators or callable terms.
2. `Operations` is a term indicating that a predicate is to be tabled with a particular form of answer subsumption (cf. Section 5.4).
3. `Operations` has the form `Predspec as Options` where

- `PredSpec` is a predicate indicator, a callable term, or a comma-list or list of predicate indicators or callable terms.
- `Options` is either a table option or a list of table options. In Version 3.3, the following table options are supported
  - `dynamic` or `dyn` which causes the predicate(s) to be treated as dynamic in addition to being tabled, and is equivalent to `?- dynamic PredSpec` [16]
  - `subsumptive` which causes the table evaluation method of the predicate(s) to use call subsumption.
  - `variant` which causes the table evaluation method of the predicate(s) to use call variance.
  - `incremental` which causes the table evaluation method of the predicate(s) to be incremental.
  - `opaque` which indicates that the tables predicate is used in the definition of an incremental table, but are not to be incrementally maintained themselves.
  - `private` which causes the predicate(s) to be treated as thread private in addition to being tabled.
  - `shared` which causes the predicate(s) to be treated as thread shared in addition to being tabled.
  - `subgoal_abstract(n)` which enables depth-n subgoal abstraction for the predicate(s).
  - `answer_abstract(n)` which enables depth-n answer abstraction for the predicate(s).

If the directive

`table` *PredList* `as` *Options*`.`

is executed, various checks are performed on *Options*. These checks are (mostly) performed before any predicates are declared as dynamic or options changed, and reduce the possibility of leaving some p/n in *PredList* with inconsistent attributes.

- If a predicate in `Predlist` has been declared as `incremental` it may be changed to `opaque` at any time; similarly, a predicate that is `opaque` may be changed to `incremental`
- If a predicate in `Predlist` has been declared to use call variance it may be changed to use call subsumption at any time; similarly, a predicate that uses call subsumption may be changed to use call variance.
- Otherwise, an attempt to change an attribute of p/n in *PredList* – i.e. whether p/n is tabled or not, dynamic or not and thread-private or thread-shared – will throw a permission error.

[16] Because dynamic is an operator, the declaration requires parentheses, e.g.: `table p/n as (dynamic).`

In addition, regardless of the state of predicates in *PredList*, if options contains an unsupported set of declarations, a table error will be thrown (see Table 5.1 for a list of supported and non-supported combinations of tabling modes and predicate properties). `Options` is throws a table error in the following cases:

- `Options` contains `dynamic` and either `opaque` or `incremental`. Tabled dynamic incremental code is not yet supported in XSB.
- `Options` contains (`incremental` or `opaque`) and (`subsumptive` or `shared`)
- `Options` contains `subsumptive` and (`variant` or `shared` or `subgoal_abstract/1` or `answer_abstract/1`)
- `Options` contains both `private` and `shared`
- `Options` contains both `incremental` and `opaque`

Error Cases

Error cases are summarized as follows. Let `Operations` be of the form `PredSpec` or `PredSpec` as `Options`. Then if

- `PredSpec` or is a variable or a comma list containing a variable
  - `instantiation_error`
- An element of `PredSpec` is neither a variable nor a comma list
  - `type_error(callable,PredSpec)`
- A predicate in `PredSpec` has been previously defined to be static or foreign and `Options` contains `dynamic` or `dyn`
  - `permission_error(modify,static_predicate)`
- `Options` is a variable or a list containing a variable
  - `instantiation_error`
- `Options` contains an element `Option` that isn't a table option (as described above)
  - `domain_error(table_option,Option)`
- `Options` contains a non-supported combination of elements (as described above)
  - `table_error`
- An option in `Options` would modify a predicate in predspec in a manner that is not allowed (as described above)
  - `permission_error`

6.15.2 Predicates for Table Inspection

The user should be aware that skeletons that are dynamically created (e.g., by `functor/3`) are located in `usermod` (refer to Section 3.4). In such a case, the tabling predicates below may not behave in the desired manner if the tabled predicates themselves have not been imported into `usermod`.

We maintain two running examples in this section for explanatory purposes. One uses variant-based tabling:

Variant Example

Program

```
:- table p/2 as variant.

p(1,2).
p(1,3).
p(1,_).
p(2,3).
```

Table

Subgoal	Answer Set	Status
p(1,Y)	p(1,2) p(1,3) p(1,Y)	complete
p(X,3)	p(1,3) p(2,3)	complete

and the other uses subsumption-based tabling:

Subsumptive Example

Program

```
:- table q/2 as subsumptive.
q(a,b).
q(b,c).
q(a,c).
```

Table

Subgoal	Answer Set	Status
q(X,Y)	q(a,b) q(b,c) q(a,c)	complete
q(a,Y)	*q(a,b)* *q(a,c)*	complete
q(X,c)	*q(b,c)* *q(a,c)*	complete

Note that in the subsumptive example, the subgoals `q(a,Y)` and `q(X,c)` are subsumed by, and hence obtain their answers from, the subgoal `q(X,Y)`.

`get_call(+CallTerm,-TableEntryHandle,-ReturnTemplate)` Tabling

If call variance is used for the predicate corresponding to `CallTerm`, then this predicate searches the table for an entry whose subgoal is a *variant* of `CallTerm`. If subsumption is used, then this predicate searches for some entry that subsumes (properly or not) `CallTerm`. In either case, should the entry exist, then the handle to this entry is assigned to the second argument, while in the third, its return template is constructed. These latter two arguments should be given as variables.

Error Cases

- `CallTerm` is not a callable term
  - `type_error(callable_term,CallTerm)`
- `CallTerm` does not correspond to a tabled predicate
  - `permission_error(table access,non-tabled predicate,CallTerm)`

Example 6.15.3

Variant Predicate

```
| ?- get_call(p(X,Y),Ent,Ret).

no
| ?- get_call(p(1,Y),Ent,Ret).

Y = _h92
Ent = 136039108
Ret = ret(_h92);

no
| ?- get_call(p(X,3),Ent,Ret).

X = _h84
Ent = 136039156
Ret = ret(_h84);

no
| ?- get_call(p(1,3),Ent,Ret).

no
```

Subsumptive Predicate

```
| ?- get_call(q(X,Y),Ent,Ret).

X = _h80
Y = _h94
Ent = 136043988
Ret = ret(_h80,_h94);

no
| ?- get_call(q(a,Y),Ent,Ret).

Y = _h88
Ent = 136069412
Ret = ret(a,_h88);

no
| ?- get_call(q(X,c),Ent,Ret).

X = _h80
Ent = 136069444
Ret = ret(_h80,c);

no
```

`get_calls(#CallTerm,-TableEntryHandle,-ReturnSkeleton)` Tabling

Identifies through backtracking each subgoal in the table which unifies with `CallTerm`. For those that do, the handle to the table entry is assigned to the second argument,

and its return skeleton is constructed in the third. These latter two arguments should be given as variables. The error terms are the same as for `get_calls/1`.

Example 6.15.4

Variant Predicate

```
| ?- get_calls(p(X,Y),Ent,Ret).

X = _h80
Y = 3
Ent = 136039156
Ret = ret(_h80);

X = 1
Y = _h94
Ent = 136039108
Ret = ret(_h94);

no
| ?- get_calls(p(X,3),Ent,Ret).

X = _h80
Ent = 136039156
Ret = ret(_h80);

X = 1
Ent = 136039108
Ret = ret(3);

no
| ?- get_calls(p(1,3),Ent,Ret).

Ent = 136039156
Ret = ret(1);

Ent = 136039108
Ret = ret(3);

no
```

Subsumptive Predicate

```
| ?- get_calls(q(X,Y),Ent,Ret).

X = a
Y = _h94
Ent = 136069412
Ret = ret(a,_h94);

X = _h80
Y = c
Ent = 136069444
Ret = ret(_h80,c);

X = _h80
Y = _h94
Ent = 136043988
Ret = ret(_h80,_h94);

no
| ?- get_calls(q(a,Y),Ent,Ret).

Y = _h88
Ent = 136069412
Ret = ret(a,_h88);

Y = c
Ent = 136069444
Ret = ret(a,c);

Y = _h88
Ent = 136043988
Ret = ret(a,_h88);

no
```

`get_calls_for_table(+PredSpec,?Call)` Tabling

Identifies through backtracking all the subgoals whose predicate is that of `PredSpec` and which unify with `Call`. `PredSpec` is left unchanged while `Call` contains the unified resultant.

Example 6.15.5

Variant Predicate

```
|?- get_calls_for_table(p(1,3),Call).

Call = p(_h142,3);

Call = p(1,_h143);

no
| ?- get_calls_for_table(p/2,Call).

Call = p(_h137,3);

Call = p(1,_h138);

no
```

Subsumptive Predicate

```
| ?- get_calls_for_table(q(X,Y),Call).

X = _h80
Y = _h94
Call = q(a,_h167);

X = _h80
Y = _h94
Call = q(_h166,c);

X = _h80
Y = _h94
Call = q(_h166,_h167);

no
```

`get_returns(+TableEntryHandle,#ReturnSkeleton)` Tabling

Backtracks through the answers for the subgoal whose table entry is referenced through the first argument, `TableEntryHandle`, and instantiates `ReturnSkeleton` with the variable bindings corresponding to the return.

The supplied values for the entry handle and return skeleton should be obtained from some previous invocation of a table-inspection predicate.

Example 6.15.6

Variant Predicate

```
| ?- get_calls(p(X,3),Ent,Ret),
     get_returns(Ent,Ret).

X = 2
Ent = 136039156    % p(X,3)
Ret = ret(2);

X = 1
Ent = 136039156
Ret = ret(1);

X = 1
Ent = 136039108    % p(1,Y)
Ret = ret(3);

X = 1
Ent = 136039108
Ret = ret(3);

no
```

Subsumptive Predicate

```
| ?- get_calls(q(a,c),Ent,Ret),
     get_returns(Ent,Ret).

Ent = 136069412    % q(a,Y)
Ret = ret(a,c);

Ent = 136069444    % q(X,c)
Ret = ret(a,c);

Ent = 136043988    % q(X,Y)
Ret = ret(a,c);

no
| ?- get_calls(q(c,a),Ent,Ret),
     get_returns(Ent,Ret).

no
```

`get_returns_and_tvs(+TableEntryHandle,#ReturnSkeleton,-TruthValue)` Tabling

Identical to `get_returns/2`, but also obtains the truth value of a given answer, setting `TruthValue` to `t` if the answer is unconditional and to `u` if it is conditional. If a conditional answer has multiple delay lists, this predicate will succeed only once, so that using this predicate may be more efficient than `get_residual/2` (although less informative).

`get_returns(+TableEntryHandle,#ReturnSkeleton,-ReturnHandle)` Tabling

Functions identically to `get_returns/2`, but also obtains a handle to the return given in the second argument.

`get_returns_for_call(+CallTerm,?AnswerTerm)` Tabling

Succeeds through backtracking for each answer of the subgoal `CallTerm` which unifies with `AnswerTerm`. Fails if `CallTerm` is not a subgoal in the table or `AnswerTerm` does not unify with any of its answers or the answer set is empty.

The answer is created in its entirety, including fresh variables; the call is *not* further instantiated. However, an explicit unification of the call with its answer may be performed if so desired.

Example 6.15.7

Variant Predicate

```
| ?- get_returns_for_call(p(1,Y),
                          AnsTerm).

Y = _h88
AnsTerm = p(1,_h161);

Y = _h88
AnsTerm = p(1,3);

Y = _h88
AnsTerm = p(1,2);

no
| ?- get_returns_for_call(p(X,Y),
                          AnsTerm).

no
| ?- get_returns_for_call(p(1,2),
                          AnsTerm).

no
```

Subsumptive Predicate

```
| ?- get_returns_for_call(q(a,Y),
                          AnsTerm).

Y = _h88
AnsTerm = q(a,c);

Y = _h88
AnsTerm = q(a,b);

no
| ?- get_returns_for_call(q(X,c),
                          AnsTerm).

X = _h80
AnsTerm = q(b,c);

X = _h80
AnsTerm = q(a,c);

no
```

`get_residual(#CallTerm,?DelayList)` Tabling

`variant_get_residual(#CallTerm,?DelayList)` Tabling

`get_residual/2` backtracks through the answers to each *completed* subgoal in the table that unifies with `CallTerm`. With each successful unification, this argument is further instantiated as well as that of the `DelayList`.

Example 6.15.8 *For the following program and table*

```
:- table p/2.
p(1,2).
p(1,3):- tnot(p(2,3)).
p(2,3):- tnot(p(1,3)).
```

Subgoal	Answers
p(1,X)	*p(1,2)* *p(1,3):- tnot(p(2,3))*
p(1,3)	*p(1,3):- tnot(p(2,3))*
p(2,3)	*p(2,3):- tnot(p(1,3))*

the completed subgoals are `p(1,X)`, `p(1,3)`, *and* `p(2,3)`. *Calls to* `get_residual/2` *will act as follows*

```
| ?- get_residual(p(X,Y),List).
```

```
X = 1       % from subgoal p(1,X)
Y = 2
List = [];

X = 1       % from subgoal p(1,X)
Y = 3
List = [tnot(p(2,3))];

X = 1       % from subgoal p(1,3)
Y = 3
List = [tnot(p(2,3))];

X = 2       % from subgoal p(2,3)
Y = 3
List = [tnot(p(1,3))];

no
```

Since the delay list of an answer consists of those literals whose truth value is unknown in the well-founded model of the program (see Chapter 5) `get_residual/2` is useful to examin the residual program (e.g. for XASP).

For other purposes, it may be desired to examine the answers for a particular subgoal, rather than for all subgoals that unifiy with `CallTerm`. In this case, `variant_get_residual/2` can be used, which backtracks through all answers for `CallTerm` if `CallTerm` is a tabled subgoal with answers, and fails otherwise. For the above example, `variant_get_residual/2` behaves as follows:

```
| ?- variant\_get_residual(p(X,Y),List).

no
| ?- variant\_get_residual(p(1,Y),List).

X = 1       % from subgoal p(1,X)
Y = 2
List = [];

X = 1       % from subgoal p(1,X)
Y = 3
List = [tnot(p(2,3))];

no
```

Error Cases

- `CallTerm` is not a callable term

  - `type_error(callable_term,CallTerm)`
- `CallTerm` does not correspond to a tabled predicate
  - `permission_error(table access,non-tabled predicate,CallTerm)`

`table_state(+CallTerm,?PredType,?CallType,?AnsSetStatus)` Tabling

`table_state(+TableEntryHandle,?PredType,?CallType,?AnsSetStatus)` Tabling

Succeeds whenever `CallTerm` is a subgoal in the table, or `TableEntryHandle` is a valid reference to a table entry, and its predicate type, the type of the call, and the status of its answer set, unify with arguments 2 through 4, respectively.

XSB defines three sets of atomic constants, one for each parameter. Taken together, they provide a detailed description of the given call. The valid combinations and their specific meaning is given in the following table. Notice that not only can these combinations describe the characteristics of a subgoal in the table, but they are also equipped to predict how a new goal would have been treated had it been called at that moment.

PredType	CallType	AnsSetStatus	Description
variant	producer	complete	Self explanatory.
		incremental_needs_reeval	An incremental table that has been invalidated, and is therefore inconsistent with a KB and needs recomputation.
		incomplete	Self explanatory.
	no_entry	undefined	The call does not appear in the table.
subsumptive	producer	complete	Self explanatory.
		incomplete	Self explanatory.
	subsumed	complete	The call is in the table and is properly subsumed by a completed producer.
		incomplete	The call is in the table and is properly subsumed by an incomplete producer.
	no_entry	complete	The call is not in the table, but if it were to be called, it would consume from a completed producer.
		incomplete	The call is not in the table, but if it had been called at this moment, it would consume from an incomplete producer.
		undefined	The call is not in the table, but if it had been called at this moment, it would be a producer.
undefined	undefined	undefined	The given predicate is not tabled.

`table_dump(+OptionList)` module: `dump_table`

`table_dump(+Stream,#Term,+OptionList)` module: `dump_table`

`table_dump/[2,3]` provides an easy method to view subgoals and answers that are

present in a table. Given an input `Term`, `table_dump/[2,3]` provides information about all tabled subgoals that are subsumed by `Term`; if `Term` is a variable, information is provided about all tables.

The information is provided at three levels of aggregation, and the form of the information is determined by the options in `OptionsList`.

- If the option `summary(true)` is set, the aggregate sum of subgoals and answers that are subsumed by `Term` is collected, along with the aggregate sum of calls **to** these subgoals. If `Term` is a variable this information is broken down by tabled predicates.
  - If `details(answers)` is set, a list is collected of every tabled subgoal S such that S is subsumed by `Term` along with the number of answers for each S and a list of those answers and the truth value of each answer (`t` if true and `u` if undefined). If `Term` is a variable this information is broken down by tabled predicates.
  - If `details(subgoals)` is set, a list is collected of all subgoals S such that S is subsumed by `Term` along with the number of answers for each S. However, unlike the action for `details(answers)` the actual list of answers for S is not returned. If `Term` is a variable this information is broken down by tabled predicates.
  - If `details(false)` is set, no detail information is provided for the actual subgoals or their answers.
- If `OptionsList` contains the option `results(X)` for some variable `X`, `X` will be instantiated upon backtracking to all infomation collected about the tables.
- If the option `output(true)` is set, the information is written to `Stream` or to `userout` in Prolog-readable form.

If not otherwise specified the default options are `summary(true)`, `details(false)`, `output(true)`.

Example Consider the program:

```
:- table p/2.
p(1,a).
p(1,b) :- p(2,b).
p(2,b) :- p(1,a).
p(3,X) :- q(X).

:- table q/1.
q(1).              q(2).

:- table r/1.
r(a).
```

```
:- table s/2.
s(1,a).            s(2,b).           s(1,a1).            s(2,b1).
```

and suppose the top-level query `?- p(X,Y)` has been made. Then `table_dump/2` provides the following information **(reformatted for readability)**:

```
| ?- table_dump(_X,[summary(true)]).

summary = p(A,B) - subgoals(3) - total_times_called(4) - total_answers(7)

X = p(_h243,_h244);

summary = q(A) - subgoals(1) - total_times_called(1) - total_answers(2).

X = q(_h228)

yes
| ?- table_dump(_X,[details(answers)]).

summary = p(A,B) - subgoals(3) - total_times_called(4) - total_answers(7).
details = p(A,B) - subgoals(3) - details([
    p(C,D) - times_called(1) - answers(5) - [p(3,1)-t,p(3,2)-t,p(2,b)-t,p(1,b)-t,p(1,a)-t]
                                          - completed,
    p(1,a) - times_called(2) - answers(1) - [p(1,a)-t]                        - completed,
    p(2,b) - times_called(1) - answers(1) - [p(2,b)-t]                        - completed]).

X = p(_h232,_h233);

summary = q(A) - subgoals(1) - total_times_called(1) - total_answers(2).
details = q(A) - subgoals(1) - details([
     q(B) - times_called(1) - answers(2) - [q(2)-t,q(1)-t] - completed]).

X = q(_h232)

yes
```

As the above example shows, each line of the summary has the form:

summary =
    Pred/Goal - *subgoals*($N_{subgoals}$) - *total_times_called*(N_{called}) - *total_answers*($N_{answers}$)

where

- *Pred/Goal* is either a term indicator, if the `Term` argument of `table_dump/[2,3]` was a variable (to indicate there should be no filtering of tabled calls); or `Term` itself.

- $N_{subgoals}$ are the total number tabled subgoals that are subsumed by *Pred/Goal* (perhaps including *Pred/Goal* itself).
- N_{called} is the total number of times all subgoals subsumed by *Pred/Goal* have been called.
- $N_{answers}$ is the total number of answers currently derived by all subgoals subsumed by *Pred/Goal*.

Each line of details has the form:

Details =
Pred/Goal - subgoals($N_{subgoals}$) *- details(List)*

where *Pred/Goal* and $N_{subgoals}$ are as above. If `details(answers)` was an input option

List =
Subgoal - times_called(N_{called}) *- answers*($N_{answers}$) *- List_of_Answers - Status*

for each *Subgoal* in the table subsumed by *Pred/Goal*. N_{called} and $N_{answers}$ are as above, while *List_of_Answers* contains $A - TV$ for each answer A with truth value TV that is currently derived for *Subgoal*. On the other hand, if `details(subgoals)` was an input option

List =
Subgoal - times_called(N_{called}) *- answers*($N_{answers}$) *- Status*

where all elements are as before. Finally *Status* is

- `completed` if *Subgoal* has been completed; and
- `scc(`N_{SCC}`)` if *Subgoal* is incomplete. N_{SCC} is relative: if N_{SCC} is greater than M_{SCC} then N_{SCC} is a descendent of M_{SCC}: i.e., subgoals in SCC M_{SCC} depend on subgoals in SCC N_{SCC}. However, these numbers should only be used relatively: at a given state in the computation there may be fewer than M_{SCC} Sccs [17].

Error Cases

- `OptionList` is a variable, or contains a variable as an element
  - `instantiation_error`
- `OptionList` is not a list

[17] XSB keeps track of SCCs through an algorithm similar to depth-first search: the numbers associated with subgoals are the depth-first numbers of the minimal back-dependency of a subgoal (cf. [60])

  - `type_error(list,OptionList)`
- `OptionList` contains an element, `O`, that is not a valid `table_dump_option`.
  - `domain_error(table_dump_option,O)`

`print_incomplete_tables` module: `tables`

These predicates, which can be useful for debugging purposes, print out each incomplete subgoal in the current state, followed by the ordinal number of the SCC to which that subgoal belongs. This information describes the dependencies among tabled predicates. In local evaluation (the default evaluation method for XSB) all subgoals in SCC m depend on all subgoals in SCC n if $m < n$. Furthermore, all subgoals in a given SCC depend on one another [18]. As its name implies, `print_incomplete_tables/[0,1]` print out SCC information only for incomplete tables; for full information about the SCCs of a computation, forest logging must be used (cf. Section 10.3).

In `print_incomplete_tables/0`, the information is output to `stdout`.

Example: For the program

```
:- table q/2.
q(0,_):- !,print_incomplete_tables.
q(3,A):- q(5,A).
q(N,A):- N1 is N - 1,q(N1,A).
```

the goal `?- q(5,foo)` will produce the output

```
q(5, foo)- scc(1).
q(4, foo)- scc(1).
q(3, foo)- scc(1).
q(2, foo)- scc(2).
q(1, foo)- scc(3).
q(0, foo)- scc(4).
```

`get_scc_dumpfile(-Filename)` module: `tables`

If the Prolog flag `exception_pre_action` is set to `print_incomplete_tables` (its default setting is `none`), then when an exception is thrown, incomplete tables and their SCC information are printed to a "SCC dumpfile" via `print_incomplete_tables/1`. (No file is generated unless the exception is thrown over at least one incomplete table.)

This predicate returns the name of the last such file generated and fails if there is no such file. Files are written to the `$XSBDIR/etc` directory with the prefix `scc_dump_`. Users are responsible for removing these files.

[18] This assumes that there is no early completion, which can remove dependencies. In batched evaluation, the dependencies are less exact – see [60] for details, as SCCs represent a dag of dependencies rather than a chain as in local evaluation.

Note that XSB backtraces (Section 12.5) provide information about the context in which an exception is thrown, but the SCC dumpfile provides explicit SCC information along with parameter values for tabled predicates.

Error Cases

- `Filename` is a not a variable
  - `instantiation_error`

`get_residual_sccs(+Subgoal,+Answer,-SCCList)` module: `tables`
`get_residual_sccs(+Subgoal,+Answer,-SCCList,-DepList,-SignList)` module: `tables`

As discussed in Section 5.3.3, answers that are undefined in the well-founded semantics are stored in XSB along with their delay lists, forming a residual program. This residual program can be materialized through the various predicates discussed above, in particular `get_residual/2` and `variant_get_residual/2`.

At times it can be useful to view the residual program as a directed graph, for instance in order to understand why a given answer might be undefined. In a manner somewhat analogous to the incremental dependency graph (Section 5.6) this graph is a directed graph whose nodes are atoms and whose edges are labelled with: 1) a sign indicating whether the edge is positive or negative; and 2) the label *depends on* or *affects*.

Example 6.15.9 Consider the program

```
:- table p/2.
p(1,2).
p(1,3):- tnot(p(2,3)).
p(2,3):- tnot(p(1,3)).          p(2,3):- r(a).
r(a):- tnot(r(b))
r(b):- tnot(r(a)).
```

to which the query ?- p(1,X) was made, generating the tables:

Subgoal	*Answers*
p(1,X)	p(1,2) p(1,3):- tnot(p(2,3))|
p(1,3)	p(1,3):- tnot(p(2,3))|
p(2,3)	p(2,3):- tnot(p(1,3))|
	p(2,3):- tnot(r(a))|
r(a)	r(a):- tnot(r(b))|
r(b)	r(b):- tnot(r(a))|

The residual dependency graph for this program and query would have a node for each subgoal/answer combination with an undefined truth value, and a dependency edge for nodes S_1/A_1 and S_2/A_2 if A_2 occurs in a literal in the delay list for S_1/A_1, and the original subgoal for A_2 was S_2 in the subcomputation for S_1. The edge also has a sign indicating whether A_2 occurs positively or negatively in the delay list for A_1. In this example, the residual dependency graph can be represented as

```
edge(p(1,X),p(1,3),p(2,3),p(2,3),neg).
edge(p(1,3),p(1,3),p(2,3),p(2,3),neg).
edge(p(2,3),p(2,3),p(1,3),p(1,3),neg).
edge(p(2,3),p(2,3),r(a),r(a),pos).
edge(r(a),r(a),r(b),r(b),neg).
edge(r(b),r(b),r(a),r(a),neg).
```

Using the residual dependency graph, a user may be able to determine why an answer A to a subgoal S was unexpectedly undefined either because S/A was involved in or depended on a loop through negation; or because S/A depended on some other answer that was undefined because of the use of bounded rationality (Section 5.5) or because of floundering and the use of `u_not/1`.

The dependency graph connected to a given subgoal/answer pair can be obtained through `get_residual_sccs/[3,5]`. Each predicate returns the list of subgoal / answer pairs along with an SCC index in a term of the form

```
ret(Subgoal,Answer,SCCIndex).
```

`get_residual_sccs/5` also returns a list indicating the direct dependencies among the SCCs, along with a list indicating whether given SCCs contain a negative edge. For the example above, the SCC information would have a form such as:

```
[ ret(p(1,X),p(1,3),1), ret(p(1,3),p(1,3),2), ret(p(2,3),p(2,3),2),
  ret(r(a),r(a),3), ret(r(b),r(b),3) ]
```

The dependency list would have a form such as:

```
[ depends(1,2), depends(2,3) ]
```

while the sign list would have a form such as:

```
[ sign(1,no_neg), sign(2,neg), sign(3,neg) ]
```

These predicates implement Tarjan's algorithm [77] in C working directly on XSB's data structures. The algorithm is $\mathcal{O}(|V|+|E|)$ where $|V|$ is the number of vertices and $|E|$ the number of edges in the dependency graph. As a result, these predicates provide

an efficient means to materialize the dependency graph, even if SCC information per se is not required [19].

6.15.3 Deleting Tables and Table Components

The following predicates are used to semantically invalidate tables and/or reclaim their space. The use of the word "tables" in this section is rather unspecific. For the purpose of deletion a table can either refer to a single subgoal and its answers, or to all subgoals and answers for a tabled predicate. Predicates are provided to invalidate tables not only for particular predicates and subgoals, but for all tabled predicates, all tabled predicates in a module, and in the multi-threaded engine all thread-private tabled predicates or all thread-shared tabled predicates. Overall, these predicates share similar characteristics.

First, an incomplete tabled subgoal S may not be abolished by the user except under special circumstances described below. This restriction is made since if S is incomplete there may be pointers to S from various elements of the current execution environment, and removing all of these pointers may be difficult to do. If one of the deletion predicates is called when the current execution environment contains a reference to a *completed* table that is being abolished, space for the abolished information is not immediately reclaimed. More precisely, if the current global tabling envonment (including suspended states) has either

- a choice point that points to an answer A;
- or a (heap) delay list that points to a subgoal S

we say that A or S is *active*. Also, since tables can be abolished and rederived during the course of an evaluation, the table deletion system marks the tables with versions. Accordingly, if a tabled predicate $P_{version}$ or subgoal $S_{version}$ to be abolished has an answer that is active in the current environment, reclamation of space for that version of P or S will be delayed until no answers for $P_{version}$ or $S_{version}$ are active. New calls to P or S, however, will derive a new table versions, rather than using the abolished information.

When conditional answers are present, abolishing a specific table or call may lead to semantic or implementational complications. Consider the conditional answer `r(a,b):-undef|` from Figure 6.1. If the predicate `r/2` (or subgoal `r(a,X)`) is abolished and later rederived, the rederivation of `r(a,X)` might have different semantics than the original derivation (e.g. if `undef` depended on a dynamic predicate whose definition has changed). From an implementation perspective, if space for `r(a,X))` is reclaimed, then the call `get_residual(p(a,X),Y)` may core dump, even if there are

[19] The actual number for each SCC index depends on how the residual dependency graph happens to be traversed; as a result it is best to rely on the index only as a "generated" name for each SCC.

no choice points for completed tables anywhere in the choice point stack. To address this problem, by default abolishing a subgoal S (predicate P) will abolish all 'vsubgoals (predicates) that (transtively) depend on S (P) [20]. In this case the goal `abolish_table_call(r(a,X))` would cause the deletion of `p(a,X)` while the goal `abolish_table_pred(r/2)` would cause the deletion of `p/2`, since there are tabled subgoals of `p/2` that depend on `r/2`. Only dependencies from subgoals or answers to the answers that are conditional on them are taken into account for table deletion: thus the deletion `r(a,X)` deletes `p(a,X)`, but not `undef`.

Users with programs that give rise to conditional answers in completed tables are encouraged to maintain this default behavior. However the default behavior may be changed either by setting a Prolog flag:

```
?- set_prolog_flag(table_gc_action,abolish_tables_singly).
```

or by calling a 2-ary abolish command with `abolish_tables_singly` in the options list.

Program

```
:- table p/2, r/2.
p(X,Y):- r(X,Y).

r(a,b):- undef.
r(a,c):- undef.
r(a,d):- undef.
r(a,e):- undef.

:- table  s/0, t/0.
s:- tnot(t).

t:- tnot(undef).

:- table undef/0.
undef :- tnot(undef).
```

Table

Subgoal	Answer Set	Status
p(a,X)	p(a,b):- r(a,b)| p(a,c):- r(a,c)|	complete
p(b,X)	p(b,d):- r(b,d)| p(b,d):- r(b,e)|	complete
r(a,X)	r(a,b):- undef| r(a,c):- undef|	complete
r(b,X)	r(b,d):- undef| r(b,d):- undef|	complete
s	s:- tnot(t)|	complete
t	t:- tnot(undef)|	complete
undef	undef:- tnot(undef)|	complete

Figure 6.1: Example for Deleting Tables (Call-Variance)

In the multi-threaded engine abolishing tables private to a thread behaves exactly as in the sequential engine, regardless of whether the tables are complete or incomplete, or contain conditional answers. In addition, when a thread T exits (by normal termination or via an exception), tables private to T are abolished automatically and their

[20] Dao Tran Minh contributed to implementing this functionality.

space reclaimed, as are any incomplete shared tables owned by T in local evaluation. Shared tables can be abolished by the user at any time, but their space will not be reclaimed until there is a single active thread.

As mentioned above, during normal execution, an incomplete tabled subgoal may not be abolished by the user, a restriction that is made to ensure correct evaluations. Accordingly, calling an `abolish_xxx` predicate when tables are incomplete raises an error. However, we note that any incomplete tables are abolished *automatically* by the system on exceptions (by the default system error handler) when the interpreter level is resumed.

Table Deletion Predicates

`abolish_table_pred(+Pred)` Tabling

Invalidates all tabled subgoals for the predicate denoted by the predicate or term indicator `Pred`. If any subgoal for `Pred` contains an answer A that is active in the current enviornment, `Pred` space reclamation for the `Pred` tables will be delayed until A is no longer active; otherwise the space for the `Pred` tables will be reclaimed immediately.

If `Pred` has a subgoal that contains a conditional answer, the default behavior will be to transitively abolish any tabled predicates with subgoals having answers that depend on any conditional answers of S. This default may be changed either by setting a Prolog flag:

```
?- set_xsb_flag(table_gc_action,abolish_tables_singly).
```

or by calling `abolish_table_pred/2` with the appropriate option. If the transitive abolishes are turned off, and `Pred` contains a conditional answer, the warning

```
abolish_table_pred/[1,2] is deleting a table with conditional answers:
delay dependencies may be corrupted.
```

will be issued.

In the multi-threaded engine, if `Pred` is shared, reclamation for `Pred` will be delayed until there is a single active thread and no answer in `Pred` is active in the current execution environment. Otherwise, the behavior of `abolish_table_pred/1` is the same as in the sequential engine.

Finally, `abolish_table_pred/1` will throw an error if the predicate to be abolished is incremental. This is because abolishing some incremental tables but not others will leave dangling pointers in the data structures used for uncremental updates. Until `abolish_table_pred/[1,2]` is extended to support incremental tables, use `abolish_table_call/[1,2]` or `abolish_all_tables/0`.

Error Cases

- `Pred` is not instantiated
  - `instantiation_error`

- `PredSpec` is not a predicate_indicator or a term_indicator
  - `domain_error(predicate_or_term_indicator,Pred)`
- `PredSpec` does not indicate a tabled predicate or indicates an incrementally tabled predicate.
  - `table_error`
- There is currently an incomplete table for an atomic subgoal of `Pred`
  - `table_error`

`abolish_table_pred(+CallTerm,+Options)` Tabling

Behaves as abolish_table_pred/1, but allows the default `table_gc_action` to be over-ridden with a flag, which can be either `abolish_tables_transitively` or `abolish_tables_singly`.

Error Cases Error cases are the same as `abolish_table_pred/1` but with the additions:

- `Options` is a variable, or contains a variable as an element
  - `instantiation_error`
- `Options` is not a list
  - `type_error(list,Options)`
- `Options` contains an option `O` that is not a table abolish option.
  - `domain_error([abolish_tables_transitively, abolish_tables_singly,O)`

`abolish_table_call(+CallTerm)` Tabling

Invalidates all entries from the table for any subgoals that unify with `CallTerm`. If a subgoal S unifying with `CallTerm` contains an answer A that is active in the current enviornment, the table entry for S will not be reclaimed until A is no longer active; otherwise the space for S will be reclaimed immediately.

If S contains a conditional answer, the default behavior will be to transitively abolish any subgoals that depend on any conditional answers of S. This default may be changed either by setting an XSB flag:

```
?- set_xsb_flag(table_gc_action,abolish_tables_singly).
```

or by calling `abolish_table_call/2` with the appropriate option. If the transitive abolishes are turned off, and S contains a conditional answer, the warning

```
abolish_table_call/1 is deleting a table with conditional answers:
delay dependencies may be corrupted.
```

will be issued.

In the multi-threaded engine, if S is a subgoal for a predicate that is shared, reclamation for S will be delayed until there is a single active thread and no answer in S is active in the current execution environment. Otherwise, the behavior of `abolish_table_call/1` is the same as in the sequential engine on tabled predicates that are thread-private.

`abolish_table_call/[1,2]` also cascades abolishes for incremental tables. If a call G is abolished, all calls that G depends on will also be abolished, so that the dependency structures that support incremental tabling will remain in a consistent state.

Error Cases

- The term spec `CallTerm` does not correspond to a tabled predicate:
  - `table_error`
- The term spec `CallTerm` unifies with a tabled subgoal that is incomplete:
  - `table_error`
- The term spec `CallTerm` is a cyclic term::
  - `table_error`

`abolish_table_call(+CallTerm,+Options)` Tabling

Behaves as abolish_table_call/1, but allows the default `table_gc_action` to be over-ridden with a flag, which can be either `abolish_tables_transitively` or `abolish_tables_singly`.

Error Cases Error cases are the same as `abolish_table_call/1` but with the additions:

- `Options` is a variable, or contains a variable as an element
  - `instantiation_error`
- `Options` is not a list
  - `type_error(list,Options)`
- `Options` contains an option `O` that is not a table abolish option.
  - `domain_error([abolish_tables_transitively, abolish_tables_singly,O)`

`abolish_all_tables` Tabling

In the single-threaded engine, removes all tables presently in the system and frees all the memory held by XSB for these structures. Predicates that have been declared tabled remain so, but information in their table is deleted. `abolish_all_tables/0` works directly on the memory structures allocated for table space. This makes it very fast for abolishing a large amount of tables, and to maintain its speed it throws an error if any completed answer A is active in the current execution environment. `abolish_all_tables/0` can be used regardless of whether there are incremental tables, or tables that use call or answer subsumption.

In the multi-threaded engine `abolish_all_tables/0` raises an error unless it is called when there is a single active thread. In that case, all shared tables are abolished as well as all private tables for the main thread. An error will be thrown if any completed answer A is active in the current environment, regardless of whether A is thread-private or thread-shared.

Error Cases

- There are incomplete tables at the time of the predicate's call;

  - `table_error`
- The current execution environment has an active answer A
  - `table_error`
- (Multi-threaded engine only) More than one thread is active:
  - `table_error`

`abolish_all_private_tables` Tabling

In the multi-threaded engine, removes all tables private to the thread and frees all the memory held by XSB for these structures, including space for conditional answers. Predicates that have been declared tabled remain so, but information in their table is deleted. `abolish_all_private_tables/0` works directly on the memory structures allocated for table space. This makes it very fast for abolishing a large amount of tables, and to maintain its speed it throws an error if any completed answer A for a private table is active in the current execution environment.

Error Cases

- There are incomplete tables at the time of the predicate's call;
  - `table_error`
- The current execution environment for the thread has an active answer A for a private table.
  - `table_error`

`abolish_all_shared_tables` Tabling

In the multi-threaded engine, removes all tables private to the thread and frees all the memory held by XSB for these structures, including space for conditional answers. Predicates that have been declared tabled remain so, but information in their table is deleted. `abolish_all_private_tables/0` works directly on the memory structures allocated for table space. This makes it very fast for abolishing a large amount of tables, and to maintain its speed it throws an error if any completed answer A for a private table is active in the current execution environment. `abolish_all_shared_tables/0` raises an error unless it is called when there is a single active thread. In that case, all shared tables are abolished, but private tables for the main thread are unaffected.

Error Cases

- There are incomplete tables at the time of the predicate's call;
  - `table_error`
- The current execution environment has an active answer A
  - `table_error`
- More than one thread is active:
  - `table_error`

`abolish_module_tables(+Module)` Tabling

Given a module name (or the default module, `usermod`), this predicate abolishes all tables for each tabled predicate in `Module`. It is implemented using a series of calls to `abolish_table_pred/1` and so inherits the behavior of that predicate.

`gc_tables(-Number)` Tabling

When a tabled subgoal or predicate is abolished, reclamation of its space may be postponed if the subgoal or predicate has an answer that is active in the current environment. A garbage collection routine is called at various points in execution to check which answers are active in the current environment, and to reclaim the space for subgoals and predicates with no active answers. In particular, space for all abolished tables is reclaimed whenever the engine re-executes the main command-line or C thread interpreter code. However for certain applications this strategy may not be adequate. For this reason, the user can explicitly call the table garbage collector to reclaim space for any deleted tabled predicates or subgoals that no longer have active answers.

`gc_tables/1` always succeeds, unifying `Number` to -1 if garbage collection was not attempted (due to multiple active threads) and otherwise to the number of tables still unreclaimed at the end of garbage collection.

Error Cases

- `Number` is not a variable
  - `type_error(variable)`

`delete_return(+TableEntryHandle,+ReturnHandle)` Tabling

Removes the answer indicated by `ReturnHandle` from the table entry referenced by `TableEntryHandle`. The value of each argument should be obtained from some previous invocation of a table-inspection predicate.

This predicate is low-level so no error checking is done. In Version 3.3, this predicate does not reclaim space for deleted returns, but simply marks the returns as invalid.

Warning: While useful for purposes such as tabled aggregation, `delete_return/2` can be difficult to use, both from an implementation and semantic perspective.

`invalidate_tables_for(+DynamicPredGoal,+Mode)` Tabling

This predicate supports invalidation of tables. Tables may become invalid if dynamic predicates on which they depend change, due to asserts or retracts. By default XSB does not change or delete tables when they become invalid; it is the user's responsibility to know when a table is no longer valid and to use the `abolish_table_*` primitives to delete any table when its contents become invalid.

This predicate gives the XSB programmer some support in managing tables and deleting them when they become invalid. To use this predicate, the user must have previously added clauses to the dynamic predicate, `invalidate_table_for/2`. That predicate should be defined to take a goal for a dynamic predicate and a

mode indicator and abolish (some) tables (or table calls) that might depend on (any instance of) that fact.
`invalidate_tables_for(+DynamicPredGoal),+Mode` simply backtracks through calls to all unifying clauses of
`invalidate_table_for(+DynamicPredGoal,+Mode)`. The `Mode` indicator can be any term as long as the two predicates agree on how they should be used. The intention is that `Mode` will be either 'assert' or 'retract' indicating the kind of database change being made.

Consider a simple example of the use of these predicates: Assume the definition of tabled predicate `ptab/3` depends on dynamic predicate `qdyn/2`. In this case, the user could initially call:

```
:- assert((invalidate_table_for(qdyn(_,_),_) :-
              abolish_table_pred(ptab(_,_,_)))).
```

to declare that when `qdyn/2` changes (in any way), the table for `ptab/3` should be abolished. Then each time a fact such as `qdyn(A,B)` is asserted to, or retracted from, `qdyn/2`, the user could call

```
:- invalidate_table_for(qdyn(A,B),_).
```

The user could use the hook mechanisms in XSB (Chapter 9) to automatically invoke
`invalidate_tables_for` whenever `assert` and/or `retract` is called.

Chapter 7

Multi-Threaded Programming in XSB

id with Version 3.0, XSB supports the use of POSIX threads to perform separable computations, and in certain cases to parallelize them. POSIX threads have a simple and clear API, and are available on all Unixes and by using open-source libraries, on Windows as well (see Section 7.8 to configure under Windows). This chapter introduces how to program with threads in XSB through a series of examplesi sections discuss performance aspects of our implementation as well as describing relevant predicates. A general knowledge of multi-threaded programming is assumed, such as can be found in [44, 8].

7.1 Getting Started with Multi-Threading

In Version 3.3 the default configuration of XSB does not include multi-threading. This is partly because multi-threading is new, and despite our efforts, the multi-threaded engine may contain bugs not present in the single-threaded engine. However the main reason is because in Version 3.3, not all libraries and packages have yet been made thread-safe so that not all configurations are supported with multi-threading. Both the XSB-calling-C and the C-calling-XSB interfaces are supported in the multi-threaded engine. All XSB libraries have been ported to the multi-threaded engine *except* the profiling library and the `string` library (which is not yet thread-safe). The packages `ODBC` and `CHR`, `FLORA-2`, and `regmatch` are supported by the multi-threaded engine, but the packages `dbdrivers`, `xpath`, `interprolog`, `smodels`, `perlmatch`, `libwww` and `posix` are not yet fully supported. We note, however that all basic/ISO Prolog functionality is thread-safe (at least, as far as we know :-).

With this in mind, making the multi-threaded engine is simple: configure and make XSB as in Chapter 3, but include the command `-enable-mt`. When you invoke the newly made

configuration of XSB you should see `engine: multi-threading` in the configuration list below the banner rather than `engine: slg-wam` as in the sequential engine.

Hello World for Beginners We naturally start with a program to print "hello world". Within the multi-threaded engine, import `thread_create/2` from the module `thread`, and type the command

```
?- thread_create(writeln('hello world'),Id)
```

you should see something like

```
Id = 1hello world
```

while the output is a little ugly, the "hello world" program does illustrate simple multi-threading at work. The calling thread (i.e. the thread controlling the command-line interpreter which we call T_{prompt}) executes the predicate `thread_create/2` which creates a thread T_{child} and immediately returns with the *XSB thread id* of the created thread. Meanwhile, T_{child} initializes its stacks and other memory areas and executes the goal `writeln('hello world')`. T_{child} and T_{prompt} share most of their process-level information: in particular they share a common I/O stream for standard output, leading to the output above. What is happening may be seen a little more easily by executing the command

```
?- thread_create((sleep(1),writeln('hello world')),Id)
```

In this case the interpreter reports that `F` is bound to a thread id, then about a second later `writeln/1` is executed.

The simple "hello world" program illustrates a couple of points. First, it is easy to create a thread in XSB and have that thread do work. Second, it can be tricky to coordinate actions among threads. We'll explore these two themes in more detail, but first suppose we are determined to extend out multi-threaded program so that it produces good output. One way to do this is to *join* T_{prompt} and T_{child} as follows

```
?- thread_create(writeln('hello world'),Id),
   thread_join(Id,ExitCode).
hello world

Id = 1
ExitCode = true
```

In this case, as soon as T_{prompt} has issued a command to create T_{child}, it executes `thread_join/2`. This latter predicate makes a system call to the underlying operating system to suspend

T_{prompt} until T_{child} has exited. `thread_join/2` returns a status term indicating whether the goal to thread `Id` succeeded, failed, exited with an error term, or was cancelled (in this case `Id` succeeded).

So far, we've introduced a few concepts that have not been fully discussed. First is the concept of an *XSB thread id*: XSB manages up to M active threads using XSB thread ids. The default for M in Version 3.3 is 1024, but M can be reset via the `max_threads` command line option to XSB (cf. Section 3.7). Once XSB is initialized, the maximum number of threads for an XSB session can be obtained at run time via the Prolog flag `max_threads` (cf. Section 6.12). It should be noted that the XSB thread id of a thread is different from the identifier of the underlying Pthread. An XSB thread id is a Prolog term, and unlike POSIX thread ids, XSB thread ids can be compared for equality using unification. The actual form of an XSB thread id, however, is subject to change between versions, so programs should not make use of the exact form of an XSB thread id. In the multi-threaded engine, the XSB thread id of any thread can be queried using the predicate `thread_self/1`.

7.2 Communication among Threads

Example 7.2.1 *Consider the program fragment*

```
:- dynamic p/1.

test:- thread_create(assert(p(1)),_X).
```

If you type the goal `?- test` *and then the goal* `?- p(X)`*, the call* `p(X)` *will fail.*

This illustrates an important point about dynamic and tabled predicates in the multi-threaded engine: by default clauses for a dynamic predicate `p/n` are private to the thread that asserts them; and by default tables created in an evaluation of a goal for `p/n` are private to the thread that evaluates the goal. This behavior contrasts to that of static code which is always shared between threads. In the example above, to allow `p(1)` to be visible to various threads, `p/1` must be declared to be shared with the following declaration.

```
:- table p/1 as shared.
```

or

```
:- dynamic p/1 as shared.
```

Alternately, dynamic and tabled predicates can be made thread-shared by default by invoking XSB with the command-line argument `-shared_predicates`, in which case a predicate may be declared thread-private through the declaration

```
:- table p/1 as private.
```

or

```
:- dynamic p/1 as private.
```

The ability to share dynamic code between predicates provides an extremely powerful mechanism for threads to communicate. So why does XSB make dynamic predicates thread-private by default? The main reason for this is that if dozens or hundreds of threads are running concurrently, shared dynamic code becomes an expensive synchronization point. Code for shared predicates must be more heavily mutexed than code for private predicates. In the case of dynamic code, XSB does not always immediately reclaim the space of retracted clause, to avoid the possibility of some computation backtracking into a clause that has been reclaimed. Rather, (like most Prologs), XSB may decide to garbage collect the space of the retracted clauses at a later time. While clause garbage collection is simple enough to implement for a single thread, garbage collecting clauses for shared dynamic predicates is difficult to do when multiple threads are active. Accordingly, in Version 3.3, space for shared dynamic clauses is not reclaimed until there is a single active thread. However for *thread-private* dynamic predicates, there is no problem in reclaiming space when multiple threads are active: from the engine's perspective garbage collection is no different than in the sequential case. Thus one set of reasons for making dynamic predicates private by default are based on efficiency [1].

The second reason for making dynamic predicates thread-private by default is semantic. Suppose thread T_1 starts a tabled computation that depends on the dynamic shared predicate `p/1`. While T_1 is computing the table, thread T_2 asserts a clause to `p/1`. T_1's table is likely to be inconsistent, leading to the problem of *read consistency* of any table that depends on thread-shared dynamic predicates. In Version 3.3, users are responsible for ensuring read consistency of any tables that depend on shared dynamic data. Future versions of XSB are intended to allow more sophisticated mechanisms for read consistency.

Not only can tables depend on thread-shared or thread-private dynamic data, but the tables themselves may be thread-shared or thread-private. Like dynamic code, the declaration `table Predspec as shared` allows sharing of tables for a predicate evaluated with call-variance to be shared among threads [2]. To some extent, tabling considerations for making a predicate thread-shared or thread-private are like those of dynamic code. Thread-private tables require fewer synchronization points overall. The situation for reclaiming space for abolished tables is analogous to reclaiming space for retracted dynamic clauses: the garbage collector treats abolished tables for thread-private predicates as in the sequential case, while space for shared tables is not reclaimed until there is a single active thread. However the precise semantics of how tabling information is shared depends on whether

[1] Future versions may offer more powerful garbage collectors for shared predicates.

[2] In Version 3.3, tabled predicates using call-subsumption are always private; an attempt to make such a predicate thread-shared throws an exception.

the multi-threaded engine is configured with the default local evaluation or with batched evaluation. As discussed in Chapter 5, local evaluation is so-named because computation always takes place in the SCC most recently created, and no answer is returned outside of an SCC until the SCC has been completely evaluated. Within this scheduling strategy it is not often useful to share answers between tables that have not been completed – as local evaluation would allow these answers to be returned only if the tables were in the same SCC. This leads to a concurrency semantics called *Shared Completed Tables* [48, 49, 51]. Shared Completed Tables can in fact be supported by a relatively simple algorithm for optimistic concurrency control. If goals to two mutually dependent tables $Table_a$ and $Table_b$ are called concurrently by two different threads, $Thread_a$ and $Thread_b$, nothing is done until it is detected that $Table_a$ and $Table_b$ are both incomplete and are contained in the same SCC of the table dependency graph. At that time, one of the threads (e.g. $Thread_a$) takes over recomputation of all tables in the SCC, and when the SCC is completed, any remaining answers are returned to other threads that had invoked goals in the SCC. While $Thread_a$ is completing this computation, $Thread_b$ suspends until the SCC is complete. Thus the semantics of Shared Completed Tables supports concurrency for the well-founded semantics, but only supports the most coarse-grained parallelism.

Batched evaluation, on the other hand, allows answers to be returned outside of an SCC before that SCC has been completed. Concurrency control for batched evaluation is similar to that for local evaluation, except in the following case. Assume as before that $Table_a$, first called by $Thread_a$, and $Table_b$ first called by $Thread_b$ are determined to be in the same SCC, and that $Thread_a$ takes over computation of subgoals in the SCC. Now, $Thread_b$, rather than suspending, may continue work. In particular, $Thread_b$ can return any answers in $Table_b$ that it finds whenever it finds them, regardless of whether they have been produced by $Thread_b$ (before $Thread_a$ took over the SCC) or by $Thread_a$ (afterwards). We call this type of concurrency semantics, *Table Parallelism*. Table Parallelism can be used to program producer-consumer examples, as well as to implement Or- and And- parallelism. Table Parallelism was first introduced in [26], but the mechanism now used for implementing Table Parallelism differs significantly from what was described there. In Version 3.3 of XSB, the implementation of Table Parallelism is experimental: in particular, it does not yet support tabled negation.

As mentioned, for either semantics of shared tables, in Version 3.3, users of thread-shared tables are responsible for ensuring read consistency. Note that, in principle, thread-shared tables may depend on thread-private tables and vice-versa. Either type of table may depend on thread-private or thread-shared dynamic code. In addition, a predicate may be *both* dynamic and tabled, and its clauses and tables may be either thread-private or thread-shared.

7.3 Thread Statuses: Joinable and Detached Threads

So far we have assumed that the goal called in `thread_create/2` terminates normally — by success or failure. But what if a thread throws an error while executing a goal? How long should error information for a thread persist, and how can it be checked?

Our approach relies on the semantics of Pthreads, which can be either *joinable* or *detached*. Within this framework, we consider a thread to be *valid* if it has not yet terminated, or if it is joinable and has not yet been joined. After a joinable Pthread T_{dead} has terminated, status information about T_{dead} persists until some other thread joins it — at which time the information is removed. On the other hand, if T_{dead} is detached, status information is removed as soon as T_{dead} terminates. Reclamation of thread status information may be contrasted to that of thread-specific data structures such as stacks. Upon normal or exceptional termination of T_{dead}, any memory automatically allocated in the process of initializing T_{dead}'s, or executing its goal – including stacks, private dynamic code, private tables is reclaimed. In addition, any mutexes held by T_{dead}, are released. On the other hand, XSB-specific *status* information about threads follows the Pthread model: by default, error information is available when joining a joinable thread, but not otherwise [3].

Example 7.3.1 *Suppose the goal*

```
?- thread_create(functor(X,Y,Z),F).
```

is executed. By default, this will produce the result

```
X = _h113
Y = _h127
Z = _h141
F = 1++Error[XSB/Runtime/P]: [Instantiation]  in arg 2 of predicate functor/3
```

In fact, the variable bindings are output to `STDOUT`*, while the error message*

```
++Error[XSB/Runtime/P]: [Instantiation]  in arg 2 of predicate functor/3
```

is output to `STDERR`*, and may be redirected. The call*

```
?- thread_join(2,Error).
```

returns

[3] This behavior can, of course, be overridden by embedding goals within `catch/3` and handling errors separately, or simply by adding a default user error handler: see Chapter 12 for details.

```
Error = exception(error(instantiation_error, in arg 2 of predicate functor/3,
              [[Forward Continuation...,... standard:call/1,... standard:catch/3],
                Backward Continuation...]))
```

In other words, `Error` *is instantiated to a* `exception/1` *structure, containing a standard XSB error term (including backtrace).*

The error term in the above example is one example of a *thread status* term. In XSB, these thread statuses are as follows.

- `running` The thread is still executing
- `true` The thread has exited and successfully evaluated its goal.
- `false` The thread has exited and failed its goal.
- `exception(Exception)` The thread has been terminated due to an uncaught exception, represented by the term `Exception` which is a standard XSB error term.
- `cancelled(Exception)` The thread has been terminated due to a thread cancellation, represented by the term `Exception` which is a standard XSB error term.
- `exited(ExitTerm)` The thread has been terminated using the predicate `thread exit/1` with `ExitTerm` as its argument.

Any of these statuses except `running` may be returned by `thread_join/2`. In Prolog, the statuses of exited threads provide much more information than C exit codes.

As with pthreads, XSB threads are created as joinable by default, but can be created as detached using an option in `thread_create/3`. Alternatively, a thread created as joinable can be made detached by `thread_detach/1`. All of the predicates mentioned in this section are fully described in Section 7.9.

7.4 Prolog Message Queues

While Prolog predicates can communicate through shared dynamic code and tables, message queues provide a useful mechanism for one thread to pass a command to another or to synchronize on the return of data. A Prolog message queue contains an arbitrary Prolog Term, and unification may be used to obtain a term from a queue. More specifically, when a producer writes *Term* into a queue, the term is copied into the queue so that no binding are shared between *Term* and the producer's stacks. *Term* may include structures or lists and need not be bound, and any variable bindings within *Term* are preserved. When a

consumer T_{cons} accesses the queue it provides a goal G and traverses the queue until it finds a term in the queue that unifies with G. If T_{cons} finds a term in the queue that unifies with G, it removes it from the queue and continues in its computation. If there is no term in the queue that unifies with G, T_{cons} will suspend until at least one other term is added to the queue. When it awakens it will retraverse the queue from the beginning to find a term that unifies with G [4]. Because of the behavior of message queues, it is usually good programming practice to ensure that terms written into the queue will unify with the goals of consumers. This can usually be done by abstracting a consumers goal (say to a variable, `X`) or by splitting one "multiplexed" queue into two separate queues.

A Prolog message queue can be *public* or *private*: a public message queue can have any number of readers and writers. In addition, each thread T also has a private message queue Q_T: any thread can write to Q_T but only T can read from it. The following example illustrates how to use private message queues:

```
test_private:-
     thread_id(Tid),
     thread_create(child(Tid),Id),
     thread_get_message('Mom Im home'(ChildId)),
     thread_send_message(ChildId,'Im in the kitchen'),
     thread_join(Id,_).

child(Parent):-
     thread_self(Id),
     thread_send_message(Parent,'Mom, Im home'(Id)),
     thread_get_message('Im in the kitchen').
```

If `?- test` is called by T_{parent}, it will obtain its own thread id, create a new thread T_{child} to execute `child/1`, wait for a message that T_{child} is operational using `thread_get_message/1`, send a message to T_{child} using `thread_send_message/2` and then wait for T_{child} to terminate. When it is created, T_{child} immediately sends a message to its parent, waits for a message back from its parent, and terminates.

It is illustrative to compare

```
test_public:-
     message_queue_create(Qid)
     thread_create(child(Qid),Id),
     thread_get_message(Qid,'Mom Im home'(ChildQ)),
     thread_send_message(ChildQ,'Im in the kitchen'),
     thread_join(Id,_),
```

[4]Note that this traversal is necessary since the position of T_{cons} may in the queue may not be valid due to the addition and deletion of terms by other threads.

```
     message_queue_destroy(Qid).

child(ParentQ):-
     message_queue_create(Qid),
     thread_send_message(ParentQ,'Mom, Im home'(Qid)),
     thread_get_message(Qid,'Im in the kitchen'),
     message_queue_destroy(Qid).
```

`test_public` is essentially the same program as `test_private`, but uses public message queues, rather than private queues. The public queues must be explicitly created and destroyed, and they are referred to via a queue id (or alias) rather than via a thread id (or alias). Like thread ids, queue ids in XSB are integers, but a user should not depend on their precise form: aliases should be used if a user wants control of queue or thread identifiers.

Thus, apart from who can read from them, private and public message queues have essentially the same behavior. In addition, any queue can be created with a bound, *size* on the number of messages (terms) it contains. If *size* is 0, the queue is taken to be unbounded. If a bounded queue already contains *size* elements, the producer will suspend until one or more elements are removed from the queue. For public queues, a size argument can be passed using the predicate `message_queue_create/2` (See Section 7.9). For private queues, and for public queues created with `message_queue_create/1`, the value for *size* is taken from the settable Prolog flag `max_queue_terms`. The default value for `max_queue_terms` is currently 100.

7.5 Thread Cancellation and Signalling

There may be a number of situations in which it is useful to give one thread the ability to cancel the execution of another thread. Within the semantics of pthreads, this is called *thread cancellation*. At the C level, thread cancellation can be tricky, as mutexes must be released, allocated memory freed, and so on. Accordingly, the predicate `thread_cancel/1` cancels XSB threads by acting purely within the SLG-WAM engine. When thread T_1 interrupts thread T_2, T_1 writes to the thread-specific XSB interrupt vector in T_2. Later, when T_2 checks its interrupt vector, it throws a cancellation error, which causes it to clean up its mutexes, memory, private tables and dynamic code, and then exit.

Thread cancellation is just a special case of Prolog thread signalling, in which one thread can signl another thread to interrupt what it is doing and execute a goal [5]. The following code provides an example of thread signalling.

```
test_signal:-
```

[5] Prolog thread signalling should be distinguished from signalling at the OS level where functions such as `pthread_kill()` or `kill()` are used.

```
     thread_self(Tid),
     thread_create(child(Tid),T1,[]),
     thread_get_message('Im alive'),
     thread_signal(T1,writeln('Excuse me, but did you just kick me?')),
     thread_join(T1,_Ball),
     writeln(test5_ok).

child(Tid):-
     thread_send_message(Tid,'Im alive'),
     loop.

loop:- loop.
```

`test_signal` begins like `test_private`, but rather than waiting for a signal from its parent, the child goes into an infinite loop. The signal interrupts the child, which writes out a message and returns to the infinite loop.

Thread signals may be any callable Prolog term. As with private message queues, each thread is created with its own private signal queue (there are no public signal queues). In XSB, threads handle Prolog signal interrupts (including cancellation messages) at the same time as attributed variable interruptions. This means that Prolog signal interrupts will be handled very quickly if SLG-WAM code is being executed. On the other hand, if a thread executing a builtin to, e.g. waiting on a mutex, the thread may be immediately awakened to process the signal, but not always: if a thread is waiting for input on a stream or socket, the thread may not handle the signal interrupt until the input is received. Furthermore, in a very few critical sections of code, thread signal handling may be distabled. However, the thread is guarenteed to handle the signal interrupt or cancellation message very shortly after it finishes the builtin.

So, while thread cancellation and signalling is useful, it must be used with a certain amount of care. Any thread can signal any other thread, and any thread can cancel any other thread, with the exception that the *main* thread, which controls the console (or interface to C or interprolog) cannot be cancelled. The main thread always has XSB thread id `0` in both the single-threaded and multi-threaded systems, and has the thread alias `main`.

7.6 Performance and other Considerations

For running programs that do not use multiple threads, the multi-threaded engine has a minimal overhead compared to the single-threaded engine. Times for single-threaded execution of Prolog or tabled programs range from about 10–20% slower to 10–20% *faster* for the multi-threaded engine compared to the single-threaded engine. Speedups for running multiple threads on multiple processors depends heavily on the applications run and on the underlying operating system.

The size of a given thread may be a consideration for multi-threaded applications, especially on a 32-bit platform (the multi-threaded engine has been tested on both 32-bit and 64-bit platforms). Each thread has an area of thread-private variables that are "global" to its own virtual machine. This area, called the *thread context*, which accounts for about 4 Kbytes of space. Much larger are the various stacks used by the threads for tabled and Prolog execution. Almost all of XSB's memory areas are fully expandable, and the initial size of the execution stacks may be set explicitly as options in `thread_create/3`. Explicitly setting a default thread stack size for an XSB thread to be smaller than the default process stack size may be useful for applications that have a large number of concurrently running threads.

Other performance considerations involve the contention by threads for shared resources. As discussed above, contention may arise when creating or abolishing tables, or when asserting or retracting dynamic code — however in either case thread-private predicates give rise to less contention than thread-shared predicates. In terms of I/O, each XSB stream up to the maximum number of file descriptors has its own mutex; as a result threads writing to different streams will not contend for I/O. Thus, in multi-threaded applications, it may be more efficient to open and close streams and access these streams explicitly, than to redirect standard input or standard output through `see/1` and `tell/1`.

7.7 Examples of Multi-Threaded Programs in XSB

Figure 7.1 shows an example of a multi-threaded goal server in XSB, which makes use of XSB's socket library (see Volume 2 of this manual) [6]. The server listens for requests from clients using `socket_accept/2` and spawns a thread to handle each request via the goal `accept_client/2` which actually calls the goals. The goals executed by the server could be tabled and take advantage of the shared table implementation, shared dynamic code, or any other mechanism in XSB. Halting of the server is done by the thread cancellation mechanism, and a shared dynamic predicate is used to make the server's thread identifier known to the other threads. Note that this is the reason a specific thread was created to execute `server_loop`, as the main thread cannot be canceled.

Figure 7.2!la uses a multi-threaded execution model to compute a series of prime numbers in parallel [7], The master thread partitions the work and creates two worker threads. The worker threads each compute its portion of the interval and return their results to the master through a message queue.

Notice how the `primes/2` predicate uses difference lists to avoid the use of the append predicate[8], and while threads don't share variables, the bindings of the terms in the messages

[6] Material in this section is based on [48].

[7] This example was inspired by a similar example for multi-threaded computation of primes in from Logtalk [52]

[8] For a description on how to program with difference lists see a Prolog programming text, such as[68]).

```
:- dynamic server_id/1 as shared.

server :-
   socket(SockFD),
   socket_set_option( SockFD, linger, SOCK_NOLINGER ),
   xsb_port(XSBport),
   socket_bind(SockFD, XSBport),
   socket_listen(SockFD,Q_LENGTH),
   thread_create( server_loop(SockFD), Id, [] ),
   assert( server_id(Iden) ),
   thread_join( Iden ).

server_loop(SockFD) :-
   socket_accept(SockFD, SockClient),
   thread_create( attend_client(SockClient) ),
   server_loop(SockFD).

attend_client(SockClient) :-
   socket_recv_term(SockClient, Goal),
   (  Goal == stop ->
      retract(server_id( Server )),
      thread_cancel( Server ),
      socket_close( SockClient ),
      thread_exit
   ;  true
   ),
   (  is_valid(Goal) ->
      call(Goal),
      socket_send_term(SockClient, Goal),
      fail,
   ;  socket_send_term(SockClient, invalid_goal(Goal))
   ),
   socket_send_term(SockClient, end),
   socket_close(SockClient).
```

Figure 7.1: A multi-threaded goal server in XSB

are correctly handled, allowing Prolog's unification to assume its full power. Although only two threads are used, the program could easily be extended to use an arbitrary number of threads

7.8 Configuring the Multi-threaded Engine under Windows

Libraries for pthreads are included on most versions of Unix and Linux. Windows also supports multi-threading, but with a somewhat different semantics and API than that of pthreads. To run multi-threaded XSB under Windows, a library must be included to translate the Pthread library, used by XSB, to the native thread API of Windows.

Different libraries are available for this purpose. Internally, the multi-threaded engine has been tested using the Win32 pthreads interface, available via `http://sourceware.org/pthreads-win32`, but other libraries may also work, including Pthread library included with Cygwin. To install the sourceware library, let `$XSBENV` be the parent directory of `$XSBDIR` the root directory of XSB – i.e. `$XSBENV` is the directory into which XSB is installed.

- Download a version such as pthreads-2005-01-25.exe or later, and extract it into `$XSBENV`
  pthreads. Add `$XSBENV\pthreads\Pre-built\lib` to your system path
- To configure with windows enter the commands:

  ```
  sh configure --enable-mt --with-wind \
  --with-includes='c:\XSBSYS\XSBENV\pthreads\Pre-built\include \
  --with-static-libraries='c:\XSBSYS\XSBENV\pthreads\Pre-built\lib

  makexsb_wind
  ```

  Note that the Unix `sh` shell must be available in order to reconfigure.
- To configure with cygwin enter the commands:

  ```
  sh configure --enable-mt \
    --with-includes='/cygdrive/c/XSBSYS/XSBENV/pthreads/Pre-built/include' \
    --with-static-libraries='/cygdrive/c/XSBSYS/XSBENV/pthreads/Pre-built/lib'

  sh makexsb --config-tag=mt
  ```

7.9 Predicates for Multi-Threading

The predicates described in this section do not address tabling or dynamic code. With only a few minor deviations the provisional working standard described in [35] is supported.

```
prime(P, I) :- I < sqrt(P),!.
prime(P, I) :- Rem is P mod I, Rem = 0, !, fail.
prime(P, I) :- I1 is I - 1, prime(P, I1).

prime(P) :- I is P - 1, prime(P, I ).

list_of_primes(I, F, Tail, Tail) :- I > F, !.
list_of_primes(I, F, [I|List], Tail) :-
    prime(I), !,
    I1 is I + 1, list_of_primes(I1, F, List, Tail).
list_of_primes(I, F, List, Tail) :-
    I1 is I + 1, list_of_primes(I1, F, List, Tail).

partition_space(N, H, H1) :-
    H is N//2, H1 is H + 1.

worker( Q, Iden, I, F, List, Tail) :-
    list_of_primes( I, F, List, Tail),
    thread_send_message( Q, primes(Iden,List,Tail) ).

master( N, L ) :-
    partition_space( N, H, H1),

    message_queue_create(Q),
    thread_create( worker(Q, p1, 1, H, L, L1) ),
    thread_create( worker(Q, p2, H1, N, L1, []) ),

    thread_get_message( Q, primes(p1,L,L1) ),
    thread_get_message( Q, primes(p2,L1,[]) ).
```

Figure 7.2: A multi-threaded program to calculate prime numbers in XSB

As a result, these predicates are substantially the same as those in SWI, YAP, and other Prologs. In the single-threaded engine, semantically correct calls to these predicates will give a miscellaneous error.

`thread_create(+Goal,ThreadId,+OptionsList)`

When called from thread T, this predicate creates a new XSB thread T_{new} to execute `Goal`. When goal either succeeds, throws an unhandled error, exits, or fails, T_{new} exits, but `thread_create/2` will succeed immediately, binding `ThreadId` to the XSB thread id of T_{new}. `Goal` must be callable, but need not be fully instantiated. No bindings from `Goal` are passed back from T to T_{new}, so communication between T_{new} and T must be through tables, asserted code, message queues or other side effects.

`OptionList` allows optional parameters in the configuration for the initial size of XSB stacks, for aliases, and to indicate whether T_{new} is to be created as detached. Note that XSB threads allow automatic stack allocation, so that the size options may be most useful for (32-bit) applications with very large numbers of threads. In this case, setting initial stack sizes to be small may allow more threads to be created on a given hardware platform. Also note that only XSB stacks are affected, the stack size of the underlying Pthread remains unaltered.

- `glsize(N)`: create thread with global (heap) plus local stack size initially set to `N` kbytes. If not specified, the default size is used. The default size can be set at the command line (cf. Section 3.7), and altered at run time by the Prolog flag `thread_glsize` (cf. Section 6.12).
- `tcpsize(N)`: create thread with trail plus choice point stack size initially set to `N` kbytes. If not specified, the default size is used (cf. Section 3.7). The default size can be set at the command line (cf. Section 3.7), and altered at run time by the Prolog flag `thread_tcpsize` (cf. Section 6.12).
- `complsize(N)`: create thread with completion stack size initially set to `N` kbytes. If not specified, the default size is used (cf. Section 3.7). The default size can be set at the command line (cf. Section 3.7), and altered at run time by the Prolog flag `thread_complsize` (cf. Section 6.12).
- `pdlsize(N)`: create thread with `N` kbytes of unification stack. If not specified, the default size is used (cf. Section 3.7). The default size can be set at the command line (cf. Section 3.7), and altered at run time by the Prolog flag `thread_pdlsize` (cf. Section 6.12).
- `detached(Boolean)`: if `Boolean` is true, creates detached thread. If `Boolean` is false, the thread created will be joinable, while if no option is given the default will be used. In Version 3.3 threads are created joinable by default, but this default can be altered at run time by the Prolog flag `thread_default` (cf. Section 6.12).
- `on_exit(Handler)`: Ensures that `Handler` is called whenever the thread exits: whether that exit arises from success of `Goal`, failure, throwing an error that is unhandled in the user's program, or an explicit call to `thread_exit/1`.

- `alias(Alias)`: Allow thread `ThreadId` to be referred to via `Alias` in all standard thread predicates. `Alias` remains active for `ThreadId` until it is joined. Note that the main XSB thread has alias `main`.

Finally, each thread is created with a signal queue and a private message queue, so these queues do not need to be explicitly created. Their size is obtained through the settable Prolog flag `max_queue_terms`.

Error Cases

- `Goal` is a variable
  - `instantiation_error`.
- `Goal` is not callable
  - `type_error(callable,Goal)`.
- `ThreadId` is not a variable
  - `type_error(variable,ThreadId)`
- `OptionList` is a partial list or contains an option that is a variable
  - `instantiation_error`
- `OptionList` is neither a list nor a partial list
  - `type_error(list,OptionsList)`
- `OptionList` contains an option, `Option` not described above
  - `domain_error(thread_option,Option)`
- An element of `OptionsList` is alias(A) and A is already associated with an existing thread, queue, mutex or stream
  - `permission_error(create,alias, A)`
- An element of `OptionsList` is alias(A) and A is not an atom
  - `type_error(atom,A)`
- An element of `OptionsList` is `on_exit(Handler)` and `Handler` is not callable
  - `type_error(callable,Handler)`.
- No more system threads are available (EAGAIN)
  - `resource_error(system threads)`

`thread_create(+Goal,-ThreadId)`
Acts as `thread_create(Goal,ThreadId,[])`.

`thread_create(+Goal)`
Acts as `thread_create(Goal,_,[detached(true)])`.

`thread_join(+Threads_or_aliases,-ExitDesignators)`

When `thread_join/2` is called by thread T, `Threads_or_aliases` must be instantiated to either 1) an XSB thread id or alias; or 2) a list where each element is an XSB thread id or an alias; `ExitDesignators` must be uninstantiated. The action of the predicate is to suspend T until all of the threads denoted by `Threads_or_aliases` have exited. At this time, any remaining resources for the threads in `ThreadIds` will have been reclaimed. Upon success `ExitDesignators` is either a the thread status of the associated thread (see page 276) or a list of such elements.

Error Cases

- `Thread_or_Aliases` is not instantiated
  - `instantiation_error`
- `Threads_or_aliases` is not a list of XSB thread ids or aliases
  - `domain_error(listof(thread_or_alias),ThreadIds)`
- `ExitDesignators` is not a variable
  - `type_error(variable,ExitDesignatorst)`
- `ThreadId` does not correspond to a valid thread
  - `existence_error(valid_thread,ThreadId)`
- `ThreadId` does not correspond to a joinable thread (i.e. `ThreadId` is detached).
  - `permission_error(join,non_joinable_thread,ThreadId)`

`thread_exit(+ExitTerm)`

Exits a thread T with `ExitTerm` after releasing any mutexes held by T, freeing any thread-specific memory allocated for T (we hope), as well as calling any exit handlers for T. `ExitTerm` will be used if the caller of T joins to T, but will be ignored in other cases. There is no need to call this routine on normal termination of a thread as it is called implicitly on success or (final) failure of a thread's goal.

Error Cases

- `ExitCode` is a variable
  - `instantiation_error`

`thread_self(?ThreadId_or_Alias)`

If `ThreadId` is an atom, unifies `ThreadId_or_Alias` with an alias of the calling thread. Otherwise, unifies `ThreadId_or_Alias` with the XSB thread id of the calling thread. There are no error conditions.

`thread_detach(+Thread_or_Alias)`

Detaches a joinable thread denoted by `Thread_or_Alias` so that all resources will be reclaimed upon its exit. The thread denoted by `ThreadId` will no longer be joinable,

once it is detached. If `Thread_or_Alias` has already exited, all resources used by `Thread_or_Alias` are removed from the system.

Error Cases

- `Thread_or_Alias` is a variable
  - `instantiation_error`
- `Thread_or_Alias` is not a thread id or alias
  - `domain_error(thread_or_alias,Thread_or_Alias)`
- `Thread_or_Alias` does not correspond to a valid thread
  - `existence_error(valid_thread,Thread_or_alias)`
- `Thread_or_Alias` is active but not joinable
  - `permission_error(thread_detach,thread,Thread_or_Alias)`

`thread_cancel(+Thread_or_Alias)`

Cancels the XSB thread denoted by `Thread_or_Alias`. The cancellation does not use Pthread cancellation mechanisms, rather it uses XSB's interrupt mechanism to set `Thread_or_Alias`'s interrupt vector [9]. When this interrupt vector is checked, `Thread_or_Alias` will throw a thread cancellation error, which can be caught within `Thread_or_Alias` like any other error. However, the default behavior is for `Thread_or_Alias` to exit with an exit ball indicating that it has been cancelled.

As noted above, an executing thread that is cancelled will exit very shortly after the `thread_cancel/1` predicate is called. Blocked threads, however, are not always guarenteed to exit when cancelled. Currently a blocked thread may be cancelled

- when it is waiting to read or write a message on a queue
- when it is executing `thread_sleep/1`

On the other hand, a blocked thread may not be cancelled while it is waiting to read from a stream or waiting for a mutex.

During critical operations a thread may want to prevent itself from being cancelled. This can be done by If `?- thread_cancel(T)` is called for a thread `T` for which cancelling has been disabled, `T` will be cancelled immediately after `T` re-enables cancellation through calling the predicate `thread_enable_cancel/0`.

The main XSB thread cannot be cancelled; apart from that any thread can cancel any other thread.

Error Cases

- `Thread_or_Alias` is not instantiated
  - `instantiation_error`

[9] This interrupt vector is checked upon every it is checked on every SLG-WAM call and execute instruction.

- `Thread_or_Alias` is not a thread id or alias
  - `domain_error(thread_or_alias,Thread_or_Alias)`
- `Thread_or_Alias` does not correspond to valid thread
  - `existence_error(valid_thread,Thread_or_Alias)`
- `Thread_or_Alias` denotes the main thread.
  - `permission_error(cancel,main_thread,Thread_or_Alias)`

`thread_signal(Thread_or_Alias,Goal)`

`thread_signal(ThreadOrAlias, Goal)` interrupts thread `ThreadOrAlias` so that it executes `Goal` at the first opportunity. Specifically, once `Goal` is placed onto the signal queue of `ThreadOrAlias` and the interrupt vector of `ThreadOrAlias` is adjusted, `thread_signal/2` succeeds. `ThreadOrAlias` handles the interrupt asynchronously, and if the interrupt is handled while `ThreadOrAlias` is executing a goal with continuation C, all solutions for `Goal` will be obtained, and the failure continuation of `Goal` will be C. If `Goal` throws an exception E, the continuation will be the handler for E.

For blocked threads, signalling works much like cancellation (described above), and a blocked thread will handle a signal whenever it can be cancelled. However, the thread does not return to the blocking operation *after* the signal – rather it will execute the signal and then execute the continuation to be taken after the blocking operation.

Error Cases

- `Thread_or_Alias` is not instantiated
  - `instantiation_error`
- `Thread_or_Alias` is not a thread id or alias
  - `domain_error(thread_or_alias,Thread_or_Alias)`
- `Thread_or_Alias` does not correspond to valid thread
  - `existence_error(valid_thread,Thread_or_Alias)`
- `Goal` is not instantiated
  - `instantiation_error`
- `Goal` is not callable
  - `type_error(callable,Goal)`

`thread_disable_cancel` module: `thread`

Disables the calling thread from being cancelled, so that it can be ensured that critical operations can run to completion. This predicate always succeeds.

`thread_enable_cancel` module: `thread`

Enables the calling thread to be cancelled. By default, threads may be cancelled, so this predicate needs to be called if `thread_disable_cancel/0` has been previously called. This predicate always succeeds.

`thread_yield`

Make the calling thread ready to be run *after* other threads of the same priority. This predicate relies on the real-time extensions to pthreads specified in POSIX 1b, and may not be available on all platforms.

Error Cases

- The current platform does not support POSIX real-time extensions
  - `misc_error`

`thread_property(?ThreadOrAlias,?Property)`

If `ThreadOrAlias` is instantiated, unifies `Property` with current properties of the thread that unify with `Property`; if `ThreadOrAlias` is a variable, backtracks through all the current threads whose properties unify with `Property`. Note that there is no guarantee that that the information returned will be valid, due to concurrency issues.

Currently `Property` can have the form

- `detached(Bool)`: if `Bool` is true the thread is detached, otherwise it is joinable.
- `alias(Alias)`: if the thread has an alias `Alias`
- `status(Status)`: see Section 7.3 for thread statuses that are currently supported.

Example: The following predicate may be used to clear resources from the thread table, although due to concurreny reasons, non-running threads may remain in the thread table after this predicate terminates.

```
clear_thread_table:-
    thread_property(Tid,status(S)),
    \+ (S = running),
    thread_join(Tid),
    fail.
clear_thread_table.
```

Error Cases

- `ThreadOrAlias` is neither a variable nor an XSB thread id nor an alias
  - `domain_error(thread_or_alias, ThreadOrAlias)`
- `ThreadOrAlias` is not associated with a valid thread
  - `existence_error(thread, ThreadOrAlias)`

`thread_sleep(+MilliSeconds)`

Causes the calling thread to sleep approximately `MilliSeconds` before resuming. A thread may be cancelled while sleeping. However, a sleeping thread that is signalled will execute the signalled goal and resume execution *without* returning to sleep.

Error Cases

- `Seconds` is a variable
  - `instantiation_error`.
- `Seconds` is not an integer
  - `type_error(integer, Seconds)`.

7.9.1 Predicates for Thread Synchronization and Communication

Threads can communicate to some extent through shared tables and dynamic code. However, it is often useful to use message queues as a synchronizable form of communication. Similarly, while the XSB engine itself is thread-safe, thread synchronization may be needed when calling a package that is not itself thread safe (see the beginning of this chapter for a list of which packages are and are not thread-safe). Synchronization may also be needed to protect data accessed by foreign function calls, or to coordinate responses to external events.

Prolog Message Queues

As described previously, each thread is created with a private message queue that is readable only by itself. The following predicates are used to communicate using private and public message queues.

`message_queue_create(-Queue,+Options)`

Creates a new public message queue with identifier `Queue`. `Options` allows optional parameters to be passed for the maximum number of terms in the queue, and for aliases of the queue.

- `max_terms(N)`: create queue so that it can contain at most `N` terms before writes to the queue block. If not specified, the default size is used. This default can be queried and altered at run time via the Prolog flag `queue_max_terms`. (cf. Section 6.12). If the flag `queue_max_terms` is set to 0, the queue size will be bounded only by available memory.
- `alias(Alias)`: Allow queue `Queue` to be referred to via `Alias` in all standard queue predicates. `Alias` remains active for `Queue` until it is destroyed.

Error Cases

- Queue is not a variable
  - `type_error(variable,Queue)`
- Options is a partial list or a list with an element that is a variable
  - instantiation error

- Options is neither a partial list or a list
  - type error(list, Options)
- `Options` contains an option, `Option` not described above
  - `domain_error(queue_option,Option)`
- An element of `Options` is `alias(A)` and `A` is already associated with an existing thread, queue, mutex or stream
  - `permission_error(create,alias, A)`
- An element of `Options` is `alias(A)` and `A` is not an atom
  - `type_error(atom,A)`

`message_queue_detroy(+Queue_or_Alias)`

Destroys a public message queue with alias or id `Queue_or_alias`, as created by `message_queue_create/[1,2]`. If any threads are currently waiting on `Queue_or_Alias` to read or write a term, they will be awakened and will throw an existence error.

Error Cases

- `Queue_or_Alias` is a variable
  - `instantiation_error`
- `Queue_or_Alias` is not a queue id or alias
  - `domain_error(queue_or_alias,Queue_or_Alias)`
- `Queue_or_Alias` denotes a private message queue or signal queue rather than a public message queue
  - `permission_error(destroy,private_signal_or_message_queue,Queue_or_Alias)`
- `Queue_or_alias` is not the queue name or alias of a public message queue.
  - `existence_error(message_queue, Queue_or_Alias)`

`thread_send_message(+Queue_or_Alias,#Message)`

`Queue_or_alias` may either be a queue id or alias, or a thread id or alias in which latter case the private queue for a thread is used. If there are fewer terms on `Queue_or_Alias` than the queue's maximum allowed number `thread_send_message/2` puts `Message` onto `Queue_or_Alias`, and returns immediately. Otherwise, the calling thread suspends until there are fewer elements on `Queue_or_Alias` than the queue's maximum allowed number, when the thread will be awakened to put `Message` onto the queue.

Error Cases

- `Queue_or_Alias` is a variable
  - `instantiation_error`
- `Queue_or_Alias` is not a queue id, queue alias, thread id, or thread alias.

- `domain_error(queue_or_alias,Queue_or_Alias)`

`thread_get_message(+Queue_or_Alias,?Message)`

If there are terms on `Queue_or_Alias` `thread_get_message/2` traverses `Queue_or_Alias` to obtain the first term T that unifies with `Message`. If T exists, the predicate returns with `Message` bound to the most general unifier of `Message` and T. If there are no terms on `Queue_or_Alias` or if no terms unify with `Message`, the calling thread suspends until at least one term is added to `Queue_or_Alias`. When the thread awakes, it will recheck `Queue` from its beginning for a term that unifies with `Message`.

Error Cases

- `Queue_or_Alias` is a variable
  - `instantiation_error`
- `Queue_or_Alias` is not a queue id or alias
  - `domain_error(queue_or_alias,Queue_or_Alias)`
  - `existence error(queue, Queue_or_Alias)`

`thread_get_message(?Message)`

Acts as `thread_get_message/2`, but on a thread's private queue.

`thread_peek_message(+Queue_or_Alias,?Message)`

If there are terms on `Queue_or_Alias` `thread_peek_message/2` traverses `Queue_or_Alias` to obtain the first term T that unifies with `Message`. If T exists, the predicate returns with `Message` bound to the most general unifier of `Message` and T. If there are no terms on `Queue_or_Alias` or if no terms unify with `Message`, the predicate fails.

Error Cases

- `Queue_or_Alias` is a variable
  - `instantiation_error`
- `Queue_or_Alias` is not a queue id or alias
  - `domain_error(queue_or_alias,Queue_or_Alias)`
- `Queue_or_Alias` is not associated with a current queue
  - `existence error(queue, Queue_or_Alias)`

`thread_peek_message(?Message)`

Acts as `thread_peek_message/2`, but on a thread's private queue.

User-defined Mutexes

Usually, running multi-threaded evaluations does not requre a user to set any mutexes – necessary mutexes are handled by XSB itself (we hope), and programs can often be written so that user-level locking is unnecessary. However, under certain conditions, locking is useful or even necessary: for instance, a user may need to set a lock so that a set of shared dynamic facts cannot be accessed when it is updated.

One of the simplest and most powerful primitives for locking are mutexes. The mutexes provided by the following predicates are *recursive*: if a thread T locks a recursive mutex M, any calls to `mutex_lock(M)` made by T will immediately succeed without suspending while M is locked. Other threads that attempt to lock M will suspend until M is unlocked. To unlock M after n calls to `mutex_lock(M)`, T must make n calls to `mutex_unlock(M)`.

When using mutexes in XSB, programmers must not only avoid explicitly creating deadlocks, but must also ensure that a mutex is unlocked when leaving a critical area, and destroyed when it is no longer needed. Making sure that this happens for successful goals, for failed goals and for goals that raise exceptions can sometimes be complicated. The predicate `with_mutex/2` handles all of these cases. We recommend using it if possible, and making use of lower-level calls to `mutex_lock/1`, `mutex_unlock/1` and `mutex_trylock/1` only in rare cases when `with_mutex/2` is not applicable.

`with_mutex(+Mutex,?Goal)`

Locks a current mutex or aliasMutex, executes `Goal` deterministically, then unlocks `Mutex`. If `Goal` leaves choice-points, these are destroyed. `Mutex` is unlocked regardless of whether `Goal` succeeds, fails or raises an exception. Any exception thrown by `Goal` is re-thrown after the mutex has been successfully unlocked.

Error Cases

- `Mutex` is a variable
  - `instantiation_error`
- `Mutex` is not a mutex id or alias
  - `domain_error(mutex_or_alias,Mutex_or_Alias)`
- `Mutex` is not associated with a current mutex.
  - `existence_error(mutex,Mutex)`
- Locking `Mutex` would give rise to a deadlock [10]
  - `permission_error(mutex,lock,Mutex)`
- `Goal` is a variable
  - instantiation error
- `Goal` is neither a variable nor a callable term
  - type error(callable, Goal)

[10] This error case handles the `EDEADLK` return code on MacOS X, and other platforms.

`mutex_create(?Mutex)`

Creates a new recursive user mutex with identifier `Mutex`. `Options` allows optional parameters to be passed, currently only for aliases of the mutex.

- `alias(Mutex)`: Allow queue `Mutex` to be referred to via `Mutex` in all standard queue predicates. `Mutex` remains active for `Mutex` until it is destroyed.

Error Cases

- Mutex is not a variable
  - `type_error(variable,Mutex)`
- Options is a partial list or a list with an element that is a variable
  - instantiation error
- Options is neither a partial list or a list
  - type error(list, Options)
- `Options` contains an option, `Option` not described above
  - `domain_error(mutex_option,Option)`
- An element of `Options` is `alias(A)` and `A` is already associated with an existing thread, queue, mutex or stream
  - `permission_error(create,alias, A)`
- An element of `Options` is `alias(A)` and `A` is not an atom
  - `type_error(atom,A)`

`mutex_destroy(+Mutex)`

Destroys a current unlocked mutex with alias or id `Mutex` along with any memory it uses.

Error Cases

- `Mutex` is a variable
  - `instantiation_error`
- `Mutex` is not a mutex id or alias
  - `domain_error(mutex_or_alias,Mutex_or_Alias)`
- `Mutex` is not associated with a current mutex.
  - `existence_error(mutex,Mutex)`
- `Mutex` is locked
  - `permission_error(mutex,destroy,Mutex)`

`mutex_lock(+Mutex)`

`mutex_lock(Mutex)` locks a (recursive) mutex with alias or id `Mutex`. Locking and unlocking mutexes should be paired carefully in order to avoid deadlocks. In particular, a programmer needs to ensure that mutexes are properly unlocked even if the protected code fails or raises an exception.

Error Cases

- `Mutex` is a variable
  - `instantiation_error`
- `Mutex` is not a mutex id or alias
  - `domain_error(mutex_or_alias,Mutex_or_Alias)`
- `Mutex` is not associated with a current mutex.
  - `existence_error(mutex,Mutex)`
- Locking `Mutex` would give rise to a deadlock [11]
  - `permission_error(mutex,lock,Mutex)`

`mutex_trylock(+Mutex)`

Works as `mutex_lock/1` but fails immediately if `Mutex` is held by another thread, rather than suspending the calling thread.

Error Cases

- `Mutex` is a variable
  - `instantiation_error`
- `Mutex` is not a mutex id or alias
  - `domain_error(mutex_or_alias,Mutex_or_Alias)`
- `Mutex` is not associated with a current mutex.
  - `existence_error(mutex,Mutex)`

`mutex_unlock(+Mutex)`

Unlocks the mutex with alias or id `Mutex` when called by the same thread that locked `Mutex`.

Error Cases

- `Mutex` is a variable
  - `instantiation_error`
- `Mutex` is not a mutex id or alias
  - `domain_error(mutex_or_alias,Mutex_or_Alias)`

[11] This error case handles the `EDEADLK` return code on MacOS X, and other platforms.

- `Mutex` is not associated with a current mutex.
  - `existence_error(mutex,Mutex)`
- `Mutex` is not held by the calling thread
  - `permission_error(unlock,mutex,Mutex)`

`mutex_unlock_all`

`mutex_unlock_all/0` unlocks all user mutexes owned by the current thread. It has no error cases.

`mutex_property(?MutexOrAlias,?Property)`

If `MutexOrAlias` is instantiated, unifies `Property` with current properties of the mutex; if `MutexOrAlias` is a variable, backtracks through all the current mutexes whose properties unify with `Property`. Note that there is no guarantee that that the information returned will be valid, due to concurrency issues.

Currently `Property` can have the form

- `alias(Alias)`: if the mutex has an alias `Alias`
- `status(Status)`. If the mutex is locked, `Status` will be a term of the form `locked(ThreadId,NumLocks)` where `ThreadId` is the thread id of the owner of the lock, and `NumLocks` is the number of times the mutex has been locked by the current owner (recall that user-defined mutexes are recursive and must be unlocked as many times as they have been locked in order to be freed). If the mutex is unlocked, `Status` will be a term of the form `unlocked`.

Example: The query

```
?- mutex_property(M,status(_)).
```

can be used to enumerate all active user-defined mutexes.

Error Cases

- `MutexOrAlias` is neither a variable nor an XSB mutex id nor an alias
  - `domain_error(mutex_or_alias, MutexOrAlias)`
- `MutexOrAlias` is not associated with an active mutex
  - `existence_error(mutex, MutexOrAlias)`
- `Property` is neither a variable nor a valid mutex property
  - `domain_error(mutex_property, Property)`

Chapter 8

Storing Facts in Tries

XSB offers a mechanism by which large numbers of facts can be directly stored and manipulated in *tries*, which can either be private to a thread or shared among threads. The mechanism described in this chapter is in some ways similar to trie-indexed asserted code as described in Section 6.14, but allows creation of tries that are shared between threads, and of associative tries that support efficient memory management [1].

When stored in a trie, facts are compiled into trie-instructions similar to those used for XSB's tables. For instance set of facts

```
{ rt(a,f(a,b),a), rt(a,f(a,X),Y), rt(b,V,d) }
```

would be stored in a trie as shown in Figure 8, where each node corresponds to an instruction in XSB's virtual machine. Using a trie for storage has the advantage that discrimination can be made on a position anywhere in a fact, and directly inserting into or deleting from a trie is 4-5x faster than with standard dynamic code. In addition, in trie-dynamic code, there is no distinction between the index and the code itself, so for many sets of facts trie storage can use much less space than standard dynamic code. For instance, Figure 8 shows how the prefix `rt(a,f(a,...` is shared for the first two facts. However, trie storage comes with tradeoffs: first, only facts can be stored in a trie; second, unlike standard dynamic code, no ordering is preserved among the facts; and third, duplicate facts are not supported.

In Version 3.3 of XSB, tries that store facts may have the following forms:

- *Private, general* tries allow arbitrary terms to be inserted in a trie. These tries are thread-private so that inserting a term in a trie Tr in one thread will not be visible to another thread. Although such tries are general, they have limitations in memory

[1] For nearly all purposes, the predicates in this chapter replace the low-level API for interned tries in previous versions, which included `trie_intern`, `trie_unintern`, `trie_interned` etc. However that API continues to be supported for low-level systems programming.

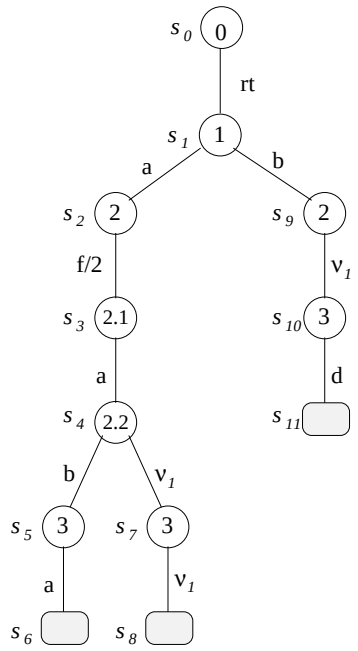

Figure 8.1: Terms Stored as a Trie

reclamation in Version 3.3 of XSB. If a term is deleted from Tr, memory will be reclaimed if it is safe to do so at the time of deletion [2]; otherwise the space will not be reclaimed until all terms in Tr are removed by truncating Tr or until the thread exits.

- *Private, associative* Associative tries are more restricted than general tries: an associative trie combines a *key* which can be any ground term, with a *value* which can be any term. Memory for deleted key-value pairs in an associative trie is always immediately reclaimed, and insert or delete operations can be faster for an associative trie than for a general trie. These tries are private to a thread, and in addition to reclaiming memory when a term is deleted, memory is reclaimed when the trie is truncated or dropped, and when the thread exits.

- *Shared, associative* tries are associative tries that are shared among threads. Memory for deleted key-value pairs is always immediately reclaimed, and when the trie is truncated or dropped.

[2] That is, if no choice points are around that may cause backtracking into Tr.

8.1 Examples of Using Tries

A handle for a trie can be obtained using the `trie_create/2` predicate. Terms can then be inserted into or deleted from that trie, and terms can be unified with information in the trie, as shown in the following example:

Example 8.1.1 First, we create a private general trie:

```
| ?- trie_create(X,[type(prge)]).
X = 1

yes
```

Next, we insert some terms into the trie

```
| ?- trie_insert(1,f(a,b)), trie_insert(1,[a,dog,walks]).

yes
```

Now we can make arbitrary queries against the trie

```
| ?- trie_unify(1,X).

X = [a,dog,walks];

X = f(a,b);

no
```

Above, a general query was made, but the query could have been any Prolog term. Now we delete a term, and see what's left.

```
| ?- trie_delete(1,f(X,B)).

X = a
B = b

yes
| ?- trie_unify(1,X).

X = [a,dog,walks];

no
```

The behavior of general tries can be constrasted with that of associative tries as seen in the next example.

Example 8.1.2 Now we start by creating a shared associative trie, with abbreviation `shas` using the multi-threaded engine

```
| ?- trie_create(X,[type(shas),alias(foo)]).
X = 1048577

yes
```

This time we used an alias so now we can use `foo` to refer to insert a couple of key-value pairs into the trie (we could also use the trie handle itself)

```
| ?- trie_insert(foo,pair(sentence(1),[a,dog,walks])),
     trie_insert(foo,pair(sentence(2),[a,man,snores])).

yes
```

However, inserting a general term into an associative trie throws an error

```
| ?- trie_insert(foo,f(a,b)).
++Error[XSB/Runtime/P]: [Domain (f(a,b) not in domain pair/2)]
in arg 2 of predicate trie_insert/2
(Inserted term must be key-value pair in trie 1048577)
```

Finally, in an associative trie, if we insert a value for a key that is already in the trie, it will *update* the value for that key.

```
| ?- trie_insert(foo,pair(sentence(1),[a,dog,snoress])).

yes
| ?- trie_unify(foo,pair(sentence(1),X)).
X = [a,dog,snores]

yes
```

8.2 Space Management for Tries

When creating or adding terms to an interned trie, XSB manages all space necessary for the terms and their indexes. However, when removing a term from a trie an issue may arise if there is a possibility of backtracking into the term to be removed; this issue also arises for retracting dynamic code. In the sequential engine and in private tries XSB's dynamic clause garbage collector handles space reclamation when terms are removed from a trie through `trie_delete/2` or similar low-level predicates. However, in the case of `trie_truncate/1` or `trie_drop/1`, an exception is thrown if there are active choice points to terms in a trie that is to be truncated or dropped.

In the multi-threaded engine the space reclamation problem becomes even more difficult for tries that can be shared among threads. In this case, no garbage collection is performed until there is a single active thread.

These space reclamation issues arise for non-associative tries only. Associative triesessentially contain key-value pairs, and so may have their space reclaimed upon deletion of a term, or upon truncation or dropping their trie, regardless of the number of active threads [3].

8.3 Predicates for Tries

The following subsections describe predicates for inserting terms into a trie, deleting terms from a trie, and unifying a term with terms in a trie, predicates for creating, dropping, and truncating tries, as well as predicates for bulk insertes into and deletes from a trie. These predicates can apply to any type of trie, and perform full error checking on their call arguments. As such, they are safer and more general than the lower-level trie predicates described in Chapter 1 of Volume 2 of this manual. Use of the predicates described here is recommended for applications unless the need for speed is paramount.

`trie_create(-TrieId,+OptionList)` module: `intern`

`OptionList` allows optional parameters in the configuration of a trie to indicate its type and whether an alias should be used. In the present version, `OptionList` may contain the following terms

- `type(Type)` where `Type` can be one of
  - `prge` (private, general) maintains information that is accessable only to the calling thread. No other restrictions are made for accessing information in a private trie. In the single-threaded engine, tries are private by default.
  - `pras` (private, associative) creates a private trie that maintains key-value pairs in a manner similar to an associative array, using the term `pair(Key,Value)`. Each key must be ground, and there may be only one value per key.
  - `shas` (shared associative) creates a shared trie that maintains key-value pairs in a manner similar to an associative array, using the term `pair(Key,Value)`. Each key must be ground, and there may be only one value per key. This option is available only in the multi-threaded engine
- `alias(Alias)`: Allow trie `TrieId` to be referred to via `Alias` in all standard trie predicates. `Alias` remains active for `TrieId` until it is dropped.
- `incremental`: Allows tables that depend on trie `TrieId` to be automatically updated as information in `TrieId` changes (cf. Section 5.6.2).

[3] Future versions of XSB may extend garbage collection to handle trie truncation, trie dropping and better space reclamation in the multi-threaded engine.

- `nonincremental`: Specifies that tables that depend on trie `TrieId` should not be automatically updated as information in `TrieId` changes (cf. Section 5.6.2).

Error Cases

- `TrieId` is not a variable
  - `type_error(variable,TrieId)`
- `OptionList` is a partial list or contains an option that is a variable
  - `instantiation_error`
- `OptionList` is neither a list nor a partial list
  - `type_error(list,OptionsList)`
- `OptionList` contains an option, `Option` not described above
  - `domain_error(trie_option,Option)`
- An element of `OptionsList` is alias(A) and A is already associated with an existing thread, queue, mutex or stream
  - `permission_error(create,alias, A)`
- An element of `OptionsList` is alias(A) and A its not an atom
  - `type_error(atom,A)`

`trie_insert(+TrieIdOrAlias,Term)` module: `intern`

Inserts `Term` into the trie denoted by `TrieIdOrAlias`. If `TrieIdOrAlias` denotes an associative trie, `Term` must be of the form `pair(Key,Value)` where `Key` is ground. If `TrieIdOrAlias` is a general trie and already contains `Term`, the predicate fails (as the same term cannot be inserted multiple times in the same trie). Similarly, if `TrieIdOrAlias` is an associative trie and already contains a value for `Key` the predicate fails.

Insertion of tries can be controlled by the flags `max_answer_term_depth`, `max_answer_list_depth`, `max_answer_term_action`, and `max_answer_list_action`, which are also used to control additions of answers to tables. Using these flags, if a term to be inserted is cyclic and exceeds a stated depth, trie insertion may either fail or throw an error depending on the associated action: see pg. 207.

Error Cases

- `TrieIdOrAlias` is a variable
  - `instantiation_error`.
- `TrieIdOrAlias` is not a trie id or alias
  - `domain_error(trie_id_or_alias,TrieIdOrAlias)`
- `TrieIdOrAlias` denotes an associative array, and `Term` does not unify with `pair(_,_)`

  - `domain_error(pair/2,Term)`
- `TrieIdOrAlias` denotes an associative array, `Term = pair(Key,Value)` but `Key` is not ground
  - `misc_error`
- `Key` or `Value` is a cyclic term, or exceeds the depth
  - `misc_error`

`trie_unify(+TrieIdOrAlias,Term)` module: `intern`

Unifies `Term` with a term in the trie denoted by `TrieIdOrAlias`. If `TrieIdOrAlias` denotes a general trie, successive unifications will succeed upon backtracking. If `TrieIdOrAlias` denotes an associative trie, `Term` must be of the form `pair(Key,Value)` where `Key` is ground.

Error Cases

- `TrieIdOrAlias` is a variable
  - `instantiation_error`.
- `TrieIdOrAlias` is not a trie id or alias
  - `domain_error(trie_id_or_alias,TrieIdOrAlias)`
- `TrieIdOrAlias` denotes an associative array, and `Term` does not unify with `pair(_,_)`
  - `domain_error(pair/2,Term)`
- `TrieIdOrAlias` denotes an associative array, `Term = pair(Key,Value)` but `Key` is not ground
  - `misc_error`

`trie_delete(+TrieIdOrAlias,Term)` module: `intern`

Deletes a term unifying with `Term` from the trie denoted by `TrieIdOrAlias`. `TrieIdOrAlias` denotes a general trie, all such terms can be deleted upon backtracking. If `TrieIdOrAlias` denotes an associative trie, `Term` must be of the form `pair(Key,Value)` where `Key` is ground. In either case, if `TrieIdOrAlias` does not contain a term unifying with `Term` the preicate fails.

Error Cases

- `TrieIdOrAlias` is a variable
  - `instantiation_error`.
- `TrieIdOrAlias` is not a trie id or alias
  - `domain_error(trie_id_or_alias,TrieIdOrAlias)`
- `TrieIdOrAlias` denotes an associative array, and `Term` does not unify with `pair(_,_)`

  - `domain_error(pair/2,Term)`
- `TrieIdOrAlias` denotes an associative array, `Term = pair(Key,Value)` but `Key` is not ground
  - `misc_error`

`trie_truncate(+TrieIdOrAlias)` module: `intern`

Removes all terms from `TrieIdOrAlias`, but does not change any of its properties (e.g. the type of the trie or its aliases).

@@

Error Cases

- `TrieIdOrAlias` is a variable
  - `instantiation_error`.
- `TrieIdOrAlias` is not a trie id or alias
  - `domain_error(trie_id_or_alias,TrieIdOrAlias)`
- There are active failure continuations to terms in `TrieIdOrAlias`
  - `miscellaneous_error`

`trie_drop(+TrieIdOrAlias)` module: `intern`

Drops `TrieIdOrAlias`. `trie_drop/1` not only removes all terms from `TrieIdOrAlias`, but also removes information about its type and any aliases the trie may have.

Error Cases

- `TrieIdOrAlias` is a variable
  - `instantiation_error`.
- `TrieIdOrAlias` is not a trie id or alias
  - `domain_error(trie_id_or_alias,TrieIdOrAlias)`
- There are active failure continuations to terms in `TrieIdOrAlias`
  - `miscellaneous_error`

`trie_bulk_insert(+TrieIdOrAlias,+Generator)` module: `intern`

Used to insert multiple terms into the trie denoted by `TrieIdOrAlias`. `Generator` must be a callable term. Upon backtracking through `Generator` its first argument should successively be instantiated to the terms to be interned in `TrieIdOrAlias`. When inserting many terms into a general trie, `trie_bulk_insert/2` is faster than repeated calls to `trie_insert/2` as it does not need to make multiple checks that the choice point stack is free of failure continuations that point into the `TrieIdOrAlias` trie. For associative tries, `trie_bulk_insert/2` can also be faster as it needs to perform fewer error checks on the arguments of the insert.

Example 8.3.1 Given the predicate

```
bulk_create(p(One,Two,Three),N):-
     for(One,1,N),
     for(Two,1,N),
     for(Three,1,N).
```

and a general trie `Trie`, the goal

```
?- trie_bulk_insert(Trie,bulk_create(_Term,N))
```

will add N^3 terms to `Trie`.

Error Cases

- `TrieIdOrAlias` is a variable
  - `instantiation_error`.
- `TrieIdOrAlias` is not a trie id or alias
  - `domain_error(trie_id_or_alias,TrieIdOrAlias)`
- `Generator` is not a compound term
  - `type_error(compound,Generator)`
- `TrieIdOrAlias` denotes an associative array, and `Generator` does not unify with `pair(_,_)`
  - `domain_error(pair/2,Term)`
- `TrieIdOrAlias` denotes an associative array, and `Generator` succeeds with a term that unifies with `pair(Key,Value)` and `Key` is not ground
  - `misc_error`
- `Key` or `Value` is a cyclic term
  - `misc_error`

`trie_bulk_delete(+TrieIdOrAlias,Term)` module: `intern`

Deletes all terms that unify with `Term` from `TrieIdOrAlias`. If `TrieIdOrAlias` denotes an associative trie, the key of the key value pair need *not* be ground.

Example 8.3.2 For the trie in the previous example, the goal

```
?- trie_bulk_delete(Trie,p(1,_,_))
```

will delete the N^2 terms that unify with `p(1,_,_)` from `TrieIdOrAlias`.

Error Cases

- `TrieIdOrAlias` is a variable
  - `instantiation_error`.
- `TrieIdOrAlias` is not a trie id or alias
  - `domain_error(trie_id_or_alias,TrieIdOrAlias)`

`trie_bulk_unify(+TrieIdOrAlias,#Term,-List)` module: `intern`

Returns in `List` all terms in `TrieIdOrAlias` that unify with `Term`. If `TrieIdOrAlias` denotes an associative trie, the key of the key value pair need *not* be ground.

This predicate is useful for two reasons. First, it provides a safe way to backtrack through an associative trie while maintaining the memory management and concurrency properties of associative tries. Second, it enforces read consistency for `TrieIdOrAlias`, regardless of whether the trie is private or shared, general or associative.

Example 8.3.3 Continuing from Example 8.3.2 the goal

```
?- trie_bulk_unify(Trie,X),List
```

will return the the $N^3 - N^2$ terms still in `TrieIdOrAlias`.

Error Cases

- `TrieIdOrAlias` is a variable
  - `instantiation_error`.
- `TrieIdOrAlias` is not a trie id or alias
  - `domain_error(trie_id_or_alias,TrieIdOrAlias)`
- `List` is not a variable
  - `type_error(variable,List)`.

`trie_property(?TrieOrAlias,?Property)` module: `intern`

If `TrieOrAlias` is instantiated, unifies `Property` with current properties of the trie; if `TrieOrAlias` is a variable, backtracks through all the current tries whose properties unify with `Property`. In the MT engine, `thread_property/2` accesses only tries private to the calling thread and shared tries; however note that there is no guarantee that that the information returned about shared tries will be valid, due to concurrency issues [4].

Currently `Property` can have the form

[4] `trie_property/2` is not yet implemented for shared tries.

- `type(Type)`: where `Type` is the type of the trie.
- `alias(Alias)`: if the trie has an alias `Alias`

Error Cases

- `TrieOrAlias` is neither a variable nor an XSB trie id nor an alias
  - `domain_error(trie, TrieOrAlias)`
- `TrieOrAlias` is not associated with a valid trie
  - `existence_error(trie, TrieOrAlias)`

8.4 Low-level Trie Manipulation Utilities

The previous sections indicate how tries can be used as an efficient mechanism to store thread-private and thread-shared terms. In this section we describe lower-level trie manipulation predicates that are suitable for implemeting XSB libraries [5]. As with other tries, these utilities are suitable for storing terms rather than exectuable clauses, use a set based semantics, and do not maintain an ordering among these terms. In addition

- These predicates create and maintain thread-private, general tries.
- These predicates do not always perform error checking. If not explicitly specified in the description of the predicate, errors returned may be confusing, and calling with improper arguments may even cause memory violations.
- For historical reasons, the ordering of arguments in these predicates is not consistent.

Despite (and sometimes because of) these limitations, the trie manipulation facilities can be extremely fast, so that interning and uninterning terms in a trie may be much faster than assert and retract in XSB or in any other Prolog.

8.4.1 A Low-Level API for Interned Tries

`new_trie(-Root)` module: `intern`

`Root` is instantiated to a handle for a new private, general trie.

`trie_intern(+Term,+Root)` module: `intern`
`trie_intern(+Term,+Root,-Leaf,-Flag,-Skel)` module: `intern`

`trie_intern/2` effectively asserts `Term` by interning into the trie designated by `Root`. If a variant of `Term` is already in `Root` the predicate succeeds, but a new copy of `Term` is not added to the trie.

[5] Flora-2, XASP, XSB's `storage` library and others use these predicates.

`trie_intern/5` acts as `trie_intern/2` but returns additional information: `Leaf` is the handle for the interned `Term` in the trie. `Flag` is 1 if the term is "old" (already exists in the trie); it is 0, if the term is newly inserted. `Skel` represents the collection of all the variables in `Term`. It has the form `ret(V1,V2,...,VN)`, exactly as in `get_calls` (see Vol. 1 of the XSB manual).

Error Cases

- `Root` is uninstantiated
  - `instantiation_error`
- `Root` is instantiated, but not an integer (trie handle)
  - `type_error(integer,Root)`

`trie_interned(?Term,+Root)` module: `intern`
`trie_interned(?Term,+Root,?Leaf,-Skel)` module: `intern`

`trie_interned/2` backtracks through the terms that unify with `Term` and that are interned into the trie represented by the handle `Root`. `Term` may be free, or partially bound.

If `Leaf` is a free variable, `trie_interned/5` works as `trie_interned/2`: it backtracks through the terms that unify with `Term` interned into the trie represented by the handle `Root`. In addition it returns `Leaf` as the handle for each such term and returns in `Skel` the collection of all the variables in `Term` using the form `ret(V1,...,Vn)`. Otherwise, if `Leaf` is bound, `trie_interned/5` will unify `Term` with the term in the trie designated by `Leaf`, returning a vector of variables in `Skel`.

Error Cases

- `Root` is uninstantiated
  - `instantiation_error`
- `Root` is instantiated, but not an integer (trie handle)
  - `type_error(integer,Root)`

`trie_unintern(+Root,+Leaf)` module: `intern`
`trie_unintern_nr(+Root,+Leaf)` module: `intern`

`trie_unintern(+Root,+Leaf)` deletes a term from a trie using the handle `Leaf`, as obtained from `trie_intern/[2,4]` or `trie_interned/[2,4]`. Space is reclaimed for the term only if it is safe to do so – if there are no failure continuations that may consume the term (cf. Section 8.2).

`trie_unintern_nr/2` does not perform space reclamation and as a result requires no garbage collection – it simply marks a term as "deleted". This makes `trie_unintern_nr/2` suitable if trie garbage collection may be an issue, and also allows it to be used in libraries that support backtrackable updates, such as XSB's `storage` library.

Error Cases

- `Root` or `Leaf` is uninstantiated
  - `instantiation_error`
- `Root` or `Leaf` is instantiated, but not an integer (trie handle or trie leaf)
  - `type_error(integer,Root)` or `type_error(integer,Leaf)`

`reclaim_uninterned_nr(+Root)` module: `intern`

Runs through the chain of leaves of the trie `Root` and deletes the terms that have been marked for deletion by `trie_unintern_nr/2`. This can be viewed either as a garbage collection step or as a commit.

Error Cases

- `Root` is uninstantiated
  - `instantiation_error`
- `Root` is instantiated, but not an integer (trie handle)
  - `type_error(integer,Root)`

`unmark_uninterned_nr(+Root,+Leaf)` module: `intern`

The term pointed to by `Leaf` should have been previously marked for deletion using `trie_unintern_nr/2`. This term is then "unmarked" (or undeleted) and becomes again a normal interned term.

Error Cases

- `Root` or `Leaf` is uninstantiated
  - `instantiation_error`
- `Root` or `Leaf` is instantiated, but not an integer (trie handle or trie leaf)
  - `type_error(integer,Root)` or `type_error(integer,Leaf)`

`delete_trie(+Root)` module: `intern`

Deletes all the terms in the trie pointed to by `Root`. Garbage collection ensures that space reclamation is performed only if it is safe to do so.

Error Cases

- `Root` is uninstantiated
  - `instantiation_error`
- `Root` is instantiated, but not an integer (trie handle)
  - `type_error(integer,Root)`
- Failure continuations point to one or more nodes in the trie with root `Root`
  - `misc_error`

Chapter 9

Hooks

Sometimes it is useful to let the user application catch certain events that occur during XSB execution. For instance, when the user asserts or retracts a clause, etc. XSB has a general mechanism by which the user program can register *hooks* to handle certain supported events. All the predicates described below must be imported from `xsb_hook`.

9.1 Adding and Removing Hooks

A hook in XSB can be either a 0-ary predicate or a unary predicate. A 0-ary hook is called without parameters and unary hooks are called with one parameter. The nature of the parameter depends on the type of the hook, as described in the next subsection.

`add_xsb_hook(+HookSpec)` module: `xsb_hook`

This predicate registers a hook; it must be imported from `xsb_hook`. `HookSpec` has the following format:

```
hook-type(your-hook-predicate(_))
```

or, if it is a 0-ary hook:

```
hook-type(your-hook-predicate)
```

For instance,

```
:- add_xsb_hook(xsb_assert_hook(foobar(_))).
```

registers the hook `foobar/1` as a hook to be called when XSB asserts a clause. Your program must include clauses that define `foobar/1`, or else an error will result.

The predicate that defines the hook type must be imported from `xsb_hook`:

```
:- import xsb_assert_hook/1 from xsb_hook.
```

or `add_xsb_hook/1` will issue an error.

`remove_xsb_hook(+HookSpec)` module: `xsb_hook`

Unregisters the specified XSB hook; imported from `xsb_hook`. For instance,

```
:- remove_xsb_hook(xsb_assert_hook(foobar(_))).
```

As before, the predicate that defines the hook type must be imported from `xsb_hook`.

9.2 Hooks Supported by XSB

The following predicates define the hook types supported by XSB. They must be imported from `xsb_hook`.

`xsb_exit_hook(_)` module: `xsb_hook`

These hooks are called just before XSB exits. You can register as many hooks as you want and all of them will be called on exit (but the order of the calls is not guaranteed). Exit hooks are all 0-ary and must be registered as such:

```
:- add_xsb_hook(xsb_exit_hook(my_own_exit_hook)).
```

`xsb_assert_hook(_)` module: `xsb_hook`

These hooks are called whenever the program asserts a clause. An assert hook must be a unary predicate, which expects the clause being asserted as a parameter. For instance,

```
:- add_xsb_hook(xsb_assert_hook(my_assert_hook(_))).
```

registers `my_assert_hook/1` as an assert hook. One can register several assert hooks and all of them will be called (but the order is not guaranteed).

`xsb_retract_hook(_)` module: `xsb_hook`

These hooks are called whenever the program retracts a clause. A retract hook must be a unary predicate, which expects as a parameter a list of the form `[Head,Body]`, which represent the head and the body parts of the clause being retracted. As with assert hooks, any number of retract hooks can be registered and all of them will be called in some order.

Chapter 10

Debugging and Profiling

10.1 Prolog-style Tracing and Debugging

XSB supports a version of the Byrd four-port debugger for interactive debugging and tracing of Prolog code. In this release (Version 3.3), it does not work very well when debugging code involving tabled predicates [1]. If one only creeps (see below), the tracing can provide some useful information. For programs that involve large amounts of tabling forest-view tracing can be used (Section 10.3). To turn on tracing, use `trace/0`, `trace/1`, or `trace/2`. To turn tracing off, use `notrace/0`.

`trace`

`notrace`

When tracing is on, the system will print a message each time a predicate is:

1. initially entered (Call),
2. successfully returned from (Exit),
3. failed back into (Redo), and
4. completely failed out of (Fail).

When debugging interactively, a message may be printed and tracer stopped and prompts for input. (See the predicates `show/1` and `leash/1` described below to modify what is traced and when the user is prompted.)

In addition to single-step tracing, the user can set spy points to influence how the tracing/debugging works. A spy point is set using `spy/1`. Spy points can be used to cause the system to enter the tracer when a particular predicate is entered. Also

[1] The current version of XSB's Prolog debugger does not include exceptions as a debugging port.

the tracer allows "leaping" from spy point to spy point during the debugging process. The debugger also has profiling capabilities, which can measure the cpu time spent in each call. The cpu time is measured only down to 0.0001-th of a second. g When the tracer prompts for input, the user may enter a return, or a single character followed by a return, with the following meanings:

- `c, <CR>`: *Creep* Causes the system to single-step to the next port (i.e. either the entry to a traced predicate called by the executed clause, or the success or failure exit from that clause).
- `a`: *Abort* Causes execution to abort and control to return to the top level interpreter.
- `b`: *Break* Calls the evaluable predicate *break*, thus invoking recursively a new incarnation of the system interpreter. The command prompt at break level n is

  n: `?-`

  The user may return to the previous break level by entering the system end-of-file character (e.g. `ctrl-D`), or typing in the atom `end_of_file`; or to the top level interpreter by typing in `abort`.
- `f`: *Fail* Causes execution to fail, thus transferring control to the Fail port of the current execution.
- `h`: *Help* Displays the table of debugging options.
- `l`: *Leap* Causes the system to resume running the program, only stopping when a spy-point is reached or the program terminates. This allows the user to follow the execution at a higher level than exhaustive tracing.
- `n`: *Nodebug* Turns off debug mode.
- `r`: *Retry (fail)* Transfers to the Call port of the current goal. Note, however, that side effects, such as database modifications etc., are not undone.
- `s`: *Skip* Causes tracing to be turned off for the entire execution of the procedure. Thus, nothing is seen until control comes back to that procedure, either at the Success or the Failure port.
- `q`: *Quasi-skip* This is like Skip except that it does not mask out spy points.
- `S`: *Verbose skip* Similar to `Skip` mode, but trace continues to be printed. The user is prompted again when the current call terminates with success or failure. This can be used to obtain a full trace to the point where an error occurred or for code profiling. (See more about profiling below.)
- `e`: *Exit* Causes immediate exit from XSB back to the operating system.

`trace(+Filename,+option)`

`trace/2` is like `trace/0` except that it is non-interactive and dumps trace information into a log file, `Filename`. Currently the only supported option is `log`. However, the

log is written in the form of Prolog facts, which can be loaded queried. The format of the facts is:

```
xsb_tracelog(CallId,CallNum,PortType,ParentCallNum,DepthOfCall,CurrentCall,Time)
```

where `CallId` is an identifier generated when XSB encounters a new top-level call. This identifier remains the same for all subgoals called while tracing that top-level call.

- `CallNum` is a generated number to show the nesting of the calls being traced. It is the same number that the user sees when tracing interactively.
- `PortType` is `'Call'`, `'Redo'`, `'Exit'`, or `'Fail'`.
- `ParentCallNum` is the call number of the parent call.
- `DepthOfCall` is the nesting depth of the current call with respect to its ancestor calls.
- `CurrentCall` is the call being traced
- `Time` is the CPU time it took to execute `CurrentCall`. On `'Call'` and `'Redo'`, `Time` is always 0 — it has a meaningful value only for the `'Exit'` and `'Fail'` log entries.

It should be noted that when calls are delayed due to the well-founded negation computation of because of the `when/2` primitive, the parent call might be off in some cases. However, the parent property repairs itself for subsequent calls.

'The name of the predicate (`xsb_tracelog`) used for logging can be changed by asserting it into the predicate `debug_tracelog_predicate/1`, which should be imported from `usermod`. For instance,

```
:- import debug_tracelog_predicate/1 from usermod.
?- assert(debug_tracelog_predicate(foobar)).
```

`spy(Preds)`

where `Preds` is a spy specification or a list of such specifications, and must be instantiated. This predicate sets spy points (conditional or unconditional) on predicates. A spy specification can be of several forms. Most simply, it is a term of the form P/N, where P is a predicate name and N its arity. Optionally, only a predicate name can be provided, in which case it refers to all predicates of any arity currently defined in `usermod`. It may optionally be prefixed by a module name, e.g. $ModName{:}P/N$. (Again, if the arity is omitted, the specification refers to all predicates of any arity with the given name currently defined in the given module.) A spy specification may also indicate a conditional spy point. A conditional spy specification is a Prolog rule, the head indicating the predicate to spy, and the body indicating conditions under which to spy. For example, to spy the predicate p/2 when the first argument is not a

variable, one would write: $spy(p(X, _) :- nonvar(X))$. (Notice that the parentheses around the rule are necessary). The body may be empty, i.e., the rule may just be a fact. The head of a rule may also be prefixed (using :) with a module name. One should not put both conditional and unconditional spy points on the same predicate.

`nospy(Preds)`
: where `Preds` is a spy specification, or a list of such specifications, and must be instantiated at the time of call. What constitutes a spy specification is described above under `spy`. `nospy` removes spy points on the specified predicates. If a specification is given in the form of a fact, all conditional spy points whose heads match that fact are removed.

`debug`
: Turns on debugging mode. This causes subsequent execution of predicates with trace or spy points to be traced, and is a no-op if there are no such predicates. The predicates `trace/0`, `trace/1`, `trace/2`, and `spy/1` cause debugging mode to be turned on automatically.

`nodebug`
: Turns off debugging mode. This causes trace and spy points to be ignored.

`debugging`
: Displays information about whether debug mode is on or not, and lists predicates that have trace points or spy points set on them.

`debug_ctl(option,value)`
: `debug_ctl/2` performs debugger control functions as described below. These commands can be entered before starting a trace or inside the trace. The latter can be done by responding with "`b`" at the prompt, which recursively invokes an XSB sub-session. At this point, you can enter the debugger control commands and type `end_of_file.` This returns XSB back to the debugger prompt, but with new settings.

1. `debug_ctl(prompt, off)` Set non-interactive mode globally. This means that trace will be printed from start to end, and the user will never be prompted during the trace.
2. `debug_ctl(prompt, on)` Make tracing/spying interactive.
3. `debug_ctl(profile, on)` Turns profiling on. This means that each time a call execution reaches the `Fail` or `Exit` port, CPU time spent in that call will be printed. The actual call can be identified by locating a `Call` prompt that has the same number as the "cpu time" message.
4. `debug_ctl(profile, off)` Turns profiling off.
5. `debug_ctl(redirect, +File)` Redirects debugging output to a file. This also includes program output, errors and warnings. Note that usually you cannot see

the contents of `+File` until it is closed, *i.e.*, until another redirect operation is performed (usually `debug_ctl(redirect, tty)`, see next).

6. `debug_ctl(redirect, tty)` Attaches the previously redirected debugging, error, program output, and warning streams back to the user terminal.
7. `debug_ctl(show, +PortList)` Allows the user to specify at which ports should trace messages be printed. `PortList` must be a list of port names, i.e., a sublist of ['Call', 'Exit', 'Redo', 'Fail'].
8. `debug_ctl(leash, +PortList)` Allows the user to specify at which ports the tracer should stop and prompt the user for direction. `PortList` must be a list of port names, i.e., a sublist of ['Call', 'Exit', 'Redo', 'Fail']. Only ports that are `show`-n can be `leash`-ed.
9. `debug_ctl(hide, +PredArityPairList)` The list must be of the form `[P1/A1, P2/A2, ...]`, *i.e.*, each either must specify a predicate-arity pair. Each predicate on the list will become non-traceable. That is, during the trace, each such predicate will be treated as an black-box procedure, and trace will not go into it.
10. `debug_ctl(unhide, ?PredArityPairList)` If the list is a predicate-arity list, every predicate on that list will become traceable again. Items in the list can contain variables. For instance, `debug_ctl(unhide, [_/2])` will make all 2-ary that were previously made untraceable traceable again. As a special case, if `PredArityPairList` is a variable, all predicates previously placed on the "untraceable"-list will be taken off.
11. `debug_ctl(hidden, -List)` This returns the list of predicates that the user said should not be traced.

10.2 Low-Level Tracing

XSB also provides a facility for low-level tracing of execution. This can be activated by invoking the emulator with the `-T` option (see Section 3.7), or through the predicate `trace/0`. It causes trace information to be printed out at every call (including those to system trap handlers). The volume of such trace information can very become large very quickly, so this method of tracing is not recommended in general.

XSB debugger also provides means for the low-level control of what must be traced. Normally, various standard predicates are masked out from the trace, since these predicates do not make sense to the application programmer. However, if tracing below the application level is needed, you can retract some of the facts specified in the file `syslib/debugger_data.P` (and in some cases assert into them). All these predicates are documented in the header of that file. Here we only mention the four predicates that an XSB developer is more likely to need. To get more trace, you should retract from the first three predicates and assert into the last one.

- `hide_this_show(Pred,Arity)`: specifies calls (predicate name and arity) that the debugger should `not` show at the prompt. However, the evaluation of this hidden call `is` traced.
- `hide_this_hide(Pred,Arity)`: specifies calls to hide. Trace remains off while evaluating those predicates. Once trace is off, there is no way to resume it until the hidden predicate exits or fails.
- `show_this_hide(Pred,Arity)`: calls to show at the prompt. However, trace is switched off right after that.
- `trace_standard_predicate(Pred,Arity)`: Normally trace doesn't go inside standard predicates (*i.e.*, those specified in `syslib/std_xsb.P`. If you need to trace some of those, you must `assert` into this predicate.

In principle, by retracting all facts from the first three predicates and asserting enough facts into the last one, it is possible to achieve the behavior that approximates the `-T` option. However, unlike `-T`, debugging can be done interactively. This does not obviate `-T`, however. First, it is easier to use `-T` than to issue multiple asserts and retracts. Second, `-T` can be used when the error occurs early on, before the moment when XSB shows its first prompt.

10.3 Analyzing the Execution of Tabled Programs

The tracing and debugging described in previous sections has proven useful for Prolog programs for 30 or more years. However, when tabling is added to Prolog, things change. First, as described in Chapter 5, tabling can be used to find the least fixed point of mutually recursive predicates. Operationally, this requires the ability to suspend one computation path and to resume another. Second, the addition of tabled negation for the well-founded semantics requires the ability to delay negative goals whose only proof may be involved in a loop through negation and to simplify these goals once their truth value has become known. Furthermore, a tabled subgoal has different states: it may be *new*; it may be *incomplete* so that new answers might be derived for it; or *completed* (completely evaluated) so that the answers may simply be read from the table. In short, tabling, which can execute much more general programs than Prolog and which can use the stronger well-founded semantics, requires a more complex set of operations than Prolog's SLDNF. Accordingsly, debugging and tracing is correspondingly more complex. Thus, while Prolog's 4-port debugger may be useful for programs that involve just a few tabled predicates, it may not be useful for programs that heavily use tabling for complex recursions, non-monotinic reasoning or other purposes.

There is currently no standard approach to debugging tabled programs. One possible approach would be to extend the 4-port debugger to include other ports for tabling operations. Such extensions have not yet been explored, and whether the paradigm of n-port

debugging can be extended to full tabling so that it can be useful to programmers is an open question. Another approach would be use the declarative approach of *justification* [32, 54] to explain why derivations were or were not made. XSB does in fact have a justification package but it is not currently robust enough to be recommended for general use. Below we present the `logforest` approach.

10.3.1 Tracing a tabled evaluation through forest logging

While the operations used for tabling are more complex than those of SLDNF, they have a clear formal operational semantics through SLG and the forest-of-trees model. We recall this model briefly below for a definite program but assume a background knowledge of tabled logic programming (see, for instance [75]).

Example 10.3.1 Figure 10.1 shows a program fragment along with an SLG forest for the query `?- reach(1,Y)` to the the right-recursive tabled predicate `reach/1`. An SLG forest consists of an SLG tree for each tabled subgoal S: this tree has root S :- S. In a definite program an SLG tree represents resolution of program clauses and answers to prove S. In Figure 10.1 each non-root node of the form $K.N$ where $N = (S$:- $Goals)\theta$ is a clause in which the bindings to a subgoal S are maintained in $S\theta$, the goals remaining to prove S are in $Goals\theta$, and the order of creation of N within the tabled evaluation is represented by a number, K (local scheduling is used in this example). Children of a root node are obtained through resolution of a tabled subgoal against program clauses. Children of non-root nodes are obtained through answer clause resolution, if the left most selected literal is tabled (e.g. children of node 3 or 11 in the tree for `reach(1,Y)`), or through program clause resolution if the leftmost selected literal is not tabled (e.g. children of nodes 2 and 18 in the tree for `reach(1,Y)`). Nodes that have empty *Goals* are termed *answers*. Note that the evaluation keeps track of each tabled subgoal S that it encounters. Later if S is selected again, resolution will use answers rather than program clauses; if no answers are available, the computation will *suspend* at that point and the evaluation will backtrack to try to derive answers using some other computation path. Once more answers have been derived, the evaluation *resumes* the suspended computation. Similarly, once the computation has backtracked through all answers available for S in the current state, the computation path will suspend, and resume after further answers are found. Thus a tabled evaluation is a fixed point computation for a set of interdependent subgoals. When it is etermined that a (perhaps singleton) set of subgoals can produce no more answers, the subgoals are completed.

The forest logging approach (`logforest`) allows one to run a tabled query and produce a log that can be interpreted as (a partial image of) an SLG forest. The log can then used to analyze program correctness, to optimize performance and so on. Because `logforest` produces a log, it superficially resembles the non-interactive trace described earlier in this chapter. However,

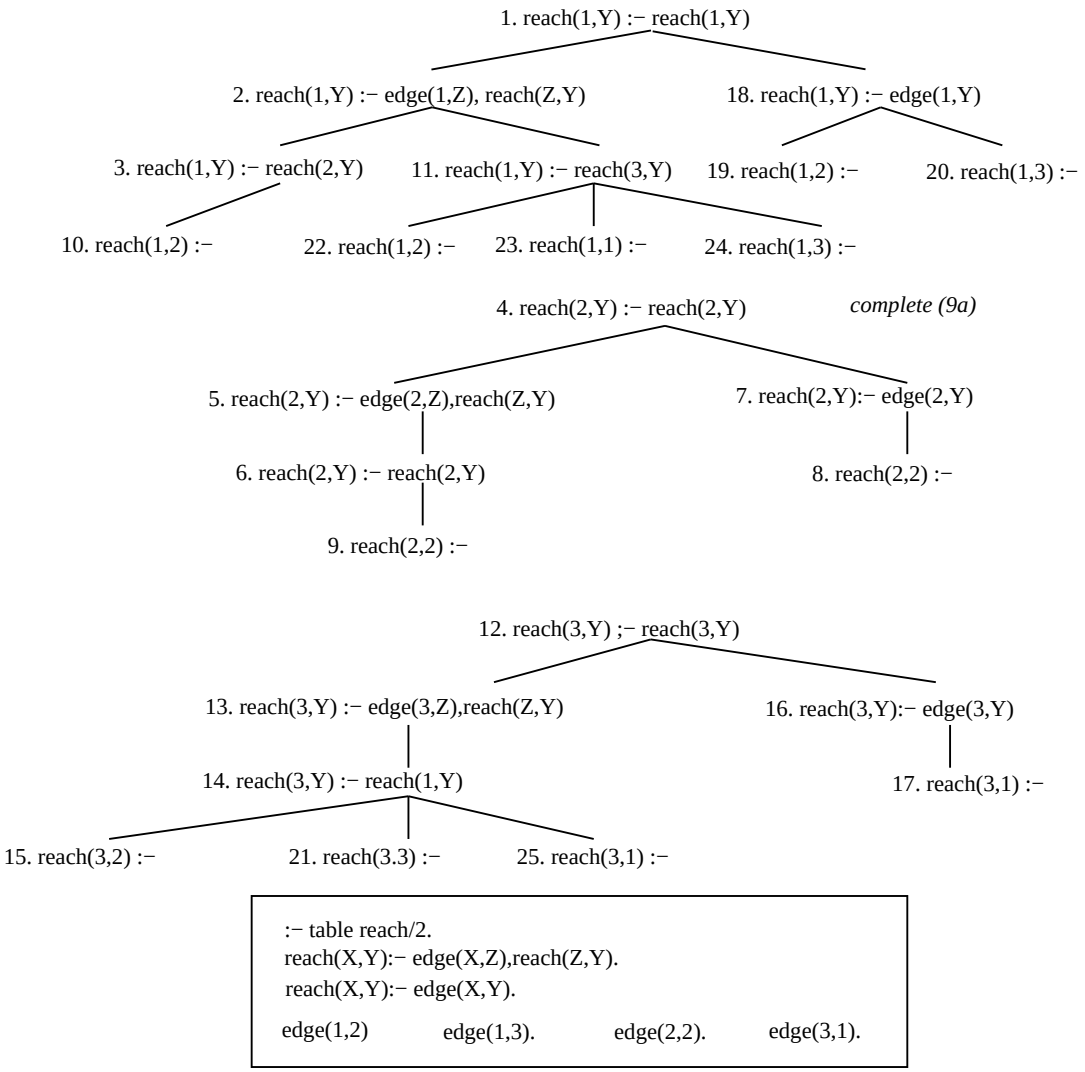

Figure 10.1: A program P_{Rrec} and SLG forest for (local) evaluation of `?- reach(1,Y)`

- `trace/1` produces a Prolog-style trace that takes little account of tabling. `logforest` structures its output according to the forest-of-trees model, and takes little account of program clause resolution.
- `logforest` is implemented in C for efficiency, while `trace/1` is built on top of XSBs interactive debugger. Unlike `trace/1`, `logforest` can therefore to produce logs for very large evaluations with little overhead.

We stress that the forest logging approch is under development and its features are subject to change.

Currently, `logforest` captures the following actions.

- *A call to a tabled subgoal* If a call to a tabled subgoal S_1 is made from a tree for S_2 a Prolog-readable fact of the form `tc(S1,S2,Stage,Counter)` is logged, where *Counter* is the ordinal number of the fact, and `Stage` is
  - `new` if S_1 is a new subgoal
  - `cmp` if S_1 is not a new subgoal and has been completed
  - `incmp` if S_1 is not a new subgoal but has *not* been completed

  For instance, in the above example, node 3 would be represented as `tc(reach(2,Y),reach(1,Y),2)` (the reason for using the counter value of 2 rather than 3 is explained below). If S_1 is the first tabled subgoal in an evaluation, S_2 is the atom *null*.
- *Derivation of a new answer* When a new answer A is derived for subgoal S and added to the table (i.e. A is not already an answer for S) a fact of the form `na(A,S,Counter)` is logged. In the above example, the answer node 9 would be represented as `na([2],reach(2,_v1),4)` where the first argument is a list of substitutions for the variables *_v1,...,_vn* in S.
- *Return of an answer to a consuming subgoal* When an answer A is returned to a consuming subgoal S in a tree for S_T, a fact of the form `ar(A,S,ST,Counter)` is logged. A log entry is made only if the table for S is incomplete (see the explanation below).
- *Subgoal completion*
  - When a set $\mathcal{S}$ of subgoals is determined to be completely evaluated and is completed, a fact of the form `cmp(S,SCCNum,Counter)` is logged for each $S \in \mathcal{S}$. Here $SCCNum$ is simply a number giving an ordinal value that can be used to group subgoals into mutually dependent sets of subgoals (here called *Strongly Conneced Components* or *SCCs*), i.e. the *SCCNum* of each $S \in \mathcal{S}$ has the same value, but that value is not used for a completion fact of any subgoal not in $\mathcal{S}$.

  - When a subgoal $\mathcal{S}$ is *early completed*, i.e. it is determined that no more answers for S are possile or are desired a fact of the form `cmp(S,ec,Counter)` is logged. If S belonged to a larger mutually dependent set $\mathcal{S}$ when it was early completed, S will also be included in the completion facts for $\mathcal{S}$.

- *Table Abolishes*
  - When a tabled subgoal S is abolished, a fact of the form `ta(subg(S),Counter)` is logged.
  - When all tables for a predicate p/n are abolished, a fact of the form `ta(pred(p/n),Counter)` is logged.
  - When all tables are abolished, a fact of the form `ta(all,Counter)` is logged.

- *Location of errors* Whenever an error is thrown and the execution is in a tree for a subgoal S, a Prolog-readable fact of the form `err(S,Counter)` is logged, where *Counter* is the ordinal number of the fact. The primary purpose of this fact is to indicate the nearest tabled call that gave rise to an uncaughterror.

`logforest` does *not* contain

- Information about the occurrence of program clause resolution either when used to produce children of tabled predicates, or when it is used to produce children whose nodes have a selected literal that is non-tabled.

- Information about the return of answers from completed tables. XSB uses a so-called *completed table optimization* which treats answer return from completed tables in a manner akin to program clause resolution.

The inclusion of the above two features in `logforest` would significantly slow down execution of XSB. However, future versions of `logforest` may include expanded logging features for negation, for call and answer subsumption and for incremental tabling [2].

Example 10.3.2 *The forest for* `reach(1,Y)` *in the foregoing example has the log file as shown in Table 10.1.*

`log_forest(+Call)` module: `tables`
`log_forest(+Call,+Options)` module: `tables`

These predicates turn on forest logging, call `Call` then turn logging off. Currently, the only option is `file(File)`, which directs the logging to the file `File`. If `Options` is an empty list or if `log_forest/1` is called, the log will be sent to standard output [3].

[2] Currently, attributes of attributed variables are not printed out.
[3] Future options will be able to turn on and off the logging of various types of facts.

Log File	Forest	Explanation
tc(reach(1,_v0),null,new,0)	node 1	
	node 2	created by program clause resol.
	node 3	created by program clause resol.
tc(reach(2,_v0),reach(1,_v0),new,1)	node 4	
	node 5	created by program clause resol.
	node 6	created by program clause resol.
tc(reach(2,_v0),reach(2,_v0),incmp,2)		repeated subgoal registered
	node 7	created by program clause resol.
	node 8	created by program clause resol.
na([2],reach(2,_v0),3)	node 8	registered as answer
ar([2],reach(2,_v0),reach(2,_v0),4)	node 9	created by answer resol.
cmp(reach(2,_v0),2,5)	9a	`reach(2,_v0)` completed
	node 10	created by return from completed table
na([2],reach(1,_v0),6)	node 10	registered as an answer
	node 11	created by program clause resol.
tc(reach(3,_v0),reach(1,_v0),new,7)	node 12	
	node 13	created by program clause resol.
	node 14	created by program clause resol.
tc(reach(1,_v0),reach(3,_v0),incmp,8)	node 14	repeated subgoal registered
ar([2],reach(1,_v0),reach(3,_v0),9)	node 15	created by answer resol.
na([2],reach(3,_v0),10)	node 15	registered as an answer
	node 16	created by program clause resol.
	node 17	created by program clause resol.
na([1],reach(3,_v0),11)	node 17	registered as an answer
	node 18	created by program clause resol.
	node 19	created by program clause resol. (repeated answer)
	node 20	created by program clause resol.
na([3],reach(1,_v0),12)	node 20	registered as an answer
ar([3],reach(1,_v0),reach(3,_v0),13)	node 21	created by answer return
na([3],reach(3,_v0),14)	node 21	registered as an answer
ar([2],reach(3,_v0),reach(1,_v0),15)	node 22	created by answer resol.
ar([1],reach(3,_v0),reach(1,_v0),16)	node 23	created by answer resol.
na([1],reach(1,_v0),17)	node 23	registered as an answer
ar([3],reach(3,_v0),reach(1,_v0),18)	node 24	created by answer resol.
ar([1],reach(1,_v0),reach(3,_v0),19)	node 25	created by answer resol.v
cmp(reach(1,_v0),1,20)		
cmp(reach(3,_v0),1,21)		

Table 10.1: Log file for computation in Figure 10.1

`load_forest_log(+File)` module: `tables`

The log produced by `log_forest/[1,2]` is a Prolog file that can be compiled and/or loaded dynamically just as any other Prolog file. However, for large logs (i.e. those of many megabytes) use of `load_dync/[1,2]` XSB commands can drastically reduce the time needed to load the file, while use of the proper `index/2` declarations can greately improve query time. The simple predicate, `load_forest_log/1` loads a log file and indexes needed arguments.

10.3.2 Analyzing the log; seeing the forest through the trees

As previously described, forest logging is based on the formal operational semantics of SLG, and as a result the log can be analyzed to query any result that can be modelled by the theory. But despite the power of forest logging, it can be difficult to use. Not all users have the background to fully understand the operational semantics of SLG. Even those users with a formal background may find it difficult to write efficient analysis routines for logs of large computations [4]. Accordingly, XSB provides routines that analyze logs and display information about a computation. These routines can answer many questions about a computation and can provide the starting point for further exploration. We introduce these routines via an extended example.

Example 10.3.3 This example arises from the actual use of forest logging to understand a Flora-2 computation [83], in which the Cyc reasoner (cf. http://www.cyc.com) was translated into Silk (cf. http://silk.semwebcentral.org) and used to answer various questions in biology. Silk itself compiles into Flora-2 which in turn compiles into XSB [5]. After translation, query answering took more resources than expected, and users wanted to determine why. Using the features of Version 3.3, the first step is to call `statistics/0` at the end of the computation. The statistics indicated that the computation took about 30 seconds of CPU time and 300 megabytes of table space, while XSB's trail had allocated over 1 gigabyte of space. The call to `statistics/0` also showed the following information:

```
8678944 variant call check/insert ops: 615067 producers, 8063877 variants.
317346 answer check/insert ops: 304899 unique inserts, 12447 redundant.
```

In other words, there were nearly 10 million tabled subgoals that were called, indicating that this computation was heavily tabled (a characteristic of most Flora-2 computations), It also shows that the average number of answers per tabled subgoal is rather small.

This basic information leads to several questions. Why were there so many tabled subgoals? Did the tabling have anything to do with the large amount of choice-point/trail

[4] I find it difficult myself!

[5] This example was run in 2012 using a 64-bit server with a large amount of RAM.

space that was allocated? Which tabled subgoals had answers? How many times did a given tabled predicate call another tabled predicate?

Some of these questions can be answered by `table_dump/[2,3]`: particularly, what tabled subgoals were called, and which had answers. However `table_dump/[2,3]` cannot provide other information, such as the dependencies of given tabled subgoals on other tabled subgoals or the order in which operations occurred. From a formal perspective, `table_dump/[2,3]` does not allow a user to analyze an entire SLG forest: only the "table", i.e., the subgoals in the forest and the unordered set of its answers. The table omits any information about interior nodes or completion information, both of which are used to compute dependency information. Dependencies are useful in analyzing most computations, but is especially important in Flora-2 computations such as this one, that make heavy use of HiLog. This use of HiLog means that the dependencies of tabled predicates on one another is not at all obvious, and may not easily be determined by static analysis.

The next step, therefore, in analyzing this computation is to rerun it with forest logging. For this computation forest logging has no impact on memory usage, but increases the time of the computation from about 30 seconds to about 52 seconds — around 73% in this case. It is worthwhile noting that the actual overhead of forest logging varies depending on how heavily the computation is tabled. The log itself had slightly over 14 million entries which were loaded into XSB via `load_forest_log/1`. The log took about 140 seconds to load and about 7.8 Gbytes of space for the log facts and their multiple and trie indexes [6].

The easiest way to start the analysis is to ask the query `?- forest_log_overview`, which for this example gives:

```
There were 613496 subgoals in 463330 (completed) SCCs.
93918 subgoals were early-completed.
0 subgoals were not completed in the log.
There were a total of 8670043 tabled subgoal calls:
    613496 were calls to new subgoals
    4467747 were calls to incomplete subgoals
    3588800 were calls to complete subgoals

Number of SCCs with 1 subgoals is 463322
Number of SCCs with 4 subgoals is 1
Number of SCCs with 7 subgoals is 1
Number of SCCs with 52 subgoals is 1
Number of SCCs with 110 subgoals is 4
Number of SCCs with 149671 subgoals is 1
```

[6] The load time for this example, about 100,000 facts/second is typical for 2012 CPUs; the size of the loaded code is larger than usual, due in part to the expansion in the size of terms caused by the HiLog encoding.

The overview extends the information shown by `statistics/0`. First, the total number of completed and non-completed SCCs is given along with a count of how many of the completed subgoals were early completed. Information about non-completed SCCs is useful, since the forest log may be analyzed for a computation that does not terminate. Since this computation did terminate, all subgoals in the log were completed [7]. Note that there is also a breakdown of calls to tabled subgoals that distinguishes whether the tabled subgoal was new, completed, or incomplete. Recall that calls to completed tabled subgoals essentialy treat the answers in the table as facts, so that these calls are efficient. Making a call to an incomplete subgoals on the other hand means that the calling and called subgoals are mutually recursive [8] and execution of recursive sets of subgoals can be expensive, especially in terms of space.

Finally, the overview report provides the distributions of tabled subgoals across SCCs. While most of the SCCs were small there was a large one, with nearly 150,000 mutually dependent subgoals. Clearly the large SCC should be examimed. The first step is to obtain its index. The query

```
get_scc_size(SCC,Index)), Index > 1000.
```

returns the information that the index of the large SCC was 39. The query `analyze_an_scc(39,userout)` then provides the following information.

```
There are 149671 subgoals and 4461290 links (average of 30.8073 edges per subgoal)
      within the SCC

There are 2 subgoals in the SCC for the predicate backchainForbidden / 0
There are 2 subgoals in the SCC for the predicate
                   http://www.cyc.com/silk/implementation/transformationPredicate / 0
:
There are 15613 subgoals in the SCC for the predicate gpLookupSentence / 3
There are 15613 subgoals in the SCC for the predicate removalSentence / 3
There are 18770 subgoals in the SCC for the predicate forwardSentence / 3
There are 18771 subgoals in the SCC for the predicate lookupSentence / 3

Calls from assertedSentence/3 to lookupSentence/3 : 32
Calls from backchainForbidden/0 to 'http://www.cyc.com/silk/implementation/transformationPredi
:
Calls from transformationSentence/2 to sbhlSentence/3 : 5479
Calls from tvaSentence/3 to removalSentence/3 : 7695
```

[7] The slight difference between the number of subgoals shown here and the number shown by `statistics/0` is due to the use of tabling in the Flora compiler.

[8] This statement is true in local evaluation but not in batched evaluation.

It is evident from the first line in this report that the vast majority of the calls to incomplete tables during this computation occur in the SCC under investigation. Since information on incomplete tables is kept in XSB's choice point stack (cf. [60]), the evaluation of SCC 39 is the likely culprit behind the large amount of stack space required. The subgoals in the SCC are first broken out by their predicate name and arity, then the edges within the SCC are broken out by the predicates of their caller and called subgoals. At this point a programmer can review the various rules for `lookupSentence/3`, `forwardSentence/3` and other predicates to determine whether the recursion is intended and if so, whether it can be simplified.

Using abstraction in the analysis

Within the SCC analysis, information about a given tabled subgoal S was abstracted to the functor and arity of S. For this example, abstraction was necessary, as reporting 150,000 subgoals or 4,000,000+ would not provide useful information for a human being. However, it could be the case that seeing the tabled subgoals themselves would be useful for a smaller SCC. Even for an SCC of this size, different levels of abstraction could be useful: mode information or type information might be useful in a given circumstance.

Example 10.3.4 Making the call `?- analyze_an_scc(39,userout,abstract_modes(_,_))` applies the predicate `abstract_modes/2` to each term, producing an output of the form:

```
There are 149671 subgoals and 4461290 links (average of 30.8073 edges per subgoal)
           within the SCC

There are 3 subgoals in the SCC for the predicate backchainRequired(g,g)
There are 2 subgoals in the SCC for the predicate backchainForbidden(g,g)
:
There are 29254 subgoals in the SCC for the predicate gpLookupSentence(g,g)
There are 29254 subgoals in the SCC for the predicate removalSentence(g,g)

Calls from assertedSentence(g,g) to lookupSentence(g,g) : 10
Calls from assertedSentence(m,g) to lookupSentence(m,g) : 22
:
Calls from transformationSentence(m,g) to sbhlSentence(m,g) : 741
Calls from tvaSentence(g,g) to removalSentence(g,g) : 7695
```

`abstract_modes(In,Out)` simply goes through each argument of `In` and unifies the corresponding argument of `Out` with a `v` if the argument is a variable, a `g` if the argument is ground, and `m` otherwise.

`abstract_modes/2` is simply an example: any term-abstraction predicate may be passed into the last argument of `analyze_an_scc/3` [9].

Analyzing Negation

Many programs that use negation are stratified in such a way that they do not require the use of DELAYING and SIMPLIFICATION operations, and the routines described in the previous section are sufficient for these programs. However if a program does not have a two-valued well-founded model, a user would often like to understand why. Even in a program that is two-valued, the heavy use of DELAYING and SIMPLIFICATION can indicate that some rules may need to be optimized by having their literals reordered.

As indicated previously, the forest log overview includes a total count of DELAYING and SIMPLIFICATION operations, as well as a count of conditional answers. In addition, SCC analysis counts negative as well as positive links within the SCC. The current version of forest logging also provides a means to examine the causes of answers that have an undefined truth value. Recall from Example **??** that there are two types of causes of an undefined truth value: either 1) a negative literal explicitly undergoes a DELAYING operation; or 2) a conditional answer may be used to resolve a literal. It can be shown that in local evaluation, a conditional answer A will never be returned out of an SCC if A is successful or failed in the well-founded model of a program. This means that if an answer for S is undefined, then it would be caused operationally by a DELAYING operation within the SCC of S or within some other SCC on which S depends. So to understand why an atom is undefined it can be useful understand the "root causes" of the delay: to examine SCCs in which DELAYING operations were executed and conditional answers were derived, but the answers could not be simplified.

Example 10.3.5 *As a use case, logging was made of execution of a Flora-2 program that tested out a new defeasibility theory. The forest log overview indicated that the top-level query was undefined:*

```
:
There were a total of 55 negative delays
There were a total of 0 simplifications
There were a total of 695 unconditional answers derived:
There were a total of 66 conditional answers derived:
```

The analysis predicate `three_valued_scc(List)` *produces a list of all SCC indices in which* DELAYING *caused the derivation of conditional answers. These SCCs can then be analyzed as discussed in the previous section.*

[9] Because of the special representation of Flora-2 terms, abstraction was used to produce the output of Example 10.3.4, while a more sophisticated version of `abstract_modes/2` was used in Example 10.3.4.

10.3.3 Discussion

Using log forest imposes a relatively minimal overhead on most computations, considering the information it can provide, and loading and analysis is relatively quick. For this example, the top level analysis took around 10 seconds, and analysing SCC 39 took about 20 seconds in Example 10.3.3 and about 60 seconds in Example 10.3.4. For more information, see [73].

10.3.4 Predicates for Forest Logging

`forest_log_overview` module: `tables`

Provides an overview of subgoals, calls, and SCCs in the forest log as indicated in Section 10.3.2.

`get_scc_size(?Index,?Size)` module: `tables`

This simple predicate determines the indices of SCCs whose size is `Size`, for use with `analyze_an_scc/[2,3]`.

`three_valued_sccs(List)` module: `tables`

If there are any SCCs in the log where delay is performed, causing conditional answers to be added that were not simplified into unconditional answers, unifies `List` with the index of all such SCCs.

`analyze_an_scc(+Index,+File)` module: `tables`
`analyze_an_scc(+Index,+File,+Abstraction)` module: `tables`

These predicates can be used to analyze the SCC indexed by `Index` in a forest log, as explained in Section 10.3.2. The output is written to `File`; calling the predicate with `File` set to `userout` causes the output to be written to the console. In `analyze_an_scc/2`, tabled subgoals are abstracted to predicate indicators, in `analyze_an_scc/3`, a two-ary abstraction predicate in `usermod` is called.

Error conditions on `File` are the same as `tell/1`.

`abstract_modes(Term,AbstractedTerm)` module: `usermod`

`abstract_modes(In,Out)` simply goes through each argument of `Term` and unifies the corresponding argument of `Abstracted` with a `v` if the argument is a variable, a `g` if the argument is ground, and `m` otherwise.

Chapter 11

Definite Clause Grammars

11.1 General Description

Definite clause grammars (DCGs) are an extension of context free grammars that have proven useful for describing natural and formal languages, and that may be conveniently expressed and executed in Prolog. A Definite Clause Grammar rule is executable because it is just a notational variant of a logic rule that has the following general form:

Head `->` *Body.*

with the declarative interpretation that "a possible form for *Head* is *Body*". The procedural interpretation of a grammar rule is that it takes an input sequence of symbols or character codes, analyses some initial portion of that list, and produces the remaining portion (possibly enlarged) as output for further analysis. In XSB, the exact form of this sequence is determined by whether XSB's *DCG mode* is set to use tabling or not, as will be discussed below. In either case, the arguments required for the input and output lists are not written explicitly in the DCG rule, but are added when the rule is translated (expanded) into an ordinary normal rule during parsing. Extra conditions, in the form of explicit Prolog literals or control constructs such as *if-then-elses* (`'->'/2`) or *cuts* (`'!'/0`), may be included in the *Body* of the DCG rule and they work exactly as one would expect.

The syntax of DCGs is orthogonal to whether tabling is used for DCGs or not. An overview of DCG syntax supported by XSB is as follows:

1. A non-terminal symbol may be any HiLog term other than a variable or a number. A variable which appears in the body of a rule is equivalent to the appearance of a call to the standard predicate `phrase/3` as it is described below.

2. A terminal symbol may be any HiLog term. In order to distinguish terminals from nonterminals, a sequence of one or more terminal symbols $\alpha, \beta, \gamma, \delta, \ldots$ is written

within a grammar rule as a Prolog list `[` $\alpha, \beta, \gamma, \delta, \ldots$ `]`, with the empty sequence written as the empty list `[]`. The list of terminals may contain variables but it has to be a proper list, or else an error message is sent to the standard error stream and the expansion of the grammar rule that contains this list will fail. If the terminal symbols are ASCII character codes, they can be written (as elsewhere) as strings.

3. Extra conditions, expressed in the form of Prolog predicate calls, can be included in the body (right-hand side) of a grammar rule by enclosing such conditions in curly brackets, `'{'` and `'}'`. For example, one can write:

```
positive_integer(N) -> [N], {integer(N), N > 0}.
```
[1]

4. The left hand side of a DCG rule must consist of a single non-terminal, possibly followed by a sequence of terminals (which must be written as a *unique* Prolog list). Thus in XSB, unlike SB-Prolog version 3.1, "push-back lists" are supported.

5. The right hand side of a DCG rule may contain alternatives (written using the usual Prolog's disjunction operator `';'` or using the usual BNF disjunction operator `'|'`.

6. The Prolog control primitives *if-then-else* (`'->'/2`), *nots* (`not/1, fail_if/1`, $'\backslash +'/1$ or `tnot/1`) and *cut* (`'!'/0`) may also be included in the right hand side of a DCG rule. These symbols need not be enclosed in curly brackets. [2] All other Prolog's control primitives, such as `repeat/0`, must be enclosed explicitly within curly brackets if they are not meant to be interpreted as non-terminal grammar symbols.

11.2 Translation of Definite Clause Grammar rules

In this section we informally describe the translation of DCG rules into normal rules in XSB. Each grammar rule is translated into a Prolog clause as it is consulted or compiled. This is accomplished through a general mechanism of defining the hook predicate `term_expansion/2`, by means of which a user can specify any desired transformation to be done as clauses are read by the reader of XSB's parser. This DCG term expansion is as follows:

A DCG rule such as:

```
p(X) -> q(X).
```

will be translated (expanded) into:

[1] A term like {`foo`} is just a syntactic-sugar for the term `'{}'(foo)`.

[2] Readers familiar with Quintus Prolog may notice the difference in the treatment of the various kinds of not. For example, in Quintus Prolog a `not/1` that is not enclosed within curly brackets is interpreted as a non-terminal grammar symbol.

```
p(X, Li, Lo) :-
      q(X, Li, Lo).
```

If there is more than one non-terminal on the right-hand side, as in

```
p(X, Y) -> q(X), r(X, Y), s(Y).
```

the corresponding input and output arguments are identified, translating into:

```
p(X, Y, Li, Lo) :-
      q(X, Li, L1),
      r(X, Y, L1, L2),
      s(Y, L2, Lo).
```

Terminals are translated using the predicate `'C'/3` (See section 11.3 for its description). For instance:

```
p(X) -> [go, to], q(X), [stop].
```

is translated into:

```
p(X, S0, S) :-
      'C'(S0, go, S1),
      'C'(S1, to, S2),
      q(X, S2, S3),
      'C'(S3, stop, S).
```

Extra conditions expressed as explicit procedure calls naturally translate into themselves. For example,

```
positive_number(X) ->
      [N], {integer(N), N > 0},
      fraction(F), {form_number(N, F, X)}.
```

translates to:

```
positive_number(X, Li, Lo) :-
      'C'(Li, N, L1),
      integer(N),
      N > 0,
      L1 = L2,
      fraction(F, L2, L3),
      form_number(N, F, N),
      L3 = Lo.
```

Similarly, a cut is translated literally.

Push-back lists (a proper list of terminals on the left-hand side of a DCG rule) translate into a sequence of `'C'/3` goals with the first and third arguments reversed. For example,

```
it_is(X), [is, not] -> [aint].
```

becomes

```
it_is(X, Li, Lo) :-
      'C'(Li, aint, L1),
      'C'(Lo, is, L2),
      'C'(L2, not, L1).
```

Disjunction has a fairly obvious translation. For example, the DCG clause:

```
expr(E) ->
        expr(X), "+", term(Y), {E is X+Y}
      | term(E).
```

translates to the Prolog rule:

```
expr(E, Li, Lo) :-
      ( expr(X, Li, L1),
        'C'(L1, 43, L2),          % 0'+ = 43
        term(Y, L2, L3)
        E is X+Y,
        L3 = Lo
      ; term(E, Li, Lo)
      ).
```

11.2.1 Definite Clause Grammars and Tabling

Tabling can be used in conjunction with Definite Clause Grammars to get the effect of a more complete parsing strategy. When Prolog is used to evaluate DCG's, the resulting parsing algorithm is *"recursive descent"*. Recursive descent parsing, while efficiently implementable, is known to suffer from several deficiencies: 1) its time can be exponential in the size of the input, and 2) it may not terminate for certain context-free grammars (in particular, those that are left or doubly recursive). By appropriate use of tabling, both of these limitations can be overcome. With appropriate tabling, the resulting parsing algorithm is a variant of *Earley's algorithm* and of *chart parsing algorithms*.

In the simplest cases, one needs only to add the directive `:- auto_table` (see Section 3.10.4) to the source file containing a DCG specification. This should generate any necessary table declarations so that infinite loops are avoided (for context-free grammars). That is, with a `:- auto_table` declaration, left-recursive grammars can be correctly processed. Of course, individual `table` directives may also be used, but note that the arity must be specified as two more than that shown in the DCG source, to account for the extra arguments added by the expansion. However, the efficiency of tabling for DCGs depends on the representation of the input and output sequences used, a topic to which we now turn.

Consider the expanded DCG rule from the previous section:

```
p(X, S0, S) :-
      'C'(S0, go, S1),
      'C'(S1, to,S2),
      q(X, S2, S3),
      'C'(S3, stop, S).
```

In a Prolog system, each input and output variable, such as `S0` or `S` is bound to a variable or a difference list. In XSB, this is called *list mode*. Thus, to parse *go to lunch stop* the phrase would be presented to the DCG rule as a list of tokens `[go,to,lunch,stop]` via a call to `phrase/3` such as:

```
phrase(p(X),[go,to,lunch,stop]).
```

or an explicit call to `p/3`, such as:

```
p(X,[go,to,lunch,stop|X],X).
```

Terminal elements of the sequence are consumed (or generated) via the predicate `'C'/3` which is defined for Prolog systems as:

```
'C'([Token|Rest],Token,Rest).
```

While such a definition would also work correctly if a DCG rule were tabled, the need to copy sequences into or out of a table can lead to behavior quadratic in the length of the input sequence (See Section 5.2.4). As an alternative, XSB allows a mode of DCGs that defines `'C'/3` as a call to a Datalog predicate `word/3` :

```
'C'(Pos,Token,Next_pos):- word(Pos,Token,Next_pos).
```

assuming that each token of the sequence has been asserted as a `word/3` fact, e.g:

```
word(0,go,1).
word(1,to,2).
word(2,lunch,3).
word(3,stop,4).
```

The above mode of executing DCGs is called *datalog mode*.

`word/3` facts are asserted via a call to the predicate `tphrase_set_string/1`. Afterwards, a grammar rule can be called either directly, or via a call to `tphrase/1`. To parse the list `[go,to,lunch,stop]` in datalog mode using the predicate `p/3` from above, the call

```
tphrase_set_string([go,to,lunch,stop])
```

would be made, afterwards the sequence could be parsed via the goal:

```
tphrase(p(X)).
```

or

```
p(X,0,F).
```

To summarize, DCGs in list mode have the same syntax as they do in datalog mode:

they just use a different definition of `'C'/3`. Of course tabled and non-tabled DCGs can use either definition of `'C'/3`. Indeed, this property is necessary for tabled DCG predicates to be able to call non-tabled DCG predicates and vice-versa. At the same time,tabled DCG rules may execute faster in datalog mode, while non-tabled DCG rules may execute faster in list mode.

Finally, we note that the mode of DCG parsing is part of XSB's state. XSB's default mode is to use list mode: the mode is set to datalog mode via a call to `tphrase_set_string/3` and back to list mode by a call to `phrase/2` or by a call to `reset_dcg_mode/0`.

11.3 Definite Clause Grammar predicates

The library predicates of XSB that support DCGs are the following:

`phrase(+Phrase, ?List)`

This predicate is true iff the list `List` can be parsed as a phrase (i.e. sequence of terminals) of type `Phrase`. `Phrase` can be any term which would be accepted as a nonterminal of the grammar (or in general, it can be any grammar rule body), and must be instantiated to a non-variable term at the time of the call; otherwise an error message is sent to the standard error stream and the predicate fails. This predicate is the usual way to commence execution of grammar rules.

If `List` is bound to a list of terminals by the time of the call, then the goal corresponds to parsing `List` as a phrase of type `Phrase`; otherwise if `List` is unbound, then the grammar is being used for generation.

`tphrase(+Phrase)`

This predicate is succeeds if the current database of `word/3` facts can be parsed via a call to the term expansion of `+Phrase` whose input argument is set to `0` and whose output argument is set to the largest `N` such that `word(_,_,N)` is currently true.

The database of `word/3` facts is assumed to have been previously set up via a call to `tphrase_set_string/1` (or variant). If the database of `word/3` facts is empty, `tphrase/1` will abort.

`phrase(+Phrase, ?List, ?Rest)`

This predicate is true iff the segment between the start of list `List` and the start of list `Rest` can be parsed as a phrase (i.e. sequence of terminals) of type `Phrase` . In other words, if the search for phrase `Phrase` is started at the beginning of list `List`, then `Rest` is what remains unparsed after `Phrase` has been found. Again, `Phrase` can be any term which would be accepted as a nonterminal of the grammar (or in general, any grammar rule body), and must be instantiated to a non-variable term at the time of the call; otherwise an error message is sent to the standard error stream and the predicate fails.

Predicate `phrase/3` is the analogue of `call/1` for grammar rule bodies, and provides a semantics for variables in the bodies of grammar rules. A variable `X` in a grammar rule body is treated as though `phrase(X)` appeared instead, `X` would expand into a call to `phrase(X, L, R)` for some lists `L` and `R`.

`expand_term(+Term1, ?Term2)`

This predicate is used to transform terms that appear in a Prolog program before the program is compiled or consulted. The default transformation performed by `expand_term/2` is that when `Term1` is a grammar rule, then `Term2` is the corresponding Prolog clause; otherwise `Term2` is simply `Term1` unchanged. If `Term1` is not of the proper form, or `Term2` does not unify with its clausal form, predicate `expand_term/2` simply fails.

Users may augment the default transformations by asserting clauses for the predicate `term_expansion/2` to `usermod`. After `term_expansion(Term_a,Term_b)` is asserted, then if a consulted file contains a clause that unifies with `Term_a` the clause will be transformed to `Term_b` before further compilation. `expand_term/2` calls user clauses for `term_expansion/2` first; if the expansion succeeds, the transformed term so obtained is used and the standard grammar rule expansion is not tried; otherwise, if `Term1` is a grammar rule, then it is expanded using `dcg/2`; otherwise, `Term1` is used as is.

Example: Suppose the following clause is asserted:

```
?- assert(term_expansion(foo(X),bar(X))).
```

and that the file `te.P` contains the clause `foo(a)` then the clause will automatically be expanded upon consulting the file:

```
| ?- [te].
[Compiling /Users/macuser/te]
[te compiled, cpu time used: 0.0170 seconds]
[te loaded]

yes
| ?- bar(X).

X = a

yes
| ?- foo(X).
++Error[XSB/Runtime/P]: [Existence (No procedure usermod : foo / 1 exists)] []
Forward Continuation...
```

However, `read/[1,2]` does not automatically perform term expansion

```
| ?- use_module(standard,[expand_term/2]).

yes
| ?- read(X),expand_term(X,Y).
foo(a).

X = foo(a)
Y = bar(a)

yes
```

`'C'(?L1, ?Terminal, ?L2)`

This predicate generally is of no concern to the user. Rather it is used in the transformation of terminal symbols in grammar rules and expresses the fact that `L1` is connected to `L2` by the terminal `Terminal`. This predicate is needed to avoid problems due to source-level transformations in the presence of control primitives such as *cuts* (`'!'/0`), or *if-then-elses* (`'->'/2`) and is defined by the single clause:

```
'C'([Token|Tokens], Token, Tokens).
```

The name 'C' was chosen for this predicate so that another useful name might not be preempted.

`tphrase_set_string(+List)`

This predicate

1. abolishes all tables;
2. retracts all `word/3` facts from XSB's store; and
3. asserts new `word/3` facts corresponding to `List` as described in Section 11.2.1.

implicitly changing the DCG mode from list to datalog.

`tphrase_set_string_keeping_tables(+List)` module: `dcg`

This predicate is the same as `tphrase_set_string`, except it does not abolish any tables. When using this predicate, the user is responsible for explicitly abolishing the necessary tables.

`tphrase_set_string_auto_abolish(+List)` module: `dcg`

This predicate is the same as `tphrase_set_string`, except it abolishes tables that have been indicated as dcg-supported tables by a previous call to `set_dcg_supported_table/1`.

`set_dcg_supported_table(+TabSkel)` module: `dcg`

This predicate is used to indicate to the DCG subsystem that a particular tabled predicate is part of a DCG grammar, and thus the contents of its table depends on

the string being parsed. `TabSkel` must be the skeleton of a tabled predicate. When `tphrase_set_string_auto_abolish/1` is called, all tables that have been indicated as DCG-supported by a call to this predicate will be abolished.

`dcg(+DCG_Rule, ?Prolog_Clause)` module: `dcg`

Succeeds iff the DCG rule `DCG_Rule` translates to the Prolog clause `Prolog_Clause`. At the time of call, `DCG_Rule` must be bound to a term whose principal functor is `'->'/2` or else the predicate fails. `dcg/2` must be explicitly imported from the module `dcg`.

11.4 Two differences with other Prologs

The DCG expansion provided by XSB is in certain cases different from the ones provided by some other Prolog systems (e.g. Quintus Prolog, SICStus Prolog and C-Prolog). The most important of these differences are:

1. XSB expands a DCG clause in such a way that when a `'!'/0` is the last goal of the DCG clause, the expanded DCG clause is always *steadfast*.

   That is, the DCG clause:

   ```
   a -> b, !  ; c.
   ```

   gets expanded to the clause:

   ```
   a(A, B) :- b(A, C), !, C = B ; c(A, B).
   ```

   and *not* to the clause:

   ```
   a(A, B) :- b(A, B), !  ; c(A, B).
   ```

   as in Quintus, SICStus and C Prolog.

   The latter expansion is not just optimized, but it can have a *different (unintended) meaning* if `a/2` is called with its second argument bound.

   However, to obtain the standard expansion provided by the other Prolog systems, the user can simply execute:

   ```
   set_dcg_style(standard).
   ```

   To switch back to the XSB-style DCG's, call

   ```
   set_dcg_style(xsb).
   ```

   This can be done anywhere in the program, or interactively. By default, XSB starts with the XSB-style DCG's. To change that, start XSB as follows:

   ```
   xsb -e "set_dcg_style(standard)."
   ```

   Problems of DCG expansion in the presence of *cuts* have been known for a long time and almost all Prolog implementations expand a DCG clause with a `'!'/0` in its

body in such a way that its expansion is steadfast, and has the intended meaning when called with its second argument bound. For that reason almost all Prologs translate the DCG clause:

```
a -> !  ; c.
```

to the clause:

```
a(A, B) :- !, B = A ; c(A, B).
```

But in our opinion this is just a special case of a `'!'/0` being the last goal in the body of a DCG clause.

Finally, we note that the choice of DCG style is orthogonal to whether the DCG mode is list or datalog.

2. Most of the control predicates of XSB need not be enclosed in curly brackets. A difference with, say Quintus, is that predicates `not/1`, $'\backslash +'/1$, or `fail_if/1` do not get expanded when encountered in a DCG clause. That is, the DCG clause:

```
a -> (true -> X = f(a) ; not(p)).
```

gets expanded to the clause:

```
a(A,B) :- (true(A,C) -> =(X,f(a),C,B) ; not p(A,B))
```

and *not* to the clause:

```
a(A,B) :- (true(A,C) -> =(X,f(a),C,B) ; not(p,A,B))
```

that Quintus Prolog expands to.

However, note that all non-control but standard predicates (for example `true/0` and `'='/2`) get expanded if they are not enclosed in curly brackets.

Chapter 12

Exception Handling

We define the term *exceptions* as errors in program execution that are handled by a non-local change in execution state. Exception handling in XSB is ISO-compatable, and has been extended to handle tabled evaluations.

12.1 The Mechanics of Exception Handling

We address the case of non-tabled evaluations before discussing the extensions for tabling.

12.1.1 Exception Handling in Non-Tabled Evaluations

The preferred mechanism for dealing with exceptions in XSB is to use the predicates `catch/3`, `throw/1`, and `default_user_error_handler/1` together. These predicates are ISO-compatable, and their use can give a great deal of control to exception handling. At a high level, when an exception is encountered an error term T is *thrown*. In a Prolog program, throwing an error term T causes XSB to examine its choice point stack until it finds a *catcher* that unifies with T. This catcher then calls a *handler*. If no explicit catcher for T exists, a default handler is invoked, which usually results in an abort, and returns execution to the top-level of the interpreter, or to the calling C function.

A handler is set up when `catch(Goal,Catcher,Handler)` is called. At this point a continuation is saved (i.e. a Prolog choice point), and `Goal` is called. If no exceptions are encountered, answers for `Goal` are obtained as usual. Within the execution of `Goal`, an exception is usually thrown by calling a Prolog predicate in the `error_handler` module, or by executing a C-level error function. However, if a user-defined error type is desired, the Prolog predicate `throw/1` can also be called directly. As mentioned above, `throw/1` searches for an ancestor of the current environment called by `catch/3` and whose catcher (second argument) unifies with `Error`. If such an ancestor is found, program execution reverts to the ancestor

and all intervening choice points are removed. The catcher's `Handler` goal is called and the exception is thereby handled. On the other hand, if no ancestor was called using `catch/3` the system checks whether a clause with head `default_user_error_handler(Term)` has been asserted, such that `Term` unifies with `Error`. If so, this handler is executed. If not, XSB's default system error handler in invoked an error message is output and execution returns to the top level of the interpreter.

The following, somewhat fanciful example, helps clarify these concepts [1]. Consider the predicate `userdiv/2` (Figure 12.1) which is designed to be called with the first argument instantiated to a number. A second number is then read from a console, and the first number is divided by the second, and unified with the second argument of `userdiv/2`. By using `catch/3` and `throw/1` together the various types of errors can be caught.

```
:- import error_writeln/1 from standard.
:- import type_error/4 from error_handler.

userdiv(X,Ans):-
        catch(userdiv1(X,Ans),mydiv1(Y),handleUserdiv(Y,X)).

userdiv1(X,Ans):-
        (number(X) -> true; type_error(number,X,userdiv1/2,1)),
        write('Enter a number: '),read(Y),
        (number(Y) -> true ; throw(mydiv1(error1(Y)))),
        (Y < 0 -> throw(mydiv1(error2(Y))); true),
        (Y =:= 0 -> throw(error(zerodivision,userdiv/1,[])); true),
        Ans is X/Y.

handleUserdiv(error1(Y),_X):-
        error_writeln(['a non-numeric denominator was entered in userdiv/1: ',Y]),fail.
handleUserdiv(error2(Y),_X):-
        error_writeln(['a negative denominator was entered in userdiv/1: ',Y]),fail.
```

Figure 12.1: The `userdiv/1` program

The behavior of this program on some representative inputs is shown below.

```
| ?- userdiv(p(1),F).
++Error[XSB/Runtime/P]: [Type (p(1) in place of number)]  in arg 1 of predicate userdiv1/2
Forward Continuation...
... machine:xsb_backtrace/1
... error_handler:type_error/4
... standard:call/1
```

[1] Code for this example can be found in `$XSBDIR/examples/exceptions.P`.

```
... x_interp:_$call/1
... x_interp:call_query/1
... standard:call/1
... standard:catch/3
... x_interp:interpreter/0
... loader:ll_code_call/3
... standard:call/1
... standard:catch/3

no
| ?- userdiv(3,F).
Enter a number: foo.
a non-numeric denominator was entered in userdiv/1: foo

no
|| ?- userdiv(3,F).
Enter a number: -1.
a negative denominator was entered in userdiv/1: -1

no
| ?- userdiv(3,Y).
Enter a number: 2.

Y = 1.5000

yes
```

Note, however the following behavior.

```
| ?- userdiv(3,F).
Enter a number: 0.
++Error[XSB/Runtime/P] uncaught exception: error(zerodivision,userdiv / 1)
Aborting...
```

By examining the program above, it can be seen that if `p(1)` is entered, the predicate `type_error/3` is called. `type_error/3` is an XSB mechanism to throw an ISO-style type error from Prolog. Such an error is known to the default system error handler which prints out a message along with a *backtrace* that indicates the calling context in which the error arose (this behavior can be controlled: see Section 12.5). Alternately, in the second case, when `-1` is entered, the error term `mydiv1(error2(-1))` is thrown, which is caught within `userdiv/2` and handled by `handleUserdiv/2`. Finally, when `0` is entered for the denominator, an error term of the form `error(zerodivision,userdiv/1)` is thrown, and that this term does not unify with the second argument of the `catch/3` literal in the body of `userdiv/1`, or with a known ISO error. The error is instead caught by XSB's default system error handler which prints an uncaught exception message and aborts to the top level of the interpreter.

XSB has two default system error handlers: one used when XSB is called as a stand-alone process, and another when XSB is embedded in a process. Each recognizes certain error formats (see Section 12.2), and handles the rest as uncaught exceptions. However, there may be times when an application requires special default handling: perhaps the application calls XSB from through a socket, so that aborts are not practical. Alternately, perhaps XSB is being called from a graphical user interface via Interprolog [9] or some other interface, and in addition to a special abort handling, one would like to display an error window. In these cases it is convenient to make use of the dynamic predicate `default_user_error_handler/1`. `default_user_error_handler/1` is called immediately before the default system error handler, and after it is ascertained that no catcher for an error term is available via a `catch/3` ancestor. It is important to note that the system error handlers catch errors only in the main thread, and do not affect errors thrown by goals executed by `thread_create/[2,3]`. Error terms thrown by goals executed by non-detached threads are stored internally, and can be obtained by `thread_join/2`. Error terms thrown by detached threads are lost when the thread exits, so that any error handling for a detached thread should be performed within the thread itself. See Chapter 7 for further information.

Accordingly, suppose the following clause is asserted into `usermod`:

```
?- assert((default_user_error_handler(error(zerodivision,Pred)):-
        error_writeln(['Aborting: division by 0 in: ',Pred]))).
```

The behavior will now be

```
| ?- userdiv(4,F).
Enter a number: 0.
Aborting: division by 0 in: userdiv / 1
```

The actions of `catch/3` and `throw/1` resemble that of the Prolog cut in that they remove choice points that lie between a call to `throw/1` and the matching `catch/3` that serves as its ancestor.

The predicate `call_cleanup/2` (cf. Section 6.11) can be used with `catch/3`, since the goal `call_cleanup(Goal,Cleanup)` executes `Cleanup` whenever computation of `Goal` is completed, whether because `Goal` has thrown an exception, has failed, or has succeeded with its last answer. `call_cleanup/2` can thus be used to release resources created by `Goal` (such as streams, mutexes, database cursors, etc.). However, if `Goal` throws an exception, `call_cleanup/2` will re-throw the exception after executing cleanup.

12.1.2 Exception Handling in Tabled Evaluation

The exception handling as previously described requires extensions in order to work well with tabled predicates. First, if an *unhandled* exception is thrown duing evaluation of a

tabled subgoal S and S is not completed, the table for S is not meaningful and should be removed. (Tables that have been completed are not affected by exceptions.) Accordingly, the user will sometimes see the message:

```
Removing incomplete tables...
```

written to standard feedback. But what about exceptions that are *caught* during the computation of S?

The proper action to take in such a case is complicated by the scheduling mechanism of tabling which, as discussed in Chapter 5, is more complex than in Prolog. Rather than a simple depth-first search, as in Prolog, tabled evaluations effectively perform a series of fixed-point computations for various sets of mutually dependent subgoals, which are termed *SCCs* [2]. In fact, a tabled evaluation can be seen as a tree of SCCs (in batched evaluation) or a chain of SCCs (in local evaluation). In a tabled evalution XSB's throw mechanism searches for the nearest catcher C among its ancestors

- whose `Catchterm` unifies with the thrown error; and
- where C is between SCCs: that is where the set of subgoals that depend on C is disjoint from the set of subgoals upon which C depends. We term this the *SCC restriction* for exception handling.

This behavior can be best understood by an example. Consider the query `a(X)` to the program in Figure 12.2 which has the following output:

```
:- table a/1, b/1, c/1,d/1.
a(X):- writeln(a_calling_b),b(X).

b(X):- writeln(b_calling_a),a(X).
b(X):- writeln(b_calling_c),catch(c(X),_,(writeln(handled_1),fail)).

c(X):- writeln(c_calling_d),d(X).
c(X):- writeln(c_aborting),abort.
d(X):- writeln(d_calling_c),catch(c(X),_,(writeln(handled_2),fail)).
```

Figure 12.2: A program to illustrate exception handling in tabled evaluations

```
| ?- a(X).
```

[2]This term is used since sets of mutually dependent subgoals are formally modelled as (approximate) *Strongly Connected Components* within a dependency graph.

```
a_calling_b
b_calling_a
b_calling_c
c_calling_d
d_calling_c
c_aborting
Removing incomplete tables...
handled_1
```

Note that there are 2 SCCs, $\{a(X), b(X)\}$ and $\{c(X), d(X)\}$. When the `abort` is called in the body of `c(X)` the catch in the body of `d(X)` is its nearest ancestor; however this catch is skipped over, and the catch in the body of `b(X)` takes effect. This catch is between the SCCs – the first SCC depends on it, but the second doesn't. Due to the SCC restriction, the actual behavior of exception handling with tabling is thus somewhat less intuitive than in Prolog. If this restriction were lifted, there would be no guarantee that there existed a unique catch that was the closest ancestor of an exception.

While the above mechanism offers a great deal of flexibility, for many cases the best approach to exception handling is to keep it simple.

1. Use catches when there will be no tabled subgoal between an exception and its catcher. For instance, sometimes it may be annoying to have `atom_codes/2` throw an exception rather than failing, if given an integer in its first argument. This can be addressed by the predicate

   ```
   my_atom_codes(X,Y):-
      catch(atom_codes(1,B),error(type_error(A,B),C,D),writeln(E)).
   ```

   which, for a type error, does not interact with tabling in any way.

2. Similarly, if only subgoals to *completed* tables occur between an exception and its catcher, exception handling behaves just as in case 1).

3. Otherwise, abort the entire tabled computation and handle it from there.

Obtaining Information about a Tabled Computation after an Exception is Thrown

XSB backtraces (Section 12.5) provide information about the context in which error is thrown, but in a tabled computation additional information is available. If the Prolog flag `exception_pre_action` is set to `print_incomplete_tables` (its default setting is `none`), then when an exception is thrown, incomplete tables and their SCC information at the time an exception is thrown are printed to a file via `print_incomplete_tables/1`. The file may be obtained through the predicate `get_scc_dumpfile/1` in the module `tables`. No file is generated unless the exception is thrown over at least one incomplete table.

12.2 Representation of ISO Errors

All exceptions that occur during the execution of an XSB program can be caught. However, by structuring error terms in a consistent manner, different classes of errors can be handled much more easily by user-defined handlers. This philosophy partly underlies the ISO Standard for defining classes of Prolog errors [33]. While the ISO standard defines various types of errors and how they should arise during execution of ISO Prolog predicates, it does not define the actual error terms a system should use. Accordingly, we define the formats for various ISO errors. Below, in Section 12.3 we provide predicates for throwing various ISO errors and performing various error checks.

In the following predicates, `Msg` is either a list of HiLog terms or a comma-list of HiLog terms. Each of the `error/2` terms below can also be represented as `error/3` terms, where the third argument is instantiated to the representation of a backtrace [3].

error(domain_error(Valid_type,Culprit),Msg) is the format of an ISO type error, where `Valid_type` is the domain expected and `Culprit` is the term observed. Unlike types, domains can be user-defined.

error(evaluation_error(Flag),Msg) is the format of an ISO evaluation error (e.g. overflow or underflow), and `Flag` is the type of evaluation error encountered.

error(existence_error(Type,Culprit),Msg) is the format of an ISO type error, where `Type` is the type of a resource and `Culprit` is the term observed (e.g., a predicate, stream, attribute handler, etc.).

error(instantiation_error,Msg)) is the format of an ISO instantiation error.

error(permission_error(Op,Obj_type,Culprit).Msg) is the format of an ISO permission error, for an operation `Op` applied to an object of type `Obj_type`, where `Culprit` was observed.

error(representation_error(Flag).Msg) is the format of an ISO representation error (e.g., the maximum arity of a predicate has been exceeded), and `Flag` is the type of representation error encountered.

error(resource_error(Flag).Msg) is the format of an ISO resource error (e.g. allowed memory has been used, or too many files have been opened), and `Flag` is the type of resource error encountered.

error(syntax_error,Msg) and `error(syntax_error(Culprit),Msg)` are alternate formats of an ISO syntax error, where `Culprit` is used for a syntactically-incorrect sequence of tokens.

[3] If a program catches errors itself, error/3 may need to be imported from `error_handler`.

error(system_error(Flag),Msg) is the format of an ISO system error, and `Flag` is the type of system error encountered.

error(type_error(Valid_type,Culprit),Msg) is the format of an ISO type error, where `Valid_type` is the type expected and `Culprit` is the term observed. This should be used for checks of Prolog types only (i.e. integers, floats, atoms, etc.)

In addition, XSB also makes use of some other types of errors.

error(table_error,Msg) is the format of an error arising when using XSB's tabling mechanism.

error(misc_error,Msg) is the format of an error that is not otherwise classified.

error(thread_cancel,Id) is the format of an error ball for a thread that has been cancelled by XSB thread `Id` (See Chapter 7 for details on thread cancellation.)

In Version 3.3 of XSB, errors for ISO predicates usually, but not not always ISO-compliant. First, when XSB determines it is out of available system memory, recovering from such an error may be difficult at best. Accordingly the computation is aborted in the sequential engine, or XSB exits in the multi-threaded engine [4]. Second, errors in XSB code sometimes arise as miscellaneous errors rather than as a designated ISO-error type.

When XSB generates a memory exception *at the OS level* (e.g., a segmentation violation or bus error) it prints out a backtrace and exits. This should be caused only by a bug in XSB or included C code. The first predicate in the backtrace that is printed in these circumstances may be incorrect or redundant. This is because the memory structures used to generate the backtrace are not always completely consistent, and so an interrupt at an unexpected point may result in the use of somewhat inconsistent information.

12.3 Predicates to Throw and Handle Errors

12.3.1 Predicates to Throw Errors

XSB provides a variety of predicates that throw errors [5]. In general, we recommend the use of predicates such as `domain_error/4` over the direct use of `throw/1` when possible.

`throw(+ErrorTerm)` ISO

Throws the error `ErrorTerm`. Execution traverses up the choice point stack until a goal of the form `catch(Goal,Term,Handler)` is found such that `Term` unifies with

[4] This does not include overflowaing a memory limit specified by the flag `max_memory`.

[5] C functions for throwing terms and ISO-style errors are described in Volume 2, Chapter 3 *Foreign Language Interface*.

ErrorTerm. In this case, Handler is called. If no catcher is found in the main thread, the system looks for a clause of default_user_error_handler(Term) such that Term unifies with ErrorTerm — if no such clause is found the default system error handler is called. In a non-main joinable thread, the error term is stored internally and the thread exits; in a detached thread, the thread exits with no action taken. throw/1 is most useful in conjunction with specialized handlers for new types of errors not already supported in XSB.

domain_error(+Valid_type,-Culprit,+Predicate,+Arg) module: error_handler

Throws a domain error. Using the default system error handler (with backtrace_on_error set to off) an example is

```
domain_error(posInt,-1,checkPosInt/3,3).
++Error[XSB/Runtime/P]: [Domain (-1 not in domain posInt)] in arg 3 of predicate
checkPosInt/3
```

evaluation_error(+Flag,+Predicate,+Arg) module: error_handler

Throws an evaluation error. Using the default system error handler (with backtrace_on_error set to off) an example is

```
evaluation_error(zero_divisor,unidiv/1,2).
++Error[XSB/Runtime/P]: [Evaluation (zero_divisor)] in arg 2 of predicate unidiv/2
```

existence_error(+Object_type,?Culprit,+Predicate,+Arg) module: error_handler

Throws an existence error. Using the default system error handler (with backtrace_on_error set to off) an example is

```
existence_error(file,'myfile.P','load_intensional_rules/2',2).
++Error[XSB/Runtime/P]: [Existence (No file myfile.P exists)]  in arg 2 of predicate
load_intensional_rules/2
```

instantiation_error(+Predicate,+Arg,+State) module: error_handler

Throws an instantiation error. Using the default system error handler, an example (with backtrace_on_error set to off) is

```
?- instantiation_error(foo/1,1,nonvar).
++Error[XSB/Runtime/P]: [Instantiation]  in arg 1 of predicate foo/1: must be nonvar
```

permission_error(+Op,+Obj_type,?Culprit,+Predicate) module: error_handler

Throws a permission error. Using the default system error handler, an example (with backtrace_on_error set to off) is

```
| ?- permission_error(write,file,'myfile.P',foo/1).
++Error[XSB/Runtime/P]: [Permission (Operation) write on file: myfile.P]  in foo/1
```

representation_error(+Flag,+Predicate,+Arg) module: error_handler

Throws a representation error. Using the default system error handler, an example (with backtrace_on_error set to off) is

```
representation_error(max_arity,assert/1,1).
++Error[XSB/Runtime/P]: [Representation (max_arity)] in arg 1 of predicate assert/1
```

`resource_error(+Flag,+Predicate)` module: `error_handler`

Throws a resource error. Using the default system error handler (with `backtrace_on_error` set to off) and example is

```
resource_error(open_files,open/3)
++Error[XSB/Runtime/P]: [Resource (open_files)] in predicate open/3
```

`type_error(+Valid_type,-Culprit,+Predicate,+Arg)` module: `error_handler`

Throws a type error. Using the default system error handler, an example (with `backtrace_on_error` set to off) is

```
| ?- type_error(atom,f(1),foo/1,1).
++Error[XSB/Runtime/P]: [Type (f(1) in place of atom)]  in arg 1 of predicate foo/1
```

`misc_error(+Message)` module: `error_handler`

Throws a miscellaneous error that will be caught by the default system handler. For good programming practice miscellaneous errors should only be thrown when the cases above are not applicable, and the type of error is not of interest for structured error handling. Such situations occur can occur for instance in debugging, during program development, or in small-special purpose programs. Note that this `misc_error/2` replaces the obsolescent XSB predicates `abort/1` and `abort/2`.

12.3.2 Predicates to Handle Errors

For best results, output for handling errors should be sent to XSB's standard error stream using the alias `user_error` or one of the predicates described below.

`catch(?Goal,?CatchTerm,+Handler)` ISO

Calls `Goal`, and sets up information so that future throws will be able to access `CatchTerm` under the mechanism mentioned above. `catch/3` does not attempt to clean up system level resources. Thus, it is left up to the handler to close open tables (via `close_open_tables/0`, close any open files, reset current input and output, and so on [6].

`default_user_error_handler(?CatchTerm)`

Handles any error terms that unify with `CatchTerm` that are not caught by invocations of `catch/3`. This predicate *does* close open tables and release mutexes held by the calling thread, but does not attempt to clean up other system level resources, which is left to the handler.

[6] cf. the default system error handler, which performs these functions, if needed.

`error_write(?Message)` module: `standard`
`error_writeln(?Message)` module: `standard`

Utility routines for user-defined error catching. These predicates output `Message` to XSB's `STDERR` stream, rather than to XSB's `STDOUT` stream, as does `write/1` and `writeln/1`. In addition, if `Message` is a comma list, the elements in the comma list are output as if they were concatenated together. Each of these predicates must be implicitly from the module `standard`.

`close_open_tables` module: `machine`

Removes table data structures for all incomplete tables, but does not affect any complete tables. In Version 3.3 this predicate should only be used to handle exceptions in `default_user_error_handler/1`. In addition, for the multi-threaded engine, this predicate unlocks any system mutexes held by the thread calling this predicate.

12.4 Convenience Predicates

The following convenience predicates are provided to make a commonly used check and to throw an ISO error if the check is not satisfied; some are written directly in C for speed. All these predicates must be imported from the module `error_handler`, which also contains provides a few other specialized checks.

`check_acyclic(?Term,+Predicate,+Arg)` module: `error_handler`

Checks that `Term` is acyclic. If so, the predicate succeeds; if not it throws a miscellaneous error.

`check_atom(?Term,+Predicate,+Arg)` module: `error_handler`

Checks that `Term` is an atom. If so, the predicate succeeds; if not it throws a type error.

`check_callable(?Term,+Predicate,+Arg)` module: `error_handler`

Checks that `Term` is callable. If so, the predicate succeeds; if not it throws a type error.

`check_ground(?Term,+Predicate,+Arg)` module: `error_handler`

Checks that `Term` is ground. If so, the predicate succeeds; if not it throws an instantiation error.

`check_integer(?Term,+Predicate,+Arg)` module: `error_handler`

Checks that `Term` is an integer. If so, the predicate succeeds; if not it throws a type error.

`check_nonvar(?Term,+Predicate,+Arg)` module: `error_handler`

Checks that `Term` is not a variable. If not, the predicate succeeds; if `Term` is a variable, it throws an instantiation error.

`check_nonvar_list(?Term,+Predicate,+Arg)` module: `error_handler`

Checks that `Term` is a list, each of whose elements is ground. If so, the predicate succeeds; if not it throws an instantiation error.

`check_one_thread(+Operation,+Object_Type,+Predicate)` module: `error_handler`

In the multi-threaded engine, `check_one_thread/3` checks that there is only one active thread: if not, a miscellaneous error is thrown indicating that `Operation` is not permitted on `ObjectType` as called by `Predicate`, when more than one thread is active. This check provides a convenient way to allow inclusion of certain operations that are difficult to make thread-safe by other means.

In the single-threaded engine this predicate always succeeds.

`check_stream(?Stream,+Predicate,+Arg)` module: `error_handler`

Checks that `Stream` is a stream. If so, the predicate succeeds; if not it throws an instantiation error [7].

`check_var(?Term,+Predicate,+Arg)` module: `error_handler`

Checks that `Term` is a variable. If so, the predicate succeeds; if not it throws an instantiation error.

12.5 Backtraces

Displaying a backtrace of the calling context of an error in addition to an error message can greatly expedite debugging. For XSB's default error handler, backtraces are printed out by default, a behavior that can be overridden for a given thread by the command: `set_prolog_flag(backtrace_on_error,off)`. For users who write their own error handlers, the following predicates can be used to manipulate backtraces.

It is important to note that Prolog backtraces differ in a significant manner from backtraces obtained from other languages, such as C backtraces produced by GDB. This is because a Prolog backtrace obtains forward continuations from the local environment stack, and in the WAM, local stack frames are only created when a given clause requires permanent variables – otherwise these stack frames are optimized away. The precise conditions for optimizing away a local stack frame require an understanding of the WAM (and of a specific compiler). However in general, longer clauses with many variables require a local stack frame and their forward continuations will be displayed, while shorter clauses with fewer variables do not and their forward continuations will not be displayed.

`xsb_backtrace(-Backtrace)` module: `machine`

Upon success `Backtrace` is bound to a structure indicating the forward continuations

[7] The representation of streams in XSB is subject to change.

for a point of execution. This structure should be treated as opaque, and manipulated by one of the predicates below.

`get_backtrace_list(+Backtrace,-PredicateList)` module: `error_handler`

Given a backtrace structure, this predicate produces a list of predicate identifiers or the form `Module:Predicate/Arity`. This list can be manipulated as desired by error handling routines.

`print_backtrace(+Backtrace)` module: `error_handler`

This predicate, which is used by XSB's default error handler, prints a backtrace structure to XSB's standard error stream.

Chapter 13

Foreign Language Interface

When XSB is used to build real-world systems, a foreign-language interface may be necessary to:

- combine XSB with existing programs and libraries, thereby forming composite systems;
- interface XSB with the operating system, graphical user interfaces or other system level programs;
- speed up certain critical operations.

XSB has both a high-level and the low-level interface to C. The low-level interface is much more flexible, but it requires greater attention to details of how the data is passed between XSB and C. To connect XSB to a C program using the high-level interface requires very little work, but the program must be used "as is" and it must take the input and produce the output supported by this high-level interface. Before describing the interfaces themselves, we first describe aspects common to both the lower- and higher-level foreign language interfaces.

The foreign language interface can also support `C++` programs. Since XSB is written in `C`, the interface functions in the foreign `C++` module must have the declaration `extern "C"`, and a separate compiler option (e.g. specifying `g++` rather than `gcc`) may need to be given to ensure proper linkage, inclusion of `C++` libraries, etc. In addition, on certain platforms compilation may need to be done externally to XSB – see the `xasp` 1package for a example of using the foreign language interface with `C++` files. For the rest of this chapter, we restrict our attention to foreign predicates written in `C`.

13.1 Foreign Language Modules

Foreign predicates must always appear in modules, and these modules can contain only foreign predicates. A foreign module differs from a Prolog module in that the foreign module's source file must appear in a `*.c` file rather than a `*.P` file (or `.pl` file). This `*.c` file cannot contain a `main()` function. Furthermore, a `*.P` file with the same name *must not* be present or else the `*.c` file is ignored and the module is compiled as a regular Prolog module. The interface part of a foreign module, which has the same syntax as that of a normal module, is written in Prolog and must appear in a `*.H` file. If the lower-level interface is used, this `*.H` file contains explicit `export/1` declarations for the the foreign predicates that are to be used by other modules; if the higher-level interface is used, the declarations have the form `foreign_pred/1`.

The Prolog predicates attached to foreign functions are deterministic, in the sense that they succeed at most once for a given call and are not re-entered on backtracking. Note that this requirement imposes no serious limitation, since it is always possible to divide a foreign predicate into the part to be done on the first call and the part to be redone on backtracking. Backtracking can then take place at the Prolog level where it is more naturally expressed.

A foreign module can be compiled or consulted just like a normal Prolog module. Currently, predicates `consult/[1,2]` recompile both the `*.c` and the `*.H` files of a foreign module when at least one of them has been changed from the time the corresponding object files have been created (see the section *Compiling and Consulting* in Volume 1) [1]. The C compiler used to compile the `*.c` files can be set as a defaults to that used for the configuration of XSB (refer to the section *Getting Started with XSB* in Volume 1). This default behavior includes the C compilation options used to compile XSB when it was configured, along with a default set of include files so that header files in XSB directories can be obtained. Alternately, the user can add options to be passed to the C compiler. To give an example, the following command will compile file `file.c` using the default C Compiler with optimization and by including `/usr/local/X11/R6/include` to the directories that will be searched for header files.

```
:- consult(file, [cc_opts('-O2 -I/usr/local/X11/R6/include')]).
```

Note in particular, that if XSB were compiled with the `-g` debugging option, then the C file will be also [2]. Any Prolog compiler options are ignored when compiling a foreign module.

[1] In addition, if a C module compiled by the single-threaded XSB engine is loaded by the multi-threaded engine, it will be recompiled, and vice-versa.

[2] In a 64-bit platform, users may override the default compilation of XSB by the configuration options `-with-bits32` or `-with-bits64`. If either of these options is used, the default compilation options will pass along the appropriate memory options. If XSB is compiled with a memory option that is not the default of the platform, and if an externally compiled C file is to be loaded into XSB, it must be ensured that the C file has been compiled with the appropriate memory options: `-m32` or `-m64` if `gcc` is used.

Prolog-specific directives such as `index`, `hilog`, `table`, `auto_table` or even `import` make no sense in the case of a foreign module and thus are ignored by the compiler. However, another directive, namely `ldoption`, is recognized in a foreign module and is used to instruct the dynamic loading and linking of the module. The syntax of the `ldoption` directive is simply:

```
:- ldoption(Option).
```

where `Option` should either be an atom or a list of atoms. Multiple `ldoption` directives may appear in the same `.H` file of a foreign module [3]. In Unix-derived systems, the foreign language interface of XSB uses `ld` command that combines object programs to create an executable file or another object program suitable for further `ld` processing. Version 3.3 of XSB assumes that the `ld` command resides in the file `/usr/bin/ld`.

13.2 Lower-Level Foreign Language Interface

Creating a foreign predicate using the lower-level foreign language interface is almost entirely a matter of writing C code. Consider the foreign module `$XSBDIR/examples/XSB_calling_c/simple_foreign.[c]`. The .H file has the form:

```
:- export minus_one/2, my_sqrt/2, change_char/4.

:- ldoption('-lm').     % link together with the math library
```

When the lower level foreign language interface is used, C functions that implement foreign predicates must return values of type `int`. The return value is not used by a Prolog argument; rather if a non-zero is returned, the foreign predicate succeeds; a zero return value means failure.

At the C level, the function that implements the Prolog predicate must have the same name as the Prolog predicate (that is declared in the `*.H` file), and must have a special *context parameter* macro. The context parameter macro allows C functions to be used with both the single-threaded and multi-threaded engines, and are described in detail in Section 13.2.1. The Prolog level arguments are converted to C data structures through several predefined functions rather than through direct parameter passing [4]. The C file `simple_foreign.c` corresponding to the above `.H` file is as follows.

[3] Mac OSX users using 10.3 or above should have the environment variable `MACOSX_DEPLOYMENT_TARGET` set to `10.3` so that the compiler generates code that can be dynamically linked by XSB. This should be done automatically by XSB on initialization, but it is useful to check if encountering problems.

[4] The inclusion of context parameters changes the lower-level interface for Version 3.0. C files written for previous versions of XSB continue to work properly for the single-threaded engine in, but will not work properly for the multi-threaded engine.

```
/*-----------------------------------------------------------------------*/

#include <math.h>
#include <stdio.h>
#include <string.h>
#include <alloca.h>

/*----- Make sure your C compiler finds the following header file.    -----
  ----- One way to do this is to include the directory XSB/emu on the -----
  ----- compiler's command line with the -I (/I in Windows) option    -----*/

#include "cinterf.h"

/*-----------------------------------------*/

int minus_one(CTXTdecl)
{
   int  i = ptoc_int(CTXTc 1);

   ctop_int(CTXTc 2, i-1);
   return TRUE;
}

/*-----------------------------------------*/

int my_sqrt(CTXTdecl)
{
   int i = ptoc_int(CTXTc 1);

   ctop_float(CTXTc 2, (float) pow((double)i, 0.5));
   return TRUE;
}

/*-----------------------------------------*/

int change_char(CTXTdecl)
{
   char *str_in;
   int  pos;
   int c;
   char *str_out;

   str_in = (char *) ptoc_string(CTXTc 1);
   str_out = (char *) alloca(strlen(str_in)+1);
   strcpy(str_out, str_in);
   pos = ptoc_int(CTXTc (2);
   c = ptoc_int(CTXTc (3);
   if (c < 0 || c > 255) /* not a character */
```

```
     return FALSE; /* this predicate will fail on the Prolog side */

   str_out[pos-1] = c;

   extern_ctop_string(CTXTc 4, str_out);
   return TRUE;
}

/*----------------------------------------------------------------------*/
```

Before describing the C program used, here is a sample session illustrating the behavior of the predicates in `simple_foreign`.

```
XSB Version 2.0 (Gouden Carolus) of June 26, 1999
[i686-pc-linux-gnu; mode: optimal; engine: slg-wam; scheduling: batched]
| ?- [simple_foreign].
[Compiling C file ./simple_foreign.c using gcc]
[Compiling Foreign Module ./simple_foreign]
[simple_foreign compiled, cpu time used: 0.0099993 seconds]
[simple_foreign loaded]

yes
| ?- change_char('Kostis', 2, w, TempStr),
     change_char(TempStr, 5, h, GrkName).

TempStr = Kwstis
GrkName = Kwsths;

no
| ?- minus_one(43, X).

X = 42;

no
| ?- minus_one(43, 42).                  % No output unification is allowed
Wrong arg in ctop_int 2a2 (Reg = 2)

yes
| ?- my_sqrt(4,X).

X = 2

yes
| ?- my_sqrt(23,X).

X = 4.7958;
```

```
no
```

Consider the function `minus_one()` above. As discussed, it takes a context parameter (explained below), and returns an integer, and as can be seen the return values can be specified by the macros `TRUE` and `FALSE`. From the Prolog perspective the first argument to `minus_one/2` is an (integer) input argument, while the second is an (integer) output argument. Input arguments for basic C types are translated from their Prolog representation to a C representation by functions of the form `ptoc\_<type>()` – here `ctop_int()`. The single parameter of such a function is the number of the Prolog argument that is to be transformed and the function returns the C representation. Output arguments are converted from C to Prolog by corresponding functions of the form `ctop_<type>()` – here `ctop_int()`. For converting C back to Prolog, the first parameter of `ctop_int()` is the number of the Prolog argument to be transformed and the second is the C value to be transformed. In the session output above, if an improper argument is given to `minus_one/2` it will emit a warning, and succeed. Also note that the call `my_sqrt(23,X)` succeeds once, but fails on backtracking since it is deterministic, as are all other foreign language functions.

The above example illustrates the exchange of *basic* types through the lower-level interface – e.g. atoms, integers, and floating-point numbers. The lower-level interface also allows a user to pass lists and terms between XSB and C as will be discussed in Section 13.2.3.

13.2.1 Context Parameters

When using the lower-level interface, *context parameters* must be added to many C functions in order for the functions to be used with XSB's multi-threaded engine. In the multi-threaded engine, variables for Prolog's virtual machine, as well as for thread-private data structures are stored in a *context structure*. This context structure must be passed to any functions that need to access elements of a thread's virtual machine – including many of the functions that are used to exchange data between Prolog and C. We note in passing that when using the multi-threaded engine, a user must ensure that foreign-language functions are thread-safe, by using standard multi-threaded programming techniques, including XSB's mutex predicates (see the Section *Predicates for Thread Synchronization* in Volume 1 of this manual). On the other hand, in the single-threaded engine virtual machine elements are kept in static variables, so that context parameters are not required.

The lower-level C interface makes use of a set of macros to address the requirements of the different engines. The data exchange functions discussed in this chapter, `ptoc_xxx`, `ctop_xxx`, `c2p_xxx`, `p2c_xxx`, and `p2p_xxx` usually, but not always, require information about a threads virtual machine state. If a C function directly or indirectly calls a data interchange function that requires a context parameter, the function must have a context parameter in its declaration, calls, and prototypes in order to be used by the multi-threaded engine. These context parameters have the following forms:

- In function *declarations*, use the macro `CTXTdecl` in the code for a function that would otherwise be `void`, and `CTXTdeclc` as the first argument in the code for a function with parameters (`CTXTdeclc` and `CTXTdecl` are similar, except that macro expansion of `CTXTdeclc` for the multi-threaded engine includes a comma). The example for `minus_one(CTXTdecl)` shows use of this macro.
- In function *calls* use the macro `CTXT` in the code for a function that would otherwise be `void`, and `CTXTc` as the first argument in the code for a function with parameters. As an example, a call to `minus_one` would have the form `minus_one(CTXT)`.
- In function *prototypes* use the macro `CTXTdecltype` in the code for a function that would otherwise be `void`, and `CTXTdecltypec` as the first argument in the code for a function with parameters. As an example, a prototype for `minus_one` would have the form `minus_one(CTXTdecltype)`.

Fortunately, when compiling with the multi-threaded engine, it is easy to determine at compile time whether context parameters are correct. If compilation of a function `foo` gives an error along the lines of:

```
foofile.c: In function ‘foo’:
foofile.c:109: error: ‘th’ undeclared (first use in this function)
```

Then the declaration of `foo` omitted a context parameter. If compilation gives an error along the lines of

```
foofile.c: In function ‘foo_caller’:
:
foofile.c:149: error: too few arguments to function ‘foo’
```

Then the call to `foo` may have omitted a context parameter.

Note that context parameters are *only* necessary if the lower-level interface is used. The higher-level interface automatically generates any context parameters it needs.

13.2.2 Exchanging Basic Data Types

The basic interface assumes that correct modes (*i.e.*, input or output parameters) and types are being passed between the C and Prolog levels. As a result, output unification should be explicitly performed in the Prolog level. The prototypes for the conversion functions between Prolog and C should be declared before the corresponding functions are used. This is done by including the `"cinterf.h"` header file. Under Unix, the XSB foreign C interface automatically finds this file in the `XSB/emu` directory. Under Windows (including Cygwin),

the user must compile and create the DLL out of the C file manually, so the compiler option '`/I...\XSB\emu`' is necessary.

The following C functions are used to convert basic types between Prolog and C.

`int ptoc_int(CTXTdeclc int N)`
: `CTXTdeclc` is a context parameter; `N` is assumed to hold a Prolog integer corresponding to the `N`th argument of a Prolog predicate. This function returns the value of that argument in as a C `int`.

`double ptoc_float(CTXTdeclc int N)`
: `CTXTdeclc` is a context parameter; `N` is assumed to hold a Prolog integer corresponding to the `N`th argument of a Prolog predicate. This function returns the value of that argument as a C `double`. By default, XSB provides double precision, but if XSB was configured with `-enable-fast-floats` less than single precision can be provided [5].

`char *ptoc_string(CTXTdeclc int N)`
: `CTXTdeclc` is a context parameter; `N` is assumed to hold a Prolog integer corresponding to the `N`th argument of a Prolog predicate. This function returns the value the C string (of type `char *`) that corresponds to this interned Prolog atom. *WARNING: the string should be copied before being manipulated in any way: otherwise unexpected results may arise whenever the interned Prolog atom is unified.*

`void ctop_int(CTXTdeclc int N, int V)`
: `CTXTdeclc` is a context parameter; argument `N` is assumed to hold a Prolog free variable, and this function binds that variable to an integer of value `V`.

`void ctop_float(CTXTdeclc int N, float V)`
: `CTXTdeclc` is a context parameter; argument `N` is assumed to hold a Prolog free variable, and this function binds that variable to a floating point number of value `V`.

`void extern_ctop_string(CTXTdeclc int N, char * V)`
: `CTXTdeclc` is a context parameter; argument `N` is assumed to hold a Prolog free variable. If needed, this function interns the string to which `V` points as a Prolog atom and then binds the variable in argument `N` to that atom.

13.2.3 Exchanging Complex Data Types

If the lower-level interface is used, exchanging basic data types is sufficient for most applications. Exchanging complex data types is also possible, although doing so is slightly

[5] The fast float configuration option does represents floating point values as directly tagged single precision values rather than as indirectly tagged double precision values. Speed increases in arithmetic can be gained from this optimization, in exchange for significant precision loss on floating point numbers.

more involved than exchanging basic types. To exchange complex data types, the lower-level interface uses only one C data type: `prolog_term`, which can point to any XSB term. On the C side, the type of the term can be checked and then processed accordingly. For instance, if the term turns out to be a structure, then it can be decomposed and the functor can be extracted along with the arguments. If the term happens to be a list, then it can be processed in a loop and each list member can be further decomposed into its atomic components. The advanced interface also provides functions to check the types of these atomic components and for converting them into C types.

We begin by presenting the functions used to exchange complex data types, before presenting a detailed example below. As when exchanging basic C types, the file `emu/cinterf.h` must be included in the C program in order to make the prototypes of the relevant functions known to the C compiler.

The first set of functions is typically used to check the type of Prolog terms passed into the C program.

`xsbBool is_attv((prolog_term) T)`
: `is_attv(T)` returns `TRUE` if `T` represents an XSB attributed variable, and `FALSE` otherwise.

`xsbBool is_float((prolog_term) T)`
: `is_float(T)` returns `TRUE` if `T` represents an XSB float value, and `FALSE` otherwise.

`xsbBool is_functor((prolog_term) T)`
: `is_functor(T)` returns `TRUE` if `T` represents an XSB structure value (not a list), and `FALSE` otherwise.

`xsbBool is_int((prolog_term) T)`
: `is_int(T)` returns `TRUE` if `T` represents an XSB integer value, and `FALSE` otherwise.

`xsbBool is_list((prolog_term) T)`
: `is_list(T)` returns `TRUE` if `T` represents an XSB list value (not nil), and `FALSE` otherwise.

`xsbBool is_nil((prolog_term) T)`
: `is_nil(T)` returns `TRUE` if `T` represents an XSB `[]` (nil) value, and `FALSE` otherwise.

`xsbBool is_string((prolog_term) T)`
: `is_string(T)` returns `TRUE` if `T` represents an XSB atom value, and `FALSE` otherwise.

`xsbBool is_var((prolog_term) T)`
: `is_var(T)` returns `TRUE` if `T` represents an XSB variable, and `FALSE` otherwise.

After checking the types of the arguments passed in from the Prolog side, the next task usually is to convert Prolog data into the types understood by C. This is done with the

following functions. The first three convert between the basic types. The last two extract the functor name and the arity. Extraction of the components of a list and the arguments of a structured term is explained later.

`int p2c_int((prolog_term) V)`
: The `prolog_term` parameter must represent a Prolog integer, and `p2c_int` returns the C representation of that integer.

`double p2c_float((prolog_term) V)`
: The `prolog_term` parameter must represent a Prolog floating point number, and `p2c_float` returns the C representation of that floating point number.

`char *p2c_string((prolog_term) V)`
: The `prolog_term` parameter must represent a (Prolog) atom, and `p2c_string` returns that atom as a C string. The pointer returned points to the actual atom name in XSB 's atom table, and thus it must NOT be modified by the calling program.

`char *p2c_functor((prolog_term) V)`
: The `prolog_term` parameter must represent a structured term (not a list). `p2c_functor` returns the name of the main functor symbol of that term as a string. The pointer returned points to the actual functor name in XSB 's space, and thus it must NOT be modified by the calling program.

`int p2c_arity((prolog_term) V)`
: The `prolog_term` parameter must represent a structured term (not a list). `p2c_arity` returns the arity of the main functor symbol of that term as a C `int`.

The next batch of functions support conversion of data in the opposite direction: from basic C types to the type `prolog_term`. These `c2p_*` functions all return a boolean value `TRUE` if successful and `FALSE` if unsuccessful. The XSB term argument must always contain an XSB variable, which will be bound to the indicated value as a side effect of the function call.

`xsbBool c2p_int(CTXTdeclc (int) N, (prolog_term) V)`
: `CTXTdeclc` is a context parameter; `c2p_int` binds the `prolog_term V` (which must be a variable) to the integer value N, creating a Prolog integer.

`xsbBool c2p_float(CTXTdeclc (double) F, (prolog_term) V)`
: `CTXTdeclc` is a context parameter; `c2p_float` binds the `prolog_term V` (which must be a variable) to the (double) float value F, creating a double Prolog float.

`xsbBool c2p_string(CTXTdeclc (char *) S, (prolog_term) V)`
: `CTXTdeclc` is a context parameter; `c2p_string` binds the `prolog_term V` (which must be a variable) to the Prolog atom corresponding to the `char *S`. During this process the Prolog atom is interned into XSB's atom table.

The following functions create Prolog data structures within a C program. This is usually done in order to pass these structures back to the Prolog side.

`xsbBool c2p_functor(CTXTdeclc (char *) S, (int) N, (prolog_term) V)`
: `CTXTdeclc` is a context parameter; `c2p_functor` binds the `prolog_term V` (which must be a variable) to an open term whose main functor symbol is given by `S` (of type char *) and whose arity is `N`. An open term is one with all arguments as new distinct variables.

`xsbBool c2p_list(CTXTdeclc (prolog_term) V)`
: `CTXTdeclc` is a context parameter; `c2p_list` binds the `prolog_term V` (which must be a variable) to an open list term, i.e., a list term with both car and cdr as new distinct variables. Note: to create an empty list use the function `c2p_nil` described below.

`xsbBool c2p_nil(CTXTdeclc (prolog_term) V)`
: `CTXTdeclc` is a context parameter; `c2p_nil` binds the `prolog_term V` (which must be a variable) to the atom `[]` (nil).

`prolog_term p2p_new()`
: Create a new Prolog variable. This is sometimes needed when you want to create a Prolog term on the C side and pass it to the Prolog side.

To use the above functions, one must be able to get access to the components of the structured Prolog terms. This is done with the help of the following functions:

`prolog_term p2p_arg((prolog_term) T, (int) A)`
: Parameter `T` must be a `prolog_term` that is a structured term (but not a list). A is a positive integer (no larger than the arity of the term) that specifies an argument position of the term `T`. `p2p_arg` returns the Ath subfield of the term `T`.

`prolog_term p2p_car((prolog_term) T)`
: Parameter `T` must be a `prolog_term` that is a list (not nil). `p2p_car` returns the car (i.e., head of the list) of the term T.

`prolog_term p2p_cdr((prolog_term) T)`
: Parameter `T` must be a `prolog_term` that is a list (not nil). `p2p_cdr` returns the cdr (i.e., tail of the list) of the term T.

It is important to realize that these functions return the actual Prolog term that is, say, the head of a list or the actual argument of a structured term. Thus, assigning a value to such a Prolog term also modifies the head of the corresponding list or the relevant argument of the structured term. It is precisely this feature that allows passing structured terms and lists from the C side to the Prolog side. For instance,

```
prolog_term plist,        /* a Prolog list           */
            structure;    /* something like f(a,b,c) */
prolog_term tail, arg;
..........
tail = p2p_cdr(plist);         /* get the list tail  */
arg  = p2p_arg(structure, 2);  /* get the second arg */

/* Assume that the list tail was supposed to be a prolog variable */
if (is_var(tail))
   c2p_nil(CTXTc tail);  /* terminate the list */
else {
   fprintf(stderr, "Something wrong with the list tail!");
   exit(1);
}
/* Assume that the argument was supposed to be a prolog variable */
c2p_string(CTXTc "abcdef", arg);
```

In the above program fragment, we assume that both the tail of the list and the second argument of the term were supposed to be bound to Prolog variables. In case of the tail, we check if this is, indeed, the case. In case of the argument, no checks are done; XSB will issue an error (which might be hard to track down) if the second argument is not currently bound to a variable.

The last batch of functions is useful for passing data in and out of the Prolog side of XSB. The first function is the only way to get a `prolog_term` out of the Prolog side; the second function is sometimes needed in order to pass complex structures from C into Prolog.

`prolog_term reg_term(CTXTdeclc (int) R)`

`CTXTdeclc` is a context parameter. Parameter R is an argument number of the Prolog predicate implemented by this C function (range 1 to 255). The function `reg_term` returns the `prolog_term` in that predicate argument.

`xsbBool p2p_unify(CTXTdeclc prolog_term T1, prolog_term T2)`

Unify the two Prolog terms. This is useful when an argument of the Prolog predicate (implemented in C) is a structured term or a list, which acts both as input and output parameter. `CTXTdeclc` is a context parameter.

For instance, consider the Prolog call `test(X, f(Z))`, which is implemented by a C function with the following fragment:

```
prolog_term newterm, newvar, z_var, arg2;
.....
/* process argument 1 */
```

```
    c2p_functor(CTXTc "func",1,reg_term(CTXTc 1));
    c2p_string(CTXTc "str",p2p_arg(reg_term(CTXTc 1),1));
    /* process argument 2 */
    arg2 = reg_term(CTXTc 2);
    z_var = p2p_arg(arg2, 1);  /* get the var Z */
    /* bind newterm to abc(V), where V is a new var */
    c2p_functor(CTXTc "abc", 1, newterm);
    newvar = p2p_arg(newterm, 1);
    newvar = p2p_new();
    ....
    /* return TRUE (success), if unify; FALSE (failure) otherwise */
    return p2p_unify(CTXTc z_var, newterm);
```

On exit, the variable `X` will be bound to the term `func(str)`. Processing argument 2 is more interesting. Here, argument 2 is used both for input and output. If `test` is called as above, then on exit Z will be bound to `abc(_h123)`, where `_h123` is some new Prolog variable. But if the call is `test(X,f(1))` or `test(X,f(Z,V))` then this call will *fail* (fail as in Prolog, *i.e.*, it is not an error), because the term passed back, `abc(_h123)`, does not unify with `f(1)` or `f(Z,V)`. This effect is achieved by the use of `p2p_unify` above.

We conclude this section with two real examples of functions that pass complex data in and out of the Prolog side of XSB. These functions are part of the POSIX regular expression matching package of XSB. The first function uses argument 2 to accept a list of complex Prolog terms from the Prolog side and does the processing on the C side. The second function does the opposite: it constructs a list of complex Prolog terms on the C side and passes it over to the Prolog side in argument 5.

(We should note that this second function could cause a heap overflow in XSB were it to build a large list of values. Instead of building a large list of values on the XSB heap, one would better design the functions to return smaller values, in which case XSB will be able to automatically expand the heap as necessary.)

```
/* XSB string substitution entry point: replace substrings specified in Arg2
   with strings in Arg3.
   In:
       Arg1: string
       Arg2: substring specification, a list [s(B1,E1),s(B2,E2),...]
       Arg3: list of replacement string
   Out:
       Arg4: new (output) string
   Always succeeds, unless error.
*/
int do_regsubstitute__(CTXTdecl)
{
  /* Prolog args are first assigned to these, so we could examine the types
```

```
   of these objects to determine if we got strings or atoms. */
prolog_term input_term, output_term;
prolog_term subst_reg_term, subst_spec_list_term, subst_spec_list_term1;
prolog_term subst_str_term=(prolog_term)0,
  subst_str_list_term, subst_str_list_term1;
char *input_string=NULL;    /* string where matches are to be found */
char *subst_string=NULL;
prolog_term beg_term, end_term;
int beg_offset=0, end_offset=0, input_len;
int last_pos = 0; /* last scanned pos in input string */
/* the output buffer is made large enough to include the input string and the
   substitution string. */
char subst_buf[MAXBUFSIZE];
char *output_ptr;
int conversion_required=FALSE; /* from C string to Prolog char list */

input_term = reg_term(CTXTc 1);  /* Arg1: string to find matches in */
if (is_string(input_term)) /* check it */
  input_string = string_val(input_term);
else if (is_list(input_term)) {
  input_string =
    p_charlist_to_c_string(input_term, input_buffer, sizeof(input_buffer),
                           "RE_SUBSTITUTE", "input string");
  conversion_required = TRUE;
} else
  xsb_abort("RE_SUBSTITUTE: Arg 1 (the input string) must be an atom or a character list");

input_len = strlen(input_string);

/* arg 2: substring specification */
subst_spec_list_term = reg_term(CTXTc 2);
if (!is_list(subst_spec_list_term) && !is_nil(subst_spec_list_term))
  xsb_abort("RE_SUBSTITUTE: Arg 2 must be a list [s(B1,E1),s(B2,E2),...]");

/* handle substitution string */
subst_str_list_term = reg_term(CTXTc 3);
if (! is_list(subst_str_list_term))
  xsb_abort("RE_SUBSTITUTE: Arg 3 must be a list of strings");

output_term = reg_term(CTXTc 4);
if (! is_var(output_term))
  xsb_abort("RE_SUBSTITUTE: Arg 4 (the output) must be an unbound variable");

subst_spec_list_term1 = subst_spec_list_term;
subst_str_list_term1 = subst_str_list_term;

if (is_nil(subst_spec_list_term1)) {
  strncpy(output_buffer, input_string, sizeof(output_buffer));
```

```
    goto EXIT;
  }
  if (is_nil(subst_str_list_term1))
    xsb_abort("RE_SUBSTITUTE: Arg 3 must not be an empty list");

  /* initialize output buf */
  output_ptr = output_buffer;

  do {
    subst_reg_term = p2p_car(subst_spec_list_term1);
    subst_spec_list_term1 = p2p_cdr(subst_spec_list_term1);

    if (!is_nil(subst_str_list_term1)) {
      subst_str_term = p2p_car(subst_str_list_term1);
      subst_str_list_term1 = p2p_cdr(subst_str_list_term1);

      if (is_string(subst_str_term)) {
        subst_string = string_val(subst_str_term);
      } else if (is_list(subst_str_term)) {
        subst_string =
          p_charlist_to_c_string(subst_str_term, subst_buf, sizeof(subst_buf),
                                 "RE_SUBSTITUTE", "substitution string");
      } else
        xsb_abort("RE_SUBSTITUTE: Arg 3 must be a list of strings");
    }

    beg_term = p2p_arg(subst_reg_term,1);
    end_term = p2p_arg(subst_reg_term,2);

    if (!is_int(beg_term) || !is_int(end_term))
      xsb_abort("RE_SUBSTITUTE: Non-integer in Arg 2");
    else{
      beg_offset = int_val(beg_term);
      end_offset = int_val(end_term);
    }
    /* -1 means end of string */
    if (end_offset < 0)
      end_offset = input_len;
    if ((end_offset < beg_offset) || (beg_offset < last_pos))
      xsb_abort("RE_SUBSTITUTE: Substitution regions in Arg 2 not sorted");

    /* do the actual replacement */
    strncpy(output_ptr, input_string + last_pos, beg_offset - last_pos);
    output_ptr = output_ptr + beg_offset - last_pos;
    if (sizeof(output_buffer)
        > (output_ptr - output_buffer + strlen(subst_string)))
      strcpy(output_ptr, subst_string);
    else
```

```
      xsb_abort("RE_SUBSTITUTE: Substitution result size %d > maximum %d",
                beg_offset + strlen(subst_string),
                sizeof(output_buffer));

    last_pos = end_offset;
    output_ptr = output_ptr + strlen(subst_string);

  } while (!is_nil(subst_spec_list_term1));

  if (sizeof(output_buffer) > (output_ptr-output_buffer+input_len-end_offset))
    strcat(output_ptr, input_string+end_offset);

 EXIT:
  /* get result out */
  if (conversion_required)
    c_string_to_p_charlist(output_buffer,output_term,"RE_SUBSTITUTE","Arg 4");
  else
    /* DO NOT intern. When atom table garbage collection is in place, then
       replace the instruction with this:
                  c2p_string(CTXTc output_buffer, output_term);
       The reason for not interning is that in Web page
       manipulation it is often necessary to process the same string many
       times. This can cause atom table overflow. Not interning allows us to
       circumvent the problem.  */
    extern_ctop_string(CTXTc 4, output_buffer);

  return(TRUE);
}


/* XSB regular expression matcher entry point
   In:
       Arg1: regexp
       Arg2: string
       Arg3: offset
       Arg4: ignorecase
   Out:
       Arg5: list of the form [match(bo0,eo0), match(bo1,eo1),...]
             where bo*,eo* specify the beginning and ending offsets of the
             matched substrings.
             All matched substrings are returned. Parenthesized expressions are
             ignored.
*/
int do_bulkmatch__(CTXTdecl)
{
  prolog_term listHead, listTail;
  /* Prolog args are first assigned to these, so we could examine the types
     of these objects to determine if we got strings or atoms. */
```

```
prolog_term regexp_term, input_term, offset_term;
prolog_term output_term = p2p_new();
char *regexp_ptr=NULL;      /* regular expression ptr               */
char *input_string=NULL;    /* string where matches are to be found */
int ignorecase=FALSE;
int return_code, paren_number, offset;
regmatch_t *match_array;
int last_pos=0, input_len;
char regexp_buffer[MAXBUFSIZE];

if (first_call)
  initialize_regexp_tbl();

regexp_term = reg_term(CTXTc 1);  /* Arg1: regexp */
if (is_string(regexp_term)) /* check it */
  regexp_ptr = string_val(regexp_term);
else if (is_list(regexp_term))
  regexp_ptr =
    p_charlist_to_c_string(regexp_term, regexp_buffer, sizeof(regexp_buffer),
                           "RE_MATCH", "regular expression");
else
  xsb_abort("RE_MATCH: Arg 1 (the regular expression) must be an atom or a character list");

input_term = reg_term(CTXTc 2);  /* Arg2: string to find matches in */
if (is_string(input_term)) /* check it */
  input_string = string_val(input_term);
else if (is_list(input_term)) {
  input_string =
    p_charlist_to_c_string(input_term, input_buffer, sizeof(input_buffer),
                           "RE_MATCH", "input string");
} else
  xsb_abort("RE_MATCH: Arg 2 (the input string) must be an atom or a character list");

input_len = strlen(input_string);

offset_term = reg_term(CTXTc 3); /* arg3: offset within the string */
if (! is_int(offset_term))
  xsb_abort("RE_MATCH: Arg 3 (the offset) must be an integer");
offset = int_val(offset_term);
if (offset < 0 || offset > input_len)
  xsb_abort("RE_MATCH: Arg 3 (=%d) must be between 0 and %d", input_len);

/* If arg 4 is bound to anything, then consider this as ignore case flag */
if (! is_var(reg_term(CTXTc 4)))
  ignorecase = TRUE;

last_pos = offset;
/* returned result */
```

```
  listTail = output_term;
  while (last_pos < input_len) {
    c2p_list(CTXTc listTail); /* make it into a list */
    listHead = p2p_car(listTail); /* get head of the list */

    return_code = xsb_re_match(regexp_ptr, input_string+last_pos, ignorecase,
                               &match_array, &paren_number);
    /* exit on no match */
    if (! return_code) break;

    /* bind i-th match to listHead as match(beg,end) */
    c2p_functor(CTXTc "match", 2, listHead);
    c2p_int(CTXTc match_array[0].rm_so+last_pos, p2p_arg(listHead,1));
    c2p_int(CTXTc match_array[0].rm_eo+last_pos, p2p_arg(listHead,2));

    listTail = p2p_cdr(listTail);
    last_pos = match_array[0].rm_eo+last_pos;
  }
  c2p_nil(CTXTc listTail); /* bind tail to nil */
  return p2p_unify(CTXTc output_term, reg_term(CTXTc 5));
}
```

13.3 Foreign Modules That Call XSB Predicates

A C function that has been called from XSB through the lower-level foreign language interface may want to call back into XSB to have XSB evaluate a predicate. This can be done by using the interface described in Chapter 3 (Volume 2) on calling XSB from another language. The interface described there allows a caller to initialize XSB and pass queries to it. However, since XSB has already called a foreign module, XSB does not need to be initialized. However it does need to manage the registers that are in use to support interaction with the foreign module currently executing. So there are some minor differences with the interface described in Chapter 3.

First, XSB should not be initialized. I.e., a foreign module should **not** call `xsb_init` or `xsb_init_string`. Second, the foreign module must protect the XSB registers it is currently using when it calls XSB. To do this, after it has retrieved its arguments into local variables and before it calls any XSB predicate, it must call `xsb_query_save(NumRegs)`, which saves the current XSB registers and initializes them to be able to accept a new query. `NumRegs` is the number of registers used to interact with the currently executing foreign routine (i.e., the arity of the predicate that called this foreign code.) When the foreign routine has completed its work, it will set the appropriate registers with the appropriate return values and return to the caller. Before it does this, it must call `xsb_query_restore()` to restore the saved registers and prepare XSB for the return. Note that it must be called before any of the output registers are accessed to set return values. (It must also be called even if no

values are returned.)

In summary the extra functions needed to call XSB from a foreign module are:

`int xsb_query_save(CTXTc (byte) NumRegs)`
: This function is used in a foreign routine that is called from XSB. It is used to save the current contents of the XSB registers and to initialize them to be prepared to accept a query. It must be called after a foreign routine collects its input arguments from the XSB registers and before it invokes any XSB predicate.

`int xsb_query_restore(CTXT)`
: This function is used in a foreign routine that is called from XSB and in turn calls an XSB predicate. It is used to restore the previously saved contents of the XSB registers. It must be called after all XSB predicates have been called and returned, and before the current foreign routine sets its output parameters and returns to XSB.

An example where a foreign module and XSB call each other recursively can be found in the directory `$XSB_DIR/examples/XSB_calling_c` and files `fibr.[cH]` and `fibp.P`.

13.4 Foreign Modules That Link Dynamically with Other Libraries

Sometimes a foreign module might have to link dynamically with other (non-XSB) libraries. Typically, this happens when the foreign module implements an interface to a large external library of utilities. One example of this is the package `libwww` in the XSB distribution, which provides a high-level interface to the W3C's Libwww library for accessing the Web. The library is compiled into a set of shared objects and the `libwww` module has to link with them as well as with XSB.

The problem here is that the loader must know at run time where to look for the shared objects to link with. On Unix systems, this is specified using the environment variable `LD_LIBRARY_PATH`; on Windows, the variable name is `LIBPATH`. For instance, under Bourne shell or its derivatives, the following will do:

```
LD_LIBRARY_PATH=dir1:dir2:dir3
export LD_LIBRARY_PATH
```

One problem with this approach is that this variable must be set before starting XSB. The other problem is that such a global setting might interact with other foreign modules.

To alleviate the problem, XSB dynamically sets `LD_LIBRARY_PATH` (`LIBPATH` on Windows) before loading foreign modules by adding the directories specified in the `-L` option in `ldoption`. Unfortunately, this works on some systems (Linux), but not on others (Solaris).

One route around this difficulty is to build a runtime library search path directly into the object code of the foreign module. This can be specified using a loader flag in `ldoption`. The problem here is that different systems use a different flag! To circumvent this, XSB provides a predicate that tries to guess the right flag for your system:

```
runtime_loader_flag(+Hint,-Flag)
```

Currently it knows about a handful of the most popular systems, but this will be expanded. The argument `Hint` is not currently used. It might be used in the future to provide `runtime_loader_flag` with additional information that can improve the accuracy of finding the right runtime flags for various systems.

The above predicate can be used as follows:

```
...,
runtime_loader_flag(_,Flag),
fmt_write_string(LDoptions, '%sdir1:dir2:dir2 %s', args(Flag,OldLDoption)),
fmt_write(File, ':- ldoption(%s).', LDoptions),
file_nl(File).
```

13.5 Higher-Level Foreign Language Interface

The high-level foreign predicate interface was designed to release the programmer from the burden of having to write low-level code to transfer data from XSB to C and vice-versa. Instead, all the user needs to do is to describe each C function and its corresponding Prolog predicates in the `.H` files. The interface then automatically generates *wrappers* that translate Prolog terms and structures to proper C types, and vice-versa. These wrappers also check for type-correctness of arguments to the C function; in addition, in Unix-derived systems the wrappers are automatically compiled and loaded along with the foreign predicates in the `.c` file [6].

As with the lower-level foreign interfaces, when predicates are defined in a foreign module `myfile.[cH]`, the predicates must be explicitly imported from the module to be used [7]. For an example of using the higher level interface, see `$XSBDIR/examples/XSB_calling_c/second_foreign.[cH]`.

13.5.1 Declaration of high level foreign predicates

The basic formats of a foreign predicate declaration are:

[6] for Windows, please see special instructions in Section 13.6.

[7] In Version 3.3, a foreign module that uses the higher-level C interface must be explicitly consulted before it can be used.

```
:- foreign_pred predname([+-]parg1, [+-]parg2,...)
        from funcname(carg1:type1, carg2:type2, ...):functype.
```

and

```
:- private_foreign_pred predname([+-]parg1, [+-]parg2,...)
        from funcname(carg1:type1, carg2:type2, ...):functype.
```

where:

`foreign_pred, private_foreign_pred`
: declares a new foreign predicate. For most cases, the declaration `foreign_pred` can be used in both the multi-threaded and the sequential engine. The declaration `private_foreign_pred` needs to be used only in the multi-threaded engine when the external foreign function, `funcname` contains a context parameter as its first argument because `funcname` needs to access thread-private data or other information from the context of the XSB thread (see Section 13.2.1). This case is uncommen, and mostly occurs for users who are creating XSB packages (e.g. the XASP interface to Smodels).

`predname`
: is the name of the foreign Prolog predicate.

`parg1, parg2, ...`
: are the predicate arguments. Each argument is preceded by either '+' or '-', indicating its mode as input or output respectively. The names of the arguments must be the same as those used in the declaration of the corresponding C function. If a C argument is used both for input and output, then the corresponding Prolog argument can appear twice: once with "+" and once with "-". In addition, a special argument `retval` is used to denote the argument that corresponds to the return value of the C function; it must always have the mode '-'.

`funcname`
: is the name of the function in the `.c` file. At compile-time a C function with name `predname` will be generated which will translate arguments from Prolog to C, call `funcname`, and then translate arguments back from C to Prolog.

`carg1, carg2, ...`
: is the list of arguments of the C function. The names used for the arguments must match the names used in the Prolog declaration.

`type1, type2, ...`
: are the types associated to the arguments of the C function. This is not the set of C types, but rather a set of descriptive types, as defined in Table 13.5.1.

Descriptive Type	Mode Usage	Associated C Type	Comments
int	+	int	integer numbers
float	+	double	floating point numbers
atom	+	unsigned long	atom represented as an unsigned long
chars	+	char *	the textual representation of an atom is passed to C as a string
chars(*size*)	+	char *	the textual representation of an atom is passed to C as a string in a buffer of size *size*
string	+	char *	a prolog list of characters is passed to C as a string
string(*size*)	+	char *	a prolog list of characters is passed to C as a string
term	+	`prolog_term`	the unique representation of a term
intptr	+	int *	the location of a given integer
floatptr	+	double *	the location of a given floating point number
atomptr	+	unsigned long *	the location of the unique representation of a given atom
charsptr	+	char **	the location of the textual representation of an atom
stringptr	+	char **	the location of the textual representation of a list of characters
termptr	+	`prolog_term` *	the location of the unique representation of a term
intptr	-	int *	the integer value returned is passed to Prolog
floatptr	-	double *	the floating point number is passed back to Prolog
charsptr	-	char **	the string returned is passed to Prolog as an atom
stringptr	-	char **	the string returned is passed back as a list of characters
atomptr	-	unsigned long *	the number returned is passed back to Prolog as the unique representation of an atom
termptr	-	`prolog_term` *	the number returned is passed to Prolog as the unique representation of a term
chars(*size*)	+-	char *	the atom is copied from Prolog to a buffer, passed to C and converted back to Prolog afterwards
string(*size*)	+-	char *	the list of characters is copied from Prolog to a buffer, passed to C and back to Prolog afterwards
intptr	+-	int *	an integer is passed from Prolog to C and from C back to Prolog
floatptr	+-	double *	a float number is passed from Prolog to C, and back to Prolog
atomptr	+-	unsigned long *	the unique representation of an atom is passed to C, and back to Prolog
charsptr	+-	char **	the atom is passed to C as a string, and a string is passed to Prolog as an atom
stringptr	+-	char **	the list of characters is passed to C, and a string passed to Prolog as a list of characters
termptr	+-	`prolog_term` *	the unique representation of a term is passed to C, and back to Prolog

Table 13.1: Allowed combinations of types and modes, and their meanings

`functype`
: is the return type of the C function.

Using the higher-level interface, the same C code can be used for both the sequential and the multi-threaded engines, and no context parameters are required in a user's C code unless thread context information is explicitly needed. However, a foreign module compiled for the single-threaded engine will need to be recompiled for the multi-threaded engine and vice-versa.

Table 13.5.1 provides the correspondence between the types allowed on the C side of a foreign module declaration and the types allowed on the Prolog side of the declaration.

In all modes and types, checks are performed to ensure the types of the arguments. Also, all arguments of type '-' are checked to be free variables at call time.

13.6 Compiling Foreign Modules on Windows and under Cygwin

Due to the complexity of creating makefiles for the different compilers under Windows, XSB doesn't attempt to compile and build DLL's for the Windows foreign modules automatically. However, for almost all typical cases the user should be able to easily adapt the sample makefile for Microsoft VC++:

```
XSB/examples/XSB_calling_c/MakefileForCreatingDLLs
```

It is important that the C program will have the following lines near the top of the file:

```
#include "xsb_config.h"
#ifdef WIN_NT
#define XSB_DLL
#endif
#include "cinterf.h"
```

Note that these same DLLs will work under Cygwin — XSB's C interface under Cygwin is like that under Windows rather than Unix.

If the above makefile cannot be adapted, then the user has to create the DLL herself. The process is, roughly, as follows: first, compile the module from within XSB. This will create the XSB-specific object file, and (if using the higher-level C interface) the *wrappers*. The *wrappers* are created in a file named `xsb_wrap_`*modulename*`.c`.

Then, create a project, using the compiler of choice, for a dynamically-linked library that exports symbols. In this project, the user must include the source code of the module along with the *wrapper* created by XSB. This DLL should be linked against the library

```
XSB\config\x86-pc-windows\bin\xsb.lib
```

which is distributed with XSB. In VC++, this library should be added as part of the linkage specification. In addition, the following directories for included header files must be specified as part of the preprocessor setup:

```
XSB\config\x86-pc-windows
XSB\prolog_includes
XSB\emu
```

In VC++, make sure you check off the "No precompiled headers" box as part of the "Precompiled headers" specification. All these options are available through the `Project»Settings` menu item.

13.7 Functions for Use in Foreign Code

In addition to functions for passing data between Prolog an C, XSB contains other functions that may be useful in Foreign C code. We mention a few here that pertain to throwing exceptions from C code (cf. Volume 1 Chapter 8: *Exception Handling*). These functions can be used by code that uses either the lower- or higher-level interface.

`void xsb_domain_error(CTXTdeclc char *valid_domain,Cell culprit,char *pred,int arity,int arg)`

Used to throw an ISO-style domain error from foreign code, indicating that `culprit` is not in domain `valid_domain` in argument `arg` of `pred/arity`.

Example: The code fragment

```
Cell num;
:
xsb_domain_error(CTXTc "not_less_than_zero",num,"atom_length",2,2);
```

in `atom_length/2` gives rise to the behavior

```
| ?- atom_length(abcde,-1).
++Error[XSB/Runtime/P]: [Domain (-1 not in domain not_less_than_zero)]
             in arg 2 of predicate atom_length/2)
```

`void xsb_existence_error(CTXTdeclc char *objType,Cell culprit,char *pred,int arity,int arg)`

Used to throw an ISO-style existence error from foreign code, indicating that an object `culprit` of type `objType` does not exist, in argument `arg` of `pred/arity`.

Example: The code fragment

```
Cell tid;
:
xsb_existence_error(CTXTc "thread",reg[2],"xsb_thread_join",1,1);
```

in `thread_join/1` gives rise to a the behavior

```
| ?- thread_join(7).
++Error[XSB/Runtime/P]: [Existence (No thread 1 exists)]
             in arg 1 of predicate thread_join/1)
```

if a thread with thread id 7 does not exist.

`void xsb_instantiation_error(CTXTdeclc char *pred,int arity,int arg,char *state)`

Used to throw an ISO-style instantiation error from foreign code. If `state` is a `NULL` pointer, the message indicates that there is an instantiation error for argument `arg` of of `pred/arity`. If `state` is non-`NULL`, the message additionally indicates that argument `arg` must be `state`.

Example: The code fragment

```
xsb_instantiation_error(CTXTc "atom_length",2,1,NULL);
```

in `atom_length/2` gives rise to a the behavior

```
| ?- atom_length(X,Y).
++Error[XSB/Runtime/P]: [Instantiation]  in arg 1 of predicate atom_length/2
```

`void xsb_misc_error(CTXTdeclc char *message,char *pred,int arity)`

Used to throw a non ISO-error from foreign code, printing `message` and indicating that the error arose in `pred/arity`.

`void xsb_permission_error(CTXTdeclc char *op,char *obj,Cell culprit,char *pred,int arity)`

Used to throw an ISO-style permission error from foreign code, indicating that an operation of type `op` on type `obj` is not permitted on `culprit`, in argument `arg` of `pred/arity`.

Example: The code fragment

```
xsb_permission_error(CTXTc "unlock mutex","mutex not held by thread",
                     xsb_thread_id,"mutex_unlock",2);
```

in `mutex_unlock/1` gives rise to a the behavior

```
| ?- mutex_unlock(mymut).
++Error[XSB/Runtime/P]: [Permission (Operation) unlock mutex on mutex not held
 by thread: 0] in predicate mutex_unlock/1)
```

if thread `0` does not own mutex `mymut`.

`void xsb_resource_error(CTXTdeclc char *resource,char *pred,int arity)`

Used to indicate that there are not sufficient resources of type `resource` for `pred/arity` to succeed.

Example: The code fragment

```
xsb_resource_error(th,"system threads","thread_create",2);
```

in `thread_create/1` gives rise to a the behavior

```
| ?- thread_create(X).
++Error[XSB/Runtime/P]: [Resource (system threads))] in predicate thread_create/2)
```

If the number of system threads has been exceeded.

`void xsb_type_error(CTXTdeclc char *valid_type,Cell culprit,char *pred,int arity,int arg)`

Used to throw an ISO-style type error from foreign code, indicating that `culprit` is not in ISO type `valid_type` in argument `arg` of `pred/arity`.

Example: The code fragment

```
Cell num;
:
if (!isinteger(num)) xsb_type_error(CTXTc "integer",num,"atom_length",2,2);
```

in `atom_length/2` gives rise to the behavior

```
| ?- atom_length(foo,a).
++Error[XSB/Runtime/P]: [Type (a in place of integer)] in arg 2
of predicate atom_length/2)
```

`void xsb_throw(CTXTdeclc prolog_term Ball)`

Used to throw a Prolog term from C code, when an ISO-style error is not required. The term can be caught and handled by the Prolog predicate `catch/3` just as any other thrown term; however if it is not caught, XSB's default error handler will treat it as an unhandled exception.

Chapter 14

Embedding XSB in a Process

There are many situations in which it is desirable to use XSB as a rule- or constraint- processing subcomponent of a larger system that is written in another language. Depending on the intended architecture, it may be appropriate for XSB to reside in its own process, separate from other components of an application, and communicating through sockets, a database, or some other mechanism. However it is often useful for XSB to reside in the same process as other components. To do this, one wants to be able to *call* XSB from the host language, providing queries for XSB to evaluate, and retrieving back the answers. An interface for calling XSB from C is provided for this purpose and is described in this chapter. Based on this C interface, XSB can also be called from Java either through a JNI or a socket-based interface, as described in the documentation for Interprolog, available through `xsb.sourceforge.net`. To call XSB from Visual Basic, a DLL is created as described in this chapter, and additional declarations must be made in visual basic as described in the web page "How to use XSB DLL from Visual Basic" `http://xsb.sourceforge.net/vbdll.html`. In addition, the interface described in this chapter has also been extended to allow XSB to be called from Delphi and Ruby. However, since all of these interfaces – Java, Ruby, Delphi and Visual Basic – depend on XSB's C API, we refer in this chapter to C programs or threads calling XSB, although each of the examples suitably modified can be extended to other calling languages.

New to Version 3.1 are extensions to the C API to allow multiple XSB threads to be called from multiple C threads [1]. In this Chapter, we provide an overview of XSB's C API, and then elaborate its use through a series of examples, beginning with a single XSB thread called by a single C thread, then showing how a C thread can interact with multiple XSB threads, and finally discuss how multiple XSB threads can interact with multiple POSIX threads. Finally, Section 14.3 describes each C function in the API.

[1] XSB's threading model is based on POSIX threads, which can be called in Windows through a variety of POSIX APIs – see Volume 1 chapter 8 *Multi-threaded Programming in XSB*.

14.1 Calling XSB from C

XSB provides several C functions (declared in `$XSBDIR/emu/cinterf.h` and defined in `$XSBDIR/emu/cinterf.c`), which can be called from C to interact with XSB as a subroutine. These functions allow a C program to interact with XSB in a number of ways.

- XSB may be initialized, using most of the parameters available from the command-line.
- XSB may then execute a series of *commands* or *queries*. A command is a deterministic query which simply succeeds or fails without performing any unification on the query term. On the other hand, a non-deterministic query can be evaluated so that its answer substitutions are retrieved one at a time, as they are produced, just as if XSB were called on a command line. Alternately a non-deterministic query can be closed in the case where not every answer to the query is needed. Only one query per thread can be active at a time. I.e., an application must completely finish processing one query to a given thread T (either by retrieving all the answers for it, or by issuing a call to `xsb_close_query()`, before trying to evaluate another using T.
- Finally, XSB can be closed, so that no more queries can be made to any XSB threads.

In general, while any functions in the C API to XSB can be intermixed, the functions can be classified as belonging to three different levels.

- *A VarString level* which uses an XSB-specific C-type definition for variable-length strings (Section 14.4), to return answers.
- *A fixed-string level* provides routines that return answers in fixed-length strings.
- *A register-oriented level* that requires users to set up queries by setting registers for XSB which are made globally available to calling functions. The mechanisms for this resemble the lower-level C interface discussed in Chapter 13. This level of interface should only be used for the single-threaded applications, as it is difficult to prevent race-conditions at this level of interface when multiple C threads are used to call XSB.

The appropriate level to use depends on the nature of the calling program, the speed desired, and the expertise of the programmer. By and large, functions in the `VarString` level are the the easiest and safest to use, but they depend on a C type definition that may not be available to all calling programs (e.g. it may be difficult to use if the calling program is not directly based on C, such as Visual Basic or Delphi). For such applications functions from the fixed-string level would need to be used instead. In general, most applications should use either functions from the `VarString` or the fixed-string level, rather than the register-oriented level. This latter level should only be used by programmers who are willing to work at a low interface level, when the utmost speed is needed by an application, and when multiple threads do not need to interact with XSB.

14.2 Examples of Calling XSB

We introduce a series of examples of how XSB would be called using the string-level interfaces. Simple examples of the register-level interface are given in the `XSB/examples/c_calling_XSB` subdirectory, in files `cmain.c`, `cmain2.c`, `ctest.P`, and `Makefile`, but are not discussed in this section.

We structure out discussion by first showing how to construct a C program to call the single-threaded engine alone in Section 14.2.1. This example is mostly pedagogic: with a small amount of extra coding a C program can be constructed to call both the single- and the multi-threaded engine, and these extensions are discussed in Section 14.2.2. Next, we show how to a C program can call and manage multiple XSB threads in Section 14.2.3. Finally, we show how multiple XSB threads can interact with multiple C threads in Section 14.2.3.

14.2.1 The XSB API for the Sequential Engine Only

We start with a simple program shown, in Figure 14.1, that will call the following XSB predicate

```
  p(a,b,c).
  p(1,2,3).
  p([1,2],[3,4],[5,6]).
  p(A,B,A).

r(c,b,a).
r(3,2,1).
r([5,6],[3,4],[1,2]).
r(_A,B,B).
```

and backtrack through unifying answers (cf. `$XSBDIR/examples/c_calling_xsb/edb.P`). . This example will only compile properly if the sequential engine is used, and its style is `not` recommended: it will be shown in Section 14.2.2 how to extend the style.

We discuss the program in Figure 14.1 in detail. This program, slightly modified so that it compiles with the multi-threaded engine is in `$XSBDIR/examples/c_calling_xsb/cvartest.c`. An executable for this program can be make most easily by calling `$XSBDIR/examples/c_calling_xsb/make.P`, which makes the executable `cvstest`.

The program begins by including some standard C headers: note that `string.h` is needed for string manipulation routines such as `strcpy`. In addition, the XSB library header `cinterf.h` is necessary for the XSB C API. Since the program in Figure 14.1 uses functions in the `VarString` interface, within `main()` the routine `XSB_StrDefine(return_string)` declares and initializes a structure of type `VarString`, named `return_string`.

```
#include <stdio.h>
#include <string.h>

/* cinterf.h is necessary for the XSB API, as well as the path manipulation routines*/
#include "cinterf.h"

extern char *xsb_executable_full_path(char *);
extern char *strip_names_from_path(char*, int);

int main(int argc, char *argv[]) {

  char init_string[1024];
  int rc;
  XSB_StrDefine(return_string);

  /* xsb_init_string() relies on the calling program to pass the absolute or relative
     path name of the XSB installation directory. We assume that the current
     program is sitting in the directory ../examples/c_calling_xsb/
     To get the installation directory, we strip 3 file names from the path. */

  strcpy(init_string,strip_names_from_path(xsb_executable_full_path(argv[0]),3));

  if (xsb_init_string(init_string) == XSB_ERROR) {
    fprintf(stderr,"++initializing XSB: %s/%s\n",xsb_get_init_error_type(),
            xsb_get_init_error_message());
    exit(XSB_ERROR);
  }

  /* Create command to consult a file: edb.P, and send it. */
  if (xsb_command_string("consult('edb.P').") == XSB_ERROR)
    fprintf(stderr,"++Error consulting edb.P: %s/%s\n",xsb_get_error_type(),xsb_get_error_message());

  rc = xsb_query_string_string("p(X,Y,Z).",&return_string,"|");
  while (rc == XSB_SUCCESS) {
    printf("Return %s\n",(return_string.string));
    rc = xsb_next_string(&return_string,"|");
  }

 if (rc == XSB_ERROR)
    fprintf(stderr,"++Query Error: %s/%s\n"xsb_get_error_type(),xsb_get_error_message());

  xsb_close();
}
```

Figure 14.1: Calling the Sequential Engine Using the `VarString` Interface

The next order of business is to initialize XSB. In order to do this, `xsb_init_string()` needs to know the installation directory for XSB, which must be passed as part of the initialization string. In Figure 14.1 this is done by manipulating the path of the executable (`cvstest`) that calls XSB. In fact any other approach would also work as long as the XSB installation directory were passed. Within the initialization string, other command line arguments can be passed to XSB if desired with the following exceptions: the arguments `-B` (boot module), `-D` (command loop driver), `-i` (interpreter) and `-d` (disassembler) cannot be used when calling XSB from a foreign language [2]. As a final point on initialization, note that the function `xsb_init()` can also be used to initialize XSB based on an argument vector and count (see Section 14.3).

Note that the calling program checks for any errors returned by `xsb_init_string()` and other API commands. In general, `xsb_init_string()` may throw an error if the XSB's installation directory has become corrupted, or for similar reasons. This mechanism for error handling is different than that used if XSB is called in its usual stand-alone mode, in which case such an error would cause XSB to exit). An error returned by XSB's API are similar to an error ball described in Volume 1 *Exception Handling* in that it has both a *type* and a *message*. For normal Prolog exceptions, XSB's API will throw the same kinds of errors as XSB called in a stand-alone (or server) mode, i.e. instantiation errors, type errors, etc. However XSB's API adds two new error types:

- `init_error` is used as the type of an error discovered upon initialization of XSB, before query and command processing has begun. If an `init_error` is raised, XSB has not been properly initialized and will not run.
- `unrecoverable_error` is used to indicate that XSB has encountered an error, (such as a memory allocation error), during command or query processing from which it cannot recover. Such an error would cause XSB to immediately exit if it were called in a stand-alone mode. In general the calling program should handle unrecoverable errors as fatal since there is a good chance that the error conditions will affect the calling program as well as XSB.

Errors raised by `xsb_init_string()` usually have type `init_type`.

and a string pointer to the associated message can be found by the function `xsb_get_init_error_message()`.

As can be seen from the example, handling errors from commands is done in manner similar to that of initialization. For non-initialization errors, a string pointer to the type can be obtained by `xsb_get_error_type()`, while a string pointer to the message can be obtained by `xsb_get_error_message()`.

Next in Figure 14.1 the file `edb.P` is consulted (containing the `p/3` and `r/3` predicates shown above). Note, that the argument to `xsb_command_string` must be a syntactically

[2] In previous versions of XSB, initialization from the C level required a `-n` option to be passed. This is no longer required.

valid Prolog term ending with a period, otherwise a syntax error will be thrown, which may be displayed through `xsb_get_error_type()` and `xsb_get_error_message()` [3].

Queries to XSB are a little more complicated than commands. Since a query may return multiple solutions, a query should usually be called from inside a loop. In Figure 14.1, the query is opened with `xsb_query_string()`. If the query has at least one answer, `xsb_query_string()` will return `XSB_SUCCESS`; if the query fails, it will return `XSB_FAILURE`, and if there is an exception it will return `XSB_ERROR` as usual. Any answer will be returned as a string in the `VarString return_string`, and each argument of the query will be separated by the character `|`. Thus, in our example, the first answer will write the string

```
a|b|c
```

Once a query has been opened, subsequent answers can be obtained via `xsb_next_string()`. These answers are written to `return_string` in the same manner as `xsb_query_string_string()`.

```
1|2|3
[1,2]|[3,4]|[5,6]
_h102|_h116|_h102
```

A query is automatically closed when no more answers can be derived from it. Alternately, a query that may have answers remaining can be closed using the command `xsb_close_query()`. If the calling application will need to pass more queries or commands to XSB nothing need be done at this point: a new queries or commands can be invoked using one of the functions just discussed. However if the calling process is finished with XSB and will never need it again during the life of the process, it can call `xsb_close()`.

An Example using Fixed Strings

Figure 14.2 shows a fragment of code indicating how the previous example would be modified if the fixed-string interface were used. Note that `return_string` now becomes a pointer to explicitly malloc-ed memory. To open the query `p(X,Y,Z)` the function `xsb_query_string_string_b()` is called, with the `_b` indicating that a fixed buffer is being used rather than a `VarString`. The call is similar to `xsb_query_string_string()`, except that the length `anslen` of the buffer pointed to by `return_string` is now also required. If the answer to be returned (including separators) is longer than `anslen`, `xsb_query_string_string_b()` will return `XSB_OVERFLOW`. If this happens, a new answer buffer can be used (here the old one is realloc-ed) and the answer retrieved via `xsb_get_last_answer_string`. Similarly, further answers are obtained via `xsb_next_string_b()` whose length must be checked. Thus the only difference between the fixed-string level and the `VarString` level is that the length of each answer should be checked and `xsb_get_last_answer_string()` called if necessary.

[3] Most XSB errors are handled in this manner when XSB is called through its API. A few errors will print directly to `stderr` and some XSB warnings will print to `stdwarn` which upon startup is dup-ed to `stderr`.

```
int retsize = 15;
char *return_string;
int anslen;

return_string = malloc(retsize);

rc = xsb_query_string_string_b(CTXTc "p(X,Y,Z).",return_string,retsize,&anslen,"|");

while (rc == XSB_SUCCESS || rc == XSB_OVERFLOW) {

  if (rc == XSB_OVERFLOW) {
    return_string = (char *) realloc(return_string,anslen);
    return_size = anslen;
    rc = xsb_get_last_answer_string(CTXTc return_string,retsize,&anslen);
  }

  printf("Return %s %d\n",return_string,anslen);
  rc = xsb_next_string_b(CTXTc return_string,15,&anslen,"|");
}
```

Figure 14.2: Calling XSB using the Fixed String Interface

14.2.2 The General XSB API

The previous section showed how to use the XSB API with both the `VarString` type and without, but did not consider the multi-threaded engine. In fact, there are different ways to use XSB's multi-threading that can have advantages for various situations. In the first mode, threads are managed from Prolog, with a single XSB thread called from the API; that XSB thread can then create another XSB thread that does work, and the first thread can return almost immediately to handle more requests from the API's caller. A second model allows the caller to manipulate a pool of several XSB threads, so that different XSB threads may be called from different threads over the API. In this model each C, Java, Ruby, or other thread could a number of different Prolog threads. In this section we sketch how to use the API to illustrate the first model, and sketch the second model in the next section.

Figure 14.3 shows how relevant portions of the previous `VarString` example can be adapted to use the multi-threaded engine. The main change is that a new variable is introduced on the C side that points to the context of the main thread. As pointed out in Chapter 13, each thread in the multi-threaded engine has a *context* in which is kept much of its thread-specific data (excluding tables and dynamic code). Of the threads running in the multi-threaded engine the thread created upon the call to `xsb_init()` is designated as the `main thread`, and is closed only upon calling `xsb_close()`.

Within the multi-threaded engine, a call to an API function such as `xsb_query_string_string()`

```
.....

/* context.h is necessary for the type of a thread context. */
#include "context.h"

int main(int argc, char *argv[])
{

  char init_string[MAXPATHLEN];
  int rc;
  XSB_StrDefine(return_string);

  strcpy(init_string,strip_names_from_path(xsb_executable_full_path(argv[0]),3));
  if (xsb_init_string(init_string) == XSB_ERROR) {
    fprintf(stderr,"++initializing XSB: %s/%s\n",xsb_get_init_error_type(),
            xsb_get_init_error_message());
    exit(XSB_ERROR);
  }

#ifdef MULTI_THREAD
  th_context *th = xsb_get_main_thread();
#endif

  /* Create command to consult a file: edb.P, and send it. */
  if (xsb_command_string(CTXTc "consult('edb.P').") == XSB_ERROR)
    fprintf(stderr,"++Error consulting edb.P: %s/%s\n",xsb_get_error_type(CTXT),
            xsb_get_error_message(CTXT));

  rc = xsb_query_string_string(CTXTc "p(X,Y,Z).",&return_string,"|");
  while (rc == XSB_SUCCESS) {
    printf("Return %s\n",(return_string.string));
    rc = xsb_next_string(CTXTc &return_string,"|");
  }

 if (rc == XSB_ERROR)
    fprintf(stderr,"++Query Error: %s/%s\n",xsb_get_error_type(CTXT),xsb_get_error_message(CTXT));

  xsb_close();
}
```

Figure 14.3: Calling the Single- or Multi-Threaded Engine Using the `VarString` Interface

is actually a call to a specific thread to do some work (using a thread context pointer). Accordingly, since any errors produced will be specific to a given thread, all calls to error reporting functions are also thread-specific. If no specific thread is needed, it may be best just to use the main thread, which is what is done in Figure 14.3. The thread context pointer `th` is initialized to the main thread using the API macro `xsb_get_main_thread()`. Afterwards, this pointer is passed into the various interface functions by making use of XSB macros defined in `context.h` In the multi-threaded engine, these macros are defined as

```
#define CTXT th
#define CTXTc th,
```

while in the single-threaded engine they are defined as empty strings, as is `xsb_get_main_thread()`. As a result the code in Figure 14.3 will compile and run properly both for the single-threaded and the multi-threaded engines.

At this stage, suppose one wanted a new thread to execute a specific command, say `do_foo`. In this case, a C call such as

```
xsb_query_string_string(CTXTc "thread_create(do_foo,Id).",&return_string,"|")
```

creates a thread to execute the command, and returns the thread id of the newly created thread in `return_string`. The behavior of this newly created thread is exactly the same as if it were created from the XSB command line: in particular the newly created thread will automatically exit upon completion of its command. As a somewhat technical point, there are two different ways of referring to XSB threads. The foreign language interfaces described in Chapter 13 and here use pointers to thread contexts so that the interfaces use much of the same code as the XSB engine. However Prolog refers to threads using thread identifiers. The two different forms can be converted into each other by the functions `xsb_thread_id_to_context()` and `xsb_thread_context_to_id()`.

14.2.3 Managing Multiple XSB Threads through the API

The ability to pass thread contexts into query and command functions allows a great deal of flexibility [4]. Once XSB is initialized, XSB threads can be created from C and can execute independently of each other, effectively giving the ability for different calling threads to query XSB in a mechanism reminiscent of database cursors.

Figure 14.4 illustrates a very simple example of this. XSB is initialized and the file `edb.P` consulted exactly as in Figure 14.4. However, the function `xsb_ccall_thread_create()` causes the XSB thread `p_th` to create a new thread, causes the new thread to call the same command loop as the main thread, and sets `r_th` to point to the context of the new thread.

[4] For the sake of brevity, we sometimes abuse notation and do not always distinguish between thread-contexts and their pointers.

```
.....
/* context.h is necessary for the type of a thread context. */
#include "context.h"

int main(int argc, char *argv[])
{

  static th_context *p_th, *r_th;
  char init_string[MAXPATHLEN];
  int rcp, rcr;
  XSB_StrDefine(p_return_string);
  XSB_StrDefine(r_return_string);

  strcpy(init_string,strip_names_from_path(xsb_executable_full_path(argv[0]),3));

  if (xsb_init_string(init_string)) {
    fprintf(stderr,"%s initializing XSB: %s/%s\n",xsb_get_init_error_type(),
            xsb_get_init_error_message());cin
    exit(XSB_ERROR);
  }

  p_th = xsb_get_main_thread();

  /* Create command to consult a file: edb.P, and send it. */
  if (xsb_command_string(p_th, "consult('edb.P').") == XSB_ERROR)
    fprintf(stderr,"++Error consulting edb.P: %s/%s\n",xsb_get_error_type(p_th),
    xsb_get_error_message(p_th));

  xsb_ccall_thread_create(p_th,&r_th);

  rcp = xsb_query_string_string(p_th,"p(X,Y,Z).",&p_return_string,"|");
  rcr = xsb_query_string_string(r_th,"r(X,Y,Z).",&r_return_string,"|");

  while (rcp == XSB_SUCCESS && rcr == XSB_SUCCESS) {

    printf("Return p %s\n",(p_return_string.string));
    rcp = xsb_next_string(p_th, &p_return_string,"|");

    printf("Return r %s\n",(r_return_string.string));
    rcr = xsb_next_string(r_th, &r_return_string,"|");
  }

 if (rcp == XSB_ERROR)
   fprintf(stderr,"++Query Error p: %s/%s\n",xsb_get_error_type(p_th),xsb_get_error_message(p_th));
 if (rcr == XSB_ERROR)
   fprintf(stderr,"++Query Error r: %s/%s\n",xsb_get_error_type(r_th),xsb_get_error_message(r_th));

 xsb_close();
}
```

Figure 14.4: Manipulating Multiple Threads Using the `VarString` Interface

The new thread `r_th` can be used for commands or queries just as `p_th`. Figure 14.4 shows that queries to the two threads can be interleaved, and errors for both threads can be checked and reported independently.

It is important to note that since each thread created by `xsb_ccall_thread_create()` goes into a command-loop similar to the command loop, it will stay around until it is explicitly killed or until XSB is closed. The call

```
xsb_kill_thread(r_th);
```

is needed to make `r_th` to exit. Once a thread is exited, all of its data structures will be freed, including those that support `xsb_get_error_type()` and `xsb_get_error_message()` [5].

14.2.4 Calling Multiple XSB Threads using Multiple C Threads

Figure 14.4 shows how two XSB threads can be created, can receive different queries and can interleave their backtracking and answer return. Although Figure 14.4 demonstrated only backtracking through simple predicates, the mechanism employed works for complicated examples using tabling, dynamic code, and other features. All this provides a sophisticated interface, but it is not "fully" multi-threaded in the following sense. When a C thread T causes XSB to execute a command or query the thread must wait until the calling function returns before proceeding. In certain applications it may be useful, for example, for T to create a C thread T_{new} which runs asynchronously from T, executing the XSB command or query and then exiting. Alternately, an application may want to have a pool of C threads that can interact with a pool of XSB threads.

XSB's C API has been designed to support these features. Figure 14.5 shows fragments of Figure 14.4 rewritten so that the routines to print out the answers to the queries `p(X,Y,Z)` and `r(X,Y,Z)` can be called from C threads specially designed for this purpose. More specifically, the routine `query_ps()` calls `p_th` to query `p(X,Y,Z)` and backtrack through its answers – its use of a single `void *` argument and a `void *` return reflect the requirements of functions that are to be called using `pthread_create()`.

We note several points about this example. First the XSB API is a low-level API that can be used to build application specific interfaces, and some experience with pthread programming is useful if multiple XSB threads are called from multiple C threads. For instance, one issue is fairness. When called from the C API each XSB thread X_T makes use of mutexes to ensure that it answers only one query or command at a time. If multiple C threads are are waiting for X_T to respond to requests or queries, there is no guarantee that the requests will be processed in any sort of order, or even that a request will eventually be handled (In order to ensure this, the calling program would have to use a queue or some other scheduling mechanism to send requests to the XSB thread). In addition, it is

[5] Note that causing XSB's main thread to exit will cause the entire process to exit – not just XSB.

important to note that, *the main XSB thread should only be called from the C thread that initialized XSB.*. This restriction is due to the current design of synchronizing an XSB thread with calling threads, and may be lifted in the future.

Protected and Non-Protected API Functions

Example 14.5 shows that, when the `Varstring` functions are used, if a single calling thread opens a query to an XSB thread X_T, X_T will be protected from queries and commands posed by other C threads until the query is closed, failed out of, or exits via an error. In fact, queries (and commands) are protected when the `Varstring` or fixed string interfaces are used. However, consider what may happen when the register level interface is used. In this case, a calling thread may call one or more API functions to set up the registers, execute a command or query, call several more API functions to obtain the output, and so on. For this reason, if an application uses API commands that depend on user manipulation of registers (`xsb_command()`,`xsb_query()`,`xsb_query_string()`, and `xsb_next()`) the user must ensure that only one calling thread interacts with an XSB thread when that thread in the course of executing a command or query. See `$XSB_DIR/examples/c_calling_xsb/cregs_thread2.c` for an example of how mutexes can be used to protect XSB threads.

When writing multi-threaded applications in XSB, be sure to be aware of how multiple threads share (and do not share) dynamic data and tables. By default dynamic predicates (and tables) are unique to a given thread. For data to be shared by multiple threads, a predicate must be declared to be `shared`. See section 7.2 for details.

14.3 A C API for XSB

14.3.1 Initializing and Closing XSB

`int xsb_init_string(char *options)`

This function is used to initialize XSB via an initialization string `*options`, and must be called before any other calls can be made. The initialization string must include the path to the XSB directory installation directory `$XSB_DIR`, which is expanded to an absolute path by XSB. Any other command line options may be included just as in a command line except `-D`, `-d`, `-B` and `-i`. For example, a call from an executable in a sibling directory of XSB might have the form

```
xsb_init_string("../XSB -e startup.");
```

which initializes XSB with the goal `?- startup.`

Return Codes

- `XSB_SUCCESS` indicates that initialization returned successfully.

```
.....

void *query_ps(void * arg) {
  int rc;
  th_context *p_th;
  XSB_StrDefine(p_return_string);
  p_th = (th_context *)arg;

  rc = xsb_query_string_string(p_th,"p(X,Y,Z).",&p_return_string,"|");
  while (rc == XSB_SUCCESS) {
    printf("Return p %s\n",(p_return_string.string));
    rc = xsb_next_string(p_th, &p_return_string,"|");
  }

 if (rc == XSB_ERROR)
   fprintf(stderr,"++Query Error p: %s/%s\n",xsb_get_error_type(p_th),xsb_get_error_message(p_th));
 return NULL;
}


int main(int argc, char *argv[]) {

  char init_string[MAXPATHLEN];
  static th_context *p_th, *r_th;
  int pstatus, rstatus;
  pthread_t pthread_id,rthread_id;
  XSB_StrDefine(p_return_string);
  XSB_StrDefine(r_return_string);

.....

  main_th = xsb_get_main_thread();

  /* Create command to consult a file: edb.P, and send it. */
  if (xsb_command_string(xsb_get_main_thread(), "consult('edb.P').") == XSB_ERROR)
    fprintf(stderr,"++Error consulting edb.P: %s/%s\n",xsb_get_error_type(main_th),
    xsb_get_error_message(main_th));

  xsb_ccall_thread_create(main_th,&r_th);
  xsb_ccall_thread_create(main_th,&p_th);

  pthread_create(&rthread_id,NULL,command_rs,r_th);
  pthread_create(&pthread_id,NULL,command_ps,p_th);
  pthread_create(&rthread_id,NULL,command_rs,r_th);
  pthread_create(&pthread_id,NULL,command_ps,p_th);

  rstatus = pthread_join(rthread_id,&rreturn);
  if (rstatus != 0) fprintf(stderr,"R join returns status %d\n",rstatus);
  pstatus = pthread_join(pthread_id,&preturn);
  if (pstatus != 0) fprintf(stderr,"P join returns status %d\n",pstatus);

 xsb_kill_thread(r_th);
 xsb_close();
}
```

Figure 14.5: Manipulating Multiple XSB Threads Using Multiple C Threads

- `XSB_ERROR`
  - `init_error` if any error occurred during initialization.
  - `permission_error` if `xsb_init_string()` is called after XSB has already been correctly initialized.

`int xsb_init(int argc, char *argv[])`

This function is a variant of `xsb_init_string()` which passes initialization arguments as an argument vector: `argc` is the count of the number of arguments in the `argv` vector. The `argv` vector is exactly as would be passed from the command line to XSB.

- `argv[0]` must be an absolute or relative path name of the XSB installation directory (*i.e.*, `$XSB_DIR`). Here is an example, which assumes that we invoke the C program from the XSB installation directory.

```
int main(int argc, char *argv[])
{
  int myargc = 1;
  char *myargv[1];

  /* XSB_init relies on the calling program to pass the addr of the XSB
     installation directory. From here, it will find all the libraries */
  myargv[0] = ".";

  /* Initialize xsb */
  xsb_init(myargc,myargv);
}
```

The return codes for `xsb_init()` are the same as those for `xsb_init_string()`.

`int xsb_close()`

This routine closes the entire connection to XSB . After this, no more calls can be made (not even calls to `xsb_init_string()` or `xsb_init()`). In Version 3.3, no guarantee is made that all space used by XSB will be restored to the process (even when the process has dynamically linked to XSB), but space for any XSB tables is freed.

Return Codes

- `XSB_SUCCESS` indicates that XSB was closed successfully.
- `XSB_ERROR`
  - `permission_error` if `xsb_closed()` when XSB has not been (correctly) initialized.

14.3.2 Passing Commands to XSB

`int xsb_command_string(th_context *th, char *cmd)`

This function passes a command to the XSB thread designated by `th` (the first argument is not used in the single-threaded engine). No query can be active in `th` when the command is called. The command is a string consisting of a Prolog (or HiLog) term terminated by a period (.).

When used in the multi-threaded engine, `xsb_command_string` protects the called thread from API calls from other pthreads until the command is finished.

Return Codes

- `XSB_SUCCESS` indicates that the command succeeded.
- `XSB_FAILURE` indicates that the command failed.
- `XSB_ERROR`
  - `permission_error` if `xsb_command_string()` is called while a query is open in `th`.
  - Otherwise, any queries thrown during execution of the command are accessable through `xsb_get_error_type(th)` and `xsb_get_error_message(th)`.

`int xsb_command(th_context *th)`

This function passes a command to the XSB thread designated by `th` (the first argument is not used in the single-threaded engine). Any previous query must have already been closed. Before calling `xsb_command()`, the calling program must construct the term representing the command in register 1 in the XSB thread's space. This can be done by using the `c2p_*` (and `p2p_*`) routines, which are described in Section 13.2.3 below. Register 2 may also be set before the call to `xsb_query()` (using `xsb_make_vars(int)` and `xsb_set_var_*()`) in which case any variables set to values in the `ret/n` term will be so bound in the call to the command goal. `xsb_command` invokes the command represented in register 1 and returns `XSB_SUCCESS` if the command succeeds, `XSB_FAILURE` if it fails, and `XSB_ERROR` if an error is thrown while executing the command.

When used in the multi-threaded engine, `xsb_command_string` *does not protect* the called thread from API calls from other pthreads until the command is finished. It is the user's responsibility to protect the XSB thread, using a mutex or other concurrency control, from the time the goal begins to be constructed in the register 1 until the command has completed.

Apart from the steps necessary to formulate the query and the lack of protection of the XSB thread, the behavior of `xsb_command()` is similar to that of `xsb_command_string()`, including its return codes.

14.3.3 Querying XSB

`int xsb_query_string_string(th_context *th, char *query, VarString *buff, char *sep)`

This function opens a query to the XSB thread designated by `th` (the first argument is not used in the single-threaded engine); it returns the first answer (if there is one) as a `VarString`. Any previous query to `th` must have already been closed. Any query may return multiple data answers. The first is found and made available to the caller as a result of this call. To get any subsequent answers, `xsb_next_string()` must be called. An example call is:

```
rc = xsb_query_string_string(th, "append(X,Y,[a,b,c]).",buff,";");
```

The second argument is the period-terminated query string. The third argument is a pointer to a variable string buffer in which the subroutine returns the answer (if any.) The variable string data type `VarString` is explained in Section 14.4. (Use `xsb_query_string_string_b()` if you cannot declare a parameter of this type in your programming language.) The last argument is a string provided by the caller, which is used to separate arguments in the returned answer. For the example query, `buff` would be set to the string:

```
[];[a,b,c]
```

which is the first answer to the append query. There are two fields of this answer, corresponding to the two variables in the query, `X` and `Y`. The bindings of those variables make up the answer and the individual fields are separated by the `sep` string, here the semicolon (`;`). In the answer string, XSB atoms are printed without quotes. Complex terms are printed in a canonical form, with atoms quoted if necessary, and lists produced in the normal list notation.

When used in the multi-threaded engine, `xsb_query_string_string` protects the called thread from API calls from other pthreads until the entire query is finished.

Return Codes

- `XSB_SUCCESS` indicates that the query succeeded.
- `XSB_FAILURE` indicates that the query failed.
- `XSB_ERROR`
  - `permission_error` if `xsb_query_string_string()` is called while a query to `th` is open.
  - Otherwise, any errors thrown during execution of the query are accessable through `xsb_get_error_type()` and `xsb_get_error_message()`.

`int xsb_query_string_string_b(th_context *th,char *query,char *buff,int bufflen,int *anslen,char *sep)`

This function provides a lower-level alternative to `xsb_query_string_string` (not using the `VarString` type), which makes it easier for non-C callers (such as Visual Basic or Delphi) to access XSB functionality. Any previous query to `th` must have already been closed. Any query may return possibly multiple data answers. The first is found and made available to the caller as a result of this call. To get any subsequent answers, `xsb_next_string_b()` or a similar function must be called. The first and last arguments are the same as in `xsb_query_string_string()`. The `buff`, `bufflen`, and `anslen` parameters are used to pass the answer (if any) back to the caller. `buff` is a character array provided by the caller in which the answer is returned. `bufflen` is the length of the buffer (`buff`) and is provided by the caller. `anslen` is returned by this routine and is the length of the computed answer. If that length is less than `bufflen`, then the answer is put in `buff` (and null-terminated). If the answer is longer than will fit in the buffer (including the null terminator), then the answer is not copied to the buffer and `XSB_OVERFLOW` is returned. In this case the caller can retrieve the answer by providing a bigger buffer (of size greater than the returned `anslen`) in a call to `xsb_get_last_answer_string()`.

When used in the multi-threaded engine, `xsb_query_string_string_b` protects the called thread from API calls from other pthreads until the entire query is finished.

Return Codes

- `XSB_SUCCESS` indicates that the query succeeded.
- `XSB_FAILURE` indicates that the query failed.
- `XSB_ERROR`
  - `permission_error` if `xsb_query_string_string_b()` is called while a query to `th` is open.
  - Otherwise, any queries thrown during execution of the command are accessable through `xsb_get_error_type()` and `xsb_get_error_message()`.
- `XSB_OVERFLOW` indicates that the query succeeded, but the answer was too long for the buffer.

`int xsb_query(th_context *th)`

This function passes a query to the XSB thread `th`. Any previous query to `th` must have already been closed. Any query may return possibly multiple data answers. The first is found and made available to the caller as a result of this call. To get any subsequent answers, `xsb_next()` or a similar function must be called. Before calling `xsb_query()` the caller must construct the term representing the query in the XSB thread's register 1 (using routines described in Section 13.2.3 below.) If the query has no answers (i.e., just fails), register 1 is set back to a free variable and `xsb_query()` returns `XSB_FAILURE`. If the query has at least one answer, the variables in the query term in register 1 are bound to those answers and `xsb_query()` returns

XSB_SUCCESS. In addition, register 2 is bound to a term whose main functor symbol is ret/n, where n is the number of variables in the query. The main subfields of this term are set to the variable values for the first answer. (These fields can be accessed by the functions p2c_*, or the functions xsb_var_*, described in Section 13.2.3 below.) Thus there are two places the answers are returned. Register 2 is used to make it easier to access them. Register 2 may also be set before the call to xsb_query() (using xsb_make_vars(int) and xsb_set_var_*()) in which case any variables set to values in the ret/n term will be so bound in the call to the goal.

When used in the multi-threaded engine, xsb_query *does not protect* the called thread from API calls from other pthreads until the query is finished, or even when the registers are being accessed. It is the user's responsibility to protect the XSB thread, using a mutex or other concurrency control, from the time the goal begins to be constructed in the register 1 until the query is closed, failed, or exited upon error.

```
int xsb_get_last_answer_string(th_context *th, char *buff, int bufflen, int *anslen)
```

This function is used only when a call xsb_query_string_string_b() or xsb_next_string_b() to th returns XSB_OVERFLOW, indicating that the buffer provided was not big enough to contain the computed answer. In that case the user may allocate a larger buffer and then call this routine to retrieve the answer (that had been saved.) Only one answer is saved per thread, so this routine must called immediately after the failing call in order to get the right answer. The parameters are the same as the 2nd through 4th parameters of xsb_query_string_string_b().

Return Codes

- XSB_OVERFLOW indicates that the answer was still too long for the buffer.

```
int xsb_query_string(th_context *th,char *query)
```

This function passes a query to the XSB thread th. The query is a string consisting of a term that can be read by the XSB reader. The string must be terminated with a period (.). Any previous query must have already been closed. In all other respects, xsb_query_string() is similar to xsb_query(), except the only way to retrieve answers is through Register 2. The ability to create the return structure and bind variables in it is particularly useful in this function.

When used in the multi-threaded engine, xsb_query_string *does not protect* the called thread from API calls from other pthreads until the query is finished, or even when the registers are being accessed. It is the user's responsibility to protect the XSB thread, using a mutex or other concurrency control, from the time the goal begins to be constructed in the register 1 until the query is closed, failed, or exited upon error.

Return Codes

- XSB_SUCCESS indicates that the query succeeded.

- `XSB_FAILURE` indicates that the query failed.
- `XSB_ERROR` indicates that an error occurred while executing the query.

`int xsb_next_string(th_context *th,VarString *buff,char *sep)`

This routine is called after `xsb_query_string()` to retrieve a subsequent answer in `buff`. If a query is not open in `th`, an error is returned. This function treats answers just as `xsb_query_string_string()`. For example after the example call

```
rc = xsb_query_string_string(th,"append(X,Y,[a,b,c]).",buff,";");
```

which returns with buff set to

```
[];[a,b,c]
```

Then a call:

```
rc = xsb_next_string(th,buff,";");
```

returns with buff set to

```
[a];[b,c]
```

the second answer to the indicated query.

In the multi-threaded engine, `xsb_next_string()` protects the XSB thread from concurrent access by other threads as long as the query was invoked by `xsb_query_string_string(_b)`.

Return Codes

- `XSB_SUCCESS` indicates that the query succeeded.
- `XSB_FAILURE` indicates that the query failed.
- `XSB_ERROR` indicates that an error occurred while executing the query.

`int xsb_next_string_b(th_context *th, char *buff, int bufflen, int *anslen, char *sep)`

This function is a variant of `xsb_next_string()` that does not use the `VarString` type. Its parameters are the same as the 3rd through 6th parameters of `xsb_query_string_string_b()`. The next answer to the current query is returned in `buff`, if there is enough space. If the buffer would overflow, this routine returns `XSB_OVERFLOW`, and the answer can be retrieved by providing a larger buffer in a call to `xsb_get_last_answer_string_b()`. In any case, the length of the answer is returned in `anslen`.

In the multi-threaded engine, `xsb_next_string()` protects the XSB thread from concurrent access by other threads as long as the query was invoked by `xsb_query_string_string(_b)`.

Return Codes

- `XSB_SUCCESS` indicates that backtracking into the query succeeded.
- `XSB_FAILURE` indicates that backtracking into the query failed.
- `XSB_ERROR` indicates that an error occurred while further executing the query.
- `XSB_OVERFLOW` indicates that backtracking into the query succeeded, but the new answer was too long for the buffer.

`int xsb_next(th_context *)`

This function is called after `xsb_query()` (which must have returned `XSB_SUCCESS`) to retrieve more answers. It rebinds the query variables in the term in register 1 and rebinds the argument fields of the `ret/n` answer term in register 2 to reflect the next answer to the query. Its return codes are as with `xsb_next_string()`.

When used in the multi-threaded engine, `xsb_next` *does not protect* the called thread from API calls from other pthreads until the query is finished, or even when the registers are being accessed. It is the user's responsibility to protect the XSB thread, using a mutex or other concurrency control, through the time that registers are accessed by the calling program.

`int xsb_close_query(th_context *th)`

This function allows a user to close a query to `th` before all its answers have been retrieved. Since XSB is (usually) a tuple-at-a-time system, answers that are not retrieved are not computed so that closing a query may save time. If a given query Q is open, it is an error to open a new query without closing Q either by retrieving all its answers or explicitly calling `xsb_close_query()` to close Q. Calling `xsb_close_query()` when no query is open gives an error message, but otherwise has no effect.

Return Codes

- `XSB_SUCCESS` indicates that the current query was closed.
- `XSB_ERROR`
  - `permission_error` if `xsb_close_query()` is called while no query is open.

14.3.4 Obtaining Information about Errors

`char * xsb_get_init_error_message()`

Used to find error messages if `xsb_init_string()` or `xsb_init()` returns `XSB_ERROR`. Any errors returned by these functions have type `init_error`. Because initialization errors occur before XSB or any of its threads have been initialized, initialization errors do not require a thread context for input.

`char * xsb_get_error_type(th_context *th)`

If a function called for `th` returned `XSB_ERROR` this function provides a pointer to a

string representing the type of the error. Types are as in Volume 1 *Exception Handling* with the addition of `init_error` for errors that occur during initialization of XSB, and `unrecoverable_error` for errors from which no recovery is possible for XSB (e.g. inability to allocate new memory).

`char *xsb_get_error_message(th_context *th)`
: If a function called for `th` returned `XSB_ERROR` this function provides a pointer to a string representing a message associated with the error. For errors raised within the Prolog portion of execution, messages are as in Volume 1 *Exception Handling*.

14.3.5 Thread Management from Calling Programs

`int xsb_ccall_thread_create(th_context *callingThread, th_context **newThread)`

: Causes `callingThread` to create a thread pointed to by `newThread`. `newThread` runs exactly the same interpreter loop as `callingThread` and all API functions will work on `newThread` just as on the main thread, or any other thread. `newThread` will be non-detached, and will inherit any private parameters from `callingThread`. To create a thread to do a specific task or a detached thread, rather than one that executes a command loop, simply call the query `thread_create/[2,3]` from one of the query functions.

`th_context *xsb_get_main_thread()`
: Returns a pointer to the thread context of XSB's main thread. If XSB has not been initialized or has been closed this function returns 0.

`xsb_tid xsb_thread_id_to_context(th_context *th)`

`th_context *xsb_thread_context_to_id(xsb_tid id)`

14.4 The Variable-length String Data Type

XSB uses variable-length strings to communicate with certain C subroutines when the size of the output that needs to be passed from the Prolog side to the C side is not known. Variable-length strings adjust themselves depending on the size of the data they must hold and are ideal for this situation. For instance, as we have seem the two subroutines `xsb_query_string_string(query,buff,sep)` and `xsb_next_string(buff,sep)` use the variable string data type, `VarString`, for their second argument. To use this data type, make sure that

```
#include "cinterf.h"
```

appears at the top of the program file. Variables of the `VarString` type are declared using a macro that must appear in the declaration section of the program:

```
XSB_StrDefine(buf);
```

There is one important consideration concerning VarString with the *automatic* storage class: they must be *destroyed* on exit (see `XSB_StrDestroy`, below) from the procedure that defines them, or else there will be a memory leak. It is not necessary to destroy static `VarString`'s.

The public attributes of the type are `int length` and `char *string`. Thus, `buf.string` represents the actual contents of the buffer and `buf.length` is the length of that data. Although the length and the contents of a `VarString` string is readily accessible, the user **must not** modify these items directly. Instead, he should use the macros provided for that purpose:

- `XSB_StrSet(VarString *vstr, char *str)`: Assign the value of the regular null-terminated C string to the `VarString vstr`. The size of `vstr` is adjusted automatically.
- `XSB_StrSetV(VarString *vstr1, VarString *vstr2)`: Like `XSB_StrSet`, but the second argument is a variable-length string, not a regular C string.
- `XSB_StrAppend(VarString *vstr, char *str)`: Append the null-terminated string `str` to the `VarString vstr`. The size of `vstr` is adjusted.
- `XSB_StrPrepend(VarString *vstr, char *str)`: Like `XSB_StrAppend`, except that `str` is prepended.
- `XSB_StrAppendV(VarString *vstr1, VarString *vstr2)`: Like `XSB_StrAppend`, except that the second string is also a `VarString`.
- `XSB_StrPrependV(VarString *vstr1, VarString *vstr2)`: Like `XSB_StrAppendV`, except that the second string is prepended.
- `XSB_StrCompare(VarString *vstr1, VarString *vstr2)`: Compares two `VarString`. If the first one is lexicographically larger, then the result is positive; if the first string is smaller, than the result is negative; if the two strings have the same content (*i.e.*, `vstr1->string` equals `vstr2->string` then the result is zero.
- `XSB_StrCmp(VarString *vstr, char *str)`: Like `XSB_StrCompare` but the second argument is a regular, null-terminated string.
- `XSB_StrAppendBlk(VarString *vstr, char *blk, int size)`: This is like `XSB_StrAppend`, but the second argument is not assumed to be null-terminated. Instead, `size` characters pointed to by `blk` are appended to `vstr`. The size of `vstr` is adjusted, but the content is *not* null terminated.

- `XSB_StrPrependBlk(VarString *vstr, char *blk, int size)`: Like `XSB_StrPrepend`, but `blk` is not assumed to point to a null-terminated string. Instead, `size` characters from the region pointed to by `blk` are prepended to `vstr`.
- `XSB_StrNullTerminate(VarString *vstr)`: Null-terminates the `VarString` string `vstr`. This is used in conjunction with `XSB_StrAppendBlk`, because the latter does not null-terminate variable-length strings.
- `XSB_StrEnsureSize(VarString *vstr, int minsize)`: Ensure that the string has room for at least `minsize` bytes. This is a low-level routine, which is used to interface to procedures that do not use `VarString` internally. If the string is larger than `minsize`, the size might actually shrink to the nearest increment that is larger `minsize`.
- `XSB_StrShrink(VarString *vstr, int increment)`: Shrink the size of `vstr` to the minimum necessary to hold the data. `increment` becomes the new increment by which `vstr` is adjusted. Since `VarString` is automatically shrunk by `XSB_StrSet`, it is rarely necessary to shrink a `VarString` explicitly. However, one might want to change the adjustment increment using this macro (the default increment is 128).
- `XSB_StrDestroy(VarString *vstr)`: Destroys a `VarString`. Explicit destruction is necessary for `VarString`'s with the automatic storage class. Otherwise, memory leak is possible.

14.5 Passing Data into an XSB Module

The previous chapter described the low-level XSB/C interface that supports passing the data of arbitrary complexity between XSB and C. However, in cases when data needs to be passed into an executable XSB module by the main C program, the following higher-level interface should suffice. (This interface is actually implemented using macros that call the lower level functions.) These routines can be used to construct commands and queries into XSB 's register 1, which is necessary before calling `xsb_query()` or `xsb_command()`.

`void xsb_make_vars((int) N)`

`xsb_make_vars` creates a return structure of arity `N` in Register 2. So this routine may called before calling any of `xsb_query`, `xsb_query_string`, `xsb_command`, or `xsb_command_string` if parameters are to be set to be sent to the goal. It must be called before calling one of the `xsb_set_var_*` routines can be called. `N` must be the number of variables in the query that is to be evaluated.

`void xsb_set_var_int((int) Val, (int) N)`

`set_and_int` sets the `N`th field in the return structure to the integer value `Val`. It is used to set the value of the `N`th variable in a query before calling `xsb_query` or

`xsb_query_string`. When called in XSB, the query will have the Nth variable set to this value.

`void xsb_set_var_string((char *) Val, (int) N)`
`set_and_string` sets the Nth field in the return structure to the atom with name `Val`. It is used to set the value of the Nth variable in a query before calling `xsb_query` or `xsb_query_string`. When called in XSB, the query will have the Nth variable set to this value.

`void xsb_set_var_float((float) Val, (int) N)`
`set_and_float` sets the Nth field in the return structure to the floating point number with value `Val`. It is used to set the value of the Nth variable in a query before calling `xsb_query` or `xsb_query_string`. When called in XSB, the query will have the Nth variable set to this value.

`prolog_int xsb_var_int((int) N)`
`xsb_var_int` is called after `xsb_query` or `xsb_query_string` returns an answer. It returns the value of the Nth variable in the query as set in the returned answer. This variable must have an integer value (which is cast to `long` in a 64-bit architecture).

`char* xsb_var_string((int) N)`
`xsb_var_string` is called after `xsb_query` or `xsb_query_string` returns an answer. It returns the value of the Nth variable in the query as set in the returned answer. This variable must have an atom value.

`prolog_float xsb_var_float((int) N)`
`xsb_var_float` is called after `xsb_query` or `xsb_query_string` returns an answer. It returns the value of the Nth variable in the query as set in the returned answer. This variable must have a floating point value (which is cast to `double` in a 64-bit architecture).

14.6 Creating an XSB Module that Can be Called from C

To create an executable that includes calls to the above C functions, these routines, and the XSB routines that they call, must be included in the link (`ld`) step.

Unix instructions: You must link your C program, which should include the main procedure, with the XSB object file located in

```
$XSBDIR/config/<your-system-architecture>/saved.o/xsb.o
```

Your program should include the file `cinterf.h` located in the `XSB/emu` subdirectory, which defines the routines described earlier, which you will need to use in order to talk to XSB. It is therefore recommended to compile your program with the option `-I$XSB_DIR/XSB/emu`.

The file `$XSB_DIR/config/your-system-architecture/modMakefile` is a makefile you can use to build your programs and link them with XSB. It is generated automatically and contains all the right settings for your architecture, but you will have to fill in the name of your program, etc.

It is also possible to compile and link your program with XSB using XSB itself as follows:

```
:- xsb_configuration(compiler_flags,CFLAGS),
        xsb_configuration(loader_flags,LDFLAGS),
        xsb_configuration(config_dir,CONFDIR),
        xsb_configuration(emudir,EMUDIR),
        xsb_configuration(compiler,Compiler),
        str_cat(CONFDIR, '/saved.o/', ObjDir),
        write('Compiling myprog.c ... '),
        shell([Compiler, ' -I', EMUDIR, ' -c ', CFLAGS, ' myprog.c ']),
        shell([Compiler, CFLAGE, ' -o ', './myprog ',
               ObjDir, 'xsb.o ', ' myprog.o ', LDFLAGS]),
        writeln(done).
```

This works for every architecture and is often more convenient than using the make files [6]. There are simple examples of C programs calling XSB in the `$XSB_DIR/examples/c_calling_XSB` directory, in files `cmain.c`, `ctest.P`, `cmain2.c`.

Windows instructions: To call XSB from C, you must build it as a DLL, which is done as follows:

```
cd $XSB_DIR\XSB\build
makexsb_wind DLL="yes"
```

The DLL, which you can call dynamically from your program is then found in

`$XSB_DIR\config\x86-pc-windows\bin\xsb.dll`

Since your program must include the file `cinterf.h`, it is recommended to compile it with the option `/I$XSB_DIR\XSB\emu`.

[6] The variable `CFLAGS` is needed in the linking stage in order to ensure that the appropriate memory option is passed if XSB is configured `-with-bits32` or `-with-bits64` to override the default on a 64-bit platform.

Chapter 15

Restrictions and Current Known Bugs

In this chapter we indicate some features and bugs of XSB that may affect the users at some point in their interaction with the system.

If at some point in your interaction with the system you suspect that you have run across a bug not mentioned below, please report it to `(xsb-contact@cs.sunysb.edu)`. Please try to find the *smallest* program that illustrates the bug and mail it to this address together with a script that shows the problem. We will do our best to fix it or to assist you to bypass it.

15.1 Current Restrictions

- The maximum arity for predicate and function symbols is 255.
- The maximum length of atoms that can be stored in an XSB *object* code file is in principle $2^{32} - 1$.
- Not all of XSB's tabling and builtins currently take account of cyclic terms, so using them may lead to XSB hanging or crashing (cf. Section 6.8). Cyclic terms can be checked using the predicate `is_cyclic/1`.
- In the current version, you should never try to rename a byte code file generated for a module, though you can move it around in your file system. Since the module name is stored in the file, renaming it causes the system to load it into wrong places. However, byte code files for non-modules can be renamed at will.
- XSB allows up to 1 Gigabyte of address space for 32-bit chips. There are various tagging schemes, which depend on the operating system and where in the 32-bit

virtual address space it allocates user memory. The most general tagging scheme (named GENERAL_TAGGING) adjusts itself to the address space in use. Other more specific tagging schemes are available for specific architectures. Floating point numbers are by default double precision when computed at runtime. Floating point numbers in the compiler are only single precision (due to the way they are represented in object byte-code files.) If `-enable-fast-floats` is specified, then 28-bit floats are used. For 64-bit platforms, addresses are stored in 60 bits. However, as the *object* code file format is the same as for the 32-bit versions, compiled constants are subject to 32-bit limitations.

- Indexing on floating-point numbers is suspect, since, as implemented in XSB, the semantics of floating-point unification is murky in the best case. Therefore, it is advisable that if you use floating point numbers in the first argument of a procedure, that you explicitly index the predicate in some other argument.

- The XSB compiler cannot distinguish the occurrences of a 0-ary predicate and a name of a module (of an import declaration) as two different entities. For that reason it fails to characterise the same symbol table entry as both a predicate and a module at the same time. As a result of this fact, a compiler error is issued and the file is not compiled. For that reason we suggest the use of mutually exclusive names for modules and 0-ary predicates, though we will try to amend this restriction in future versions of XSB.

- Tabled predicates that use call-subsumption do not handle calls that use attributed variables, and may not use answer subsumption or incremental tabling.

15.2 Known Bugs

- The reader cannot read an infix operator immediately followed by a left parenthesis. In such a case you get a syntax error. To avoid the syntax error just leave a blank between the infix operator and the left parenthesis. For example, instead of writing:

  ```
  | ?- X=(a,b).
  ```

  write:

  ```
  | ?- X= (a,b).
  ```

- The reader cannot properly read an operator defined as both a prefix and an infix operator. For instance the declaration

  ```
  :- op(1200,xf,'<=').
  :- op(1200,xfx,'<=').
  ```

will lead to a syntax error.

- When the code of a predicate is reloaded many times, if the old code is still in use at the time of loading, unexpected errors may occur, due to the fact that the space of the old code is reclaimed and may be used for other purposes.
- Currently, term comparisons (`==`,`@<=`,`@<`,`@>`, and `@>=`) do not work for terms that overflow the C-recursion stack (terms that contain more than 10,000 variables and/or function symbols).

Appendix A

GPP - Generic Preprocessor

Version 2.0 - (c) Denis Auroux 1996-99
`http://www.math.polytechnique.fr/cmat/auroux/prog/gpp.html`

As of version 2.1, XSB uses *gpp* as a source code preprocessor for Prolog programs. This helps maintain consistency between the C and the Prolog parts of XSB through the use of the same .h files. In addition, the use of macros improves the readability of many Prolog programs, especially those that deal with low-level aspects of XSB. Chapter 3.10 explains how *gpp* is invoked in XSB.

A.1 Description

gpp is a general-purpose preprocessor with customizable syntax, suitable for a wide range of preprocessing tasks. Its independence on any programming language makes it much more versatile than *cpp*, while its syntax is lighter and more flexible than that of *m4*.

gpp is targeted at all common preprocessing tasks where *cpp* is not suitable and where no very sophisticated features are needed. In order to be able to process equally efficiently text files or source code in a variety of languages, the syntax used by *gpp* is fully customizable. The handling of comments and strings is especially advanced.

Initially, gpp only understands a minimal set of built-in macros, called *meta-macros*. These meta-macros allow the definition of *user macros* as well as some basic operations forming the core of the preprocessing system, including conditional tests, arithmetic evaluation, and syntax specification. All user macro definitions are global, i.e. they remain valid until explicitly removed; meta-macros cannot be redefined. With each user macro definition gpp keeps track of the corresponding syntax specification so that a macro can be safely invoked regardless of any subsequent change in operating mode.

In addition to macros, gpp understands comments and strings, whose syntax and behavior can be widely customized to fit any particular purpose. Internally comments and strings are the same construction, so everything that applies to comments applies to strings as well.

A.2 Syntax

```
gpp [-o outfile] [-I/include/path] [-Dname=val ...]
    [-z|+z] [-x] [-m] [-n] [-C|-T|-H|-P|-U ... [-M ...]]
    [+c<n> str1 str2] [-c str1]
    [+s<n> str1 str2 c] [infile]
```

A.3 Options

gpp recognizes the following command-line switches and options:

- **-h**
  Print a short help message.
- **-o** outfile
  Specify a file to which all output should be sent (by default, everything is sent to standard output).
- **-I** /include/path
  Specify a path where the *#include* meta-macro will look for include files if they are not present in the current directory. The default is /usr/include if no -I option is specified. Multiple -I options may be specified to look in several directories.
- **-D** name=val
  Define the user macro *name* as equal to *val*. This is strictly equivalent to using the *#define* meta-macro, but makes it possible to define macros from the command-line. If *val* makes references to arguments or other macros, it should conform to the syntax of the mode specified on the command-line. Note that macro argument naming is not allowed on the command-line.
- **+z**
  Set text mode to Unix mode (LF terminator). Any CR character in the input is systematically discarded. This is the default under Unix systems.
- **-z**
  Set text mode to DOS mode (CR-LF terminator). In this mode all CR characters are removed from the input, and all output LF characters are converted to CR-LF. This is the default if gpp is compiled with the WIN_NT option.

- **-x**
  Enable the use of the *#exec* meta-macro. Since *#exec* includes the output of an arbitrary shell command line, it may cause a potential security threat, and is thus disabled unless this option is specified.

- **-m**
  Enable automatic mode switching to the cpp compatibility mode if the name of an included file ends in '.h' or '.c'. This makes it possible to include C header files with only minor modifications.

- **-n**
  Prevent newline or whitespace characters from being removed from the input when they occur as the end of a macro call or of a comment. By default, when a newline or whitespace character forms the end of a macro or a comment it is parsed as part of the macro call or comment and therefore removed from output. Use the -n option to keep the last character in the input stream if it was whitespace or a newline.

- **-U** arg1 ... arg9
  User-defined mode. The nine following command-line arguments are taken to be respectively the macro start sequence, the macro end sequence for a call without arguments, the argument start sequence, the argument separator, the argument end sequence, the list of characters to stack for argument balancing, the list of characters to unstack, the string to be used for referring to an argument by number, and finally the quote character (if there is none an empty string should be provided). These settings apply both to user macros and to meta-macros, unless the -M option is used to define other settings for meta-macros. See the section on syntax specification for more details.

- **-M** arg1 ... arg7
  User-defined mode specifications for meta-macros. This option can only be used together with -M. The seven following command-line arguments are taken to be respectively the macro start sequence, the macro end sequence for a call without arguments, the argument start sequence, the argument separator, the argument end sequence, the list of characters to stack for argument balancing, and the list of characters to unstack. See below for more details.

- **(default mode)**
  The default mode is a vaguely cpp-like mode, but it does not handle comments, and presents various incompatibilities with *cpp*. Typical meta-macros and user macros look like this:

  ```
  #define x y
  macro(arg,...)
  ```

  This mode is equivalent to

```
-U "" "" "(" "," ")" "(" ")" "#" "\\"
-M "#" "\n" " " " " "\n" "(" ")"
```

- **-C**
  cpp compatibility mode. This is the mode where gpp's behavior is the closest to that of cpp. Unlike in the default mode, meta-macro expansion occurs only at the beginning of lines, and C comments and strings are understood. This mode is equivalent to

```
-n -U "" "" "(" "," ")" "(" ")" "#" ""
-M "\n#\w" "\n" " " " " "\n" "" ""
+c "/*" "*/" +c "//" "\n" +c "\\\n" ""
+s "\"" "\"" "\\" +s "'" "'" "\\"
```

- **-T**
  TeX-like mode. In this mode, typical meta-macros and user macros look like this:

```
\define{x}{y}
\macro{arg}{...}
```

  No comments are understood. This mode is equivalent to

```
-U "\\" "" "{" "}{" "}" "{" "}" "#" "@"
```

- **-H**
  HTML-like mode. In this mode, typical meta-macros and user macros look like this:

```
<#define x|y>
<#macro arg|...>
```

  No comments are understood. This mode is equivalent to

```
-U "<#" ">" "\B" "|" ">" "<" ">" "#" "\\"
```

- **-P**
  Prolog-compatible cpp-like mode. This mode differs from the cpp compatibility mode by its handling of comments, and is equivalent to

```
-n -U "" "" "(" "," ")" "(" ")" "#" ""
-M "\n#\w" "\n" " " " " "\n" "" ""
+ccss "\!o/*" "*/" +ccss "%" "\n" +ccii "\\\n" ""
+s "\"" "\"" "" +s "\!#'" "'" ""
```

- **+c** <n> str1 str2
  Specify comments. Any unquoted occurrence of *str1* will be interpreted as the beginning of a comment. All input up to the first following occurrence of *str2* will be discarded. This option may be used multiple times to specify different types of comment delimiters. The optional parameter <*n*> can be specified to alter the behavior of the comment and e.g. turn it into a string or make it ignored under certain circumstances, see below.

- **-c** str1
  Un-specify comments or strings. The comment/string specification whose start sequence is *str1* is removed. This is useful to alter the built-in comment specifications of a standard mode, e.g. the cpp compatibility mode.

- **+s** <n> str1 str2 c
  Specify strings. Any unquoted occurrence of *str1* will be interpreted as the beginning of a string. All input up to the first following occurrence of *str2* will be output as is without any evaluation. The delimiters themselves are output. If *c* is non-empty, its first character is used as a *string-quote character*, i.e. a character whose presence immediately before an occurrence of *str2* prevents it from terminating the string. The optional parameter <*n*> can be specified to alter the behavior of the string and e.g. turn it into a comment, enable macro evaluation inside the string, or make the string specification ignored under certain circumstances, see below.

- **-s** str1
  Un-specify comments or strings. Identical to -c.

- **infile**
  Specify an input file from which gpp reads its input. If no input file is specified, input is read from standard input.

A.4 Syntax Specification

The syntax of a macro call is the following : it must start with a sequence of characters matching the *macro start sequence* as specified in the current mode, followed immediately by the name of the macro, which must be a valid *identifier*, i.e. a sequence of letters, digits, or underscores ("_"). The macro name must be followed by a *short macro end sequence* if the macro has no arguments, or by a sequence of arguments initiated by an *argument start sequence*. The various arguments are then separated by an *argument separator*, and the macro ends with a *long macro end sequence*.

In all cases, the parameters of the current context, i.e. the arguments passed to the body being evaluated, can be referred to by using an *argument reference sequence* followed by a digit between 1 and 9. Macro parameters may alternately be named (see below). Furthermore, to avoid interference between the gpp syntax and the contents of the input file a *quote*

character is provided. The quote character can be used to prevent the interpretation of a macro call, comment, or string as anything but plain text. The quote character "protects" the following character, and always gets removed during evaluation. Two consecutive quote characters evaluate as a single quote character.

Finally, to facilitate proper argument delimitation, certain characters can be "stacked" when they occur in a macro argument, so that the argument separator or macro end sequence are not parsed if the argument body is not balanced. This allows nesting macro calls without using quotes. If an improperly balanced argument is needed, quote characters should be added in front of some stacked characters to make it balanced.

The macro construction sequences described above can be different for meta-macros and for user macros: this is e.g. the case in cpp mode. Note that, since meta-macros can only have up to two arguments, the delimitation rules for the second argument are somewhat sloppier, and unquoted argument separator sequences are allowed in the second argument of a meta-macro.

Unless one of the standard operating modes is selected, the above syntax sequences can be specified either on the command-line, using the -M and -U options respectively for meta-macros and user macros, or inside an input file via the *#mode meta* and *#mode user* meta-macro calls. In both cases the mode description consists of 9 parameters for user macro specifications, namely the macro start sequence, the short macro end sequence, the argument start sequence, the argument separator, the long macro end sequence, the string listing characters to stack, the string listing characters to unstack, the argument reference sequence, and finally the quote character. As explained below these sequences should be supplied using the syntax of C strings; they must start with a non-alphanumeric character, and in the first five strings special matching sequences can be used (see below). If the argument corresponding to the quote character is the empty string that functionality is disabled. For meta-macro specifications there are only 7 parameters, as the argument reference sequence and quote character are shared with the user macro syntax.

The structure of a comment/string is the following : it must start with a sequence of characters matching the given *comment/string start sequence*, and always ends at the first occurrence of the *comment/string end sequence*, unless it is preceded by an odd number of occurrences of the *string-quote character* (if such a character has been specified). In certain cases comment/strings can be specified to enable macro evaluation inside the comment/string: in that case, if a quote character has been defined for macros it can be used as well to prevent the comment/string from ending, with the difference that the macro quote character is always removed from output whereas the string-quote character is always output. Also note that under certain circumstances a comment/string specification can be *disabled*, in which case the comment/string start sequence is simply ignored. Finally, it is possible to specify a *string warning character* whose presence inside a comment/string will cause gpp to output a warning (this is useful e.g. to locate unterminated strings in cpp mode). Note that input files are not allowed to contain unterminated comments/strings.

A comment/string specification can be declared from within the input file using the *#mode comment* meta-macro call (or equivalently *#mode string*), in which case the number of C strings to be given as arguments to describe the comment/string can be anywhere between 2 and 4: the first two arguments (mandatory) are the start sequence and the end sequence, and can make use of the special matching sequences (see below). They may not start with alphanumeric characters. The first character of the third argument, if there is one, is used as string-quote character (use an empty string to disable the functionality), and the first character of the fourth argument, if there is one, is used as string-warning character. A specification may also be given from the command-line, in which case there must be two arguments if using the +c option and three if using the +s option.

The behavior of a comment/string is specified by a three-character modifier string, which may be passed as an optional argument either to the +c/+s command-line options or to the *#mode comment*/*#mode string* meta-macros. If no modifier string is specified, the default value is "ccc" for comments and "sss" for strings. The first character corresponds to the behavior inside meta-macro calls (including user-macro definitions since these come inside a *#define* meta-macro call), the second character corresponds to the behavior inside user-macro parameters, and the third character corresponds to the behavior outside of any macro call. Each of these characters can take the following values:

- **i**: disable the comment/string specification.
- **c**: comment (neither evaluated nor output).
- **s**: string (the string and its delimiter sequences are output as is).
- **q**: quoted string (the string is output as is, without the delimiter sequences).
- **C**: evaluated comment (macros are evaluated, but output is discarded).
- **S**: evaluated string (macros are evaluated, delimiters are output).
- **Q**: evaluated quoted string (macros are evaluated, delimiters are not output).

Important note: any occurrence of a comment/string start sequence inside another comment/string is always ignored, even if macro evaluation is enabled. In other words, comments/strings cannot be nested. In particular, the 'Q' modifier can be a convenient way of defining a syntax for temporarily disabling all comment and string specifications.

Syntax specification strings should always be provided as C strings, whether they are given as arguments to a *#mode* meta-macro call or on the command-line of a Unix shell. If command-line arguments are given via another method than a standard Unix shell, then the shell behavior must be emulated, i.e. the surrounding "" quotes should be removed, all occurrences of '\\' should be replaced by a single backslash, and similarly '\"' should be replaced by '"'. Sequences like '\n' are recognized by gpp and should be left as is.

Special sequences matching certain subsets of the character set can be used. They are of the form '\x', where x is one of:

- **b**: matches any sequence of one or more spaces or TAB characters ('\b' is identical to ' ').
- **w**: matches any sequence of zero or more spaces or TAB characters.
- **B**: matches any sequence of one or more spaces, tabs or newline characters.
- **W**: matches any sequence of zero or more spaces, tabs or newline characters.
- **a**: an alphabetic character ('a' to 'z' and 'A' to 'Z').
- **A**: an alphabetic character, or a space, tab or newline.
- **#**: a digit ('0' to '9').
- **i**: an identifier character. The set of matched characters is customizable using the *#mode charset id* command. The default setting matches alphanumeric characters and underscores ('a' to 'z', 'A' to 'Z', '0' to '9' and '_').
- **t**: a TAB character.
- **n**: a newline character.
- **o**: an operator character. The set of matched characters is customizable using the *#mode charset op* command. The default setting matches all characters in "+-*/\^<>=`~:.?@#&!%|", except in Prolog mode where '!', '%' and '|' are not matched.
- **O**: an operator character or a parenthesis character. The set of additional matched characters in comparison with '\o' is customizable using the *#mode charset par* command. The default setting is to have the characters in "()[]{}" as parentheses.

Moreover, all of these matching subsets except '\w' and '\W' can be negated by inserting a '!', i.e. by writing '\!x' instead of '\x'.

Note an important distinctive feature of *start sequences*: when the first character of a macro or comment/string start sequence is ' ' or one of the above special sequences, it is not taken to be part of the sequence itself but is used instead as a context check: for example a start sequence beginning with '\n' matches only at the beginning of a line, but the matching newline character is not taken to be part of the sequence. Similarly a start sequence beginning with ' ' matches only if some whitespace is present, but the matching whitespace is not considered to be part of the start sequence and is therefore sent to output. If a context check is performed at the very beginning of a file (or more generally of any body to be evaluated), the result is the same as matching with a newline character (this makes it possible for a cpp-mode file to start with a meta-macro call).

A.5 Evaluation Rules

Input is read sequentially and interpreted according to the rules of the current mode. All input text is first matched against the specified comment/string start sequences of the current mode (except those which are disabled by the 'i' modifier), unless the body being evaluated is the contents of a comment/string whose modifier enables macro evaluation. The most recently defined comment/string specifications are checked for first. Important note: comments may not appear between the name of a macro and its arguments (doing so results in undefined behavior).

Anything that is not a comment/string is then matched against a possible meta-macro call, and if that fails too, against a possible user-macro call. All remaining text undergoes substitution of argument reference sequences by the relevant argument text (empty unless the body being evaluated is the definition of a user macro) and removal of the quote character if there is one.

Note that meta-macro arguments are passed to the meta-macro prior to any evaluation (although the meta-macro may choose to evaluate them, see meta-macro descriptions below). In the case of the *#mode* meta-macro, gpp temporarily adds a comment/string specification to enable recognition of C strings ("...") and prevent any evaluation inside them, so no interference of the characters being put in the C string arguments to *#mode* with the current syntax is to be feared.

On the other hand, the arguments to a user macro are systematically evaluated, and then passed as context parameters to the macro definition body, which gets evaluated with that environment. The only exception is when the macro definition is empty, in which case its arguments are not evaluated. Note that gpp temporarily switches back to the mode in which the macro was defined in order to evaluate it: so it is perfectly safe to change the operating mode between the time when a macro is defined and the time when it is called. Conversely, if a user macro wishes to work with the current mode instead of the one that was used to define it it needs to start with a *#mode restore* call and end with a *#mode save* call.

A user macro may be defined with named arguments (see *#define* description below). In that case, when the macro definition is being evaluated, each named parameter causes a temporary virtual user-macro definition to be created; such a macro may only be called without arguments and simply returns the text of the corresponding argument.

Note that, since macros are evaluated when they are called rather than when they are defined, any attempt to call a recursive macro causes undefined behavior except in the very specific case when the macro uses *#undef* to erase itself after finitely many loop iterations.

Finally, a special case occurs when a user macro whose definition does not involve any arguments (neither named arguments nor the argument reference sequence) is called in a mode where the short user-macro end sequence is empty (e.g. cpp or TeX mode). In that

case it is assumed to be an *alias macro*: its arguments are first evaluated in the current mode as usual, but instead of being passed to the macro definition as parameters (which would cause them to be discarded) they are actually appended to the macro definition, using the syntax rules of the mode in which the macro was defined, and the resulting text is evaluated again. It is therefore important to note that, in the case of a macro alias, the arguments actually get evaluated twice in two potentially different modes.

A.6 Meta-macros

These macros are always pre-defined. Their actual calling sequence depends on the current mode; here we use cpp-like notation.

- **#define** x y
  This defines the user macro x as y. y can be any valid gpp input, and may for example refer to other macros. x must be an identifier (i.e. a sequence of alphanumeric characters and '_'), unless named arguments are specified. If x is already defined, the previous definition is overwritten. If no second argument is given, x will be defined as a macro that outputs nothing. Neither x nor y are evaluated; the macro definition is only evaluated when it is called, not when it is declared.

  It is also possible to name the arguments in a macro definition: in that case, the argument x should be a user-macro call whose arguments are all identifiers. These identifiers become available as user-macros inside the macro definition; these virtual macros must be called without arguments, and evaluate to the corresponding macro parameter.

- **#defeval** x y
  This acts in a similar way to *#define*, but the second argument y is evaluated immediately. Since user macro definitions are also evaluated each time they are called, this means that the macro y will undergo *two* successive evaluations. The usefulness of *#defeval* is considerable, as it is the only way to evaluate something more than once, which can be needed e.g. to force evaluation of the arguments of a meta-macro that normally doesn't perform any evaluation. However since all argument references evaluated at define-time are understood as the arguments of the body in which the macro is being defined and not as the arguments of the macro itself, usually one has to use the quote character to prevent immediate evaluation of argument references.

- **#undef** x
  This removes any existing definition of the user macro x.

- **#ifdef** x
  This begins a conditional block. Everything that follows is evaluated only if the identifier x is defined, until either a *#else* or a *#endif* statement is reached. Note

however that the commented text is still scanned thoroughly, so its syntax must be valid. It is in particular legal to have the *#else* or *#endif* statement ending the conditional block appear as only the result of a user-macro expansion and not explicitly in the input.

- **#ifndef** x
  This begins a conditional block. Everything that follows is evaluated only if the identifier x is not defined.

- **#ifeq** x y
  This begins a conditional block. Everything that follows is evaluated only if the results of the evaluations of x and y are identical as character strings. Any leading or trailing whitespace is ignored for the comparison. Note that in cpp-mode any unquoted whitespace character is understood as the end of the first argument, so it is necessary to be careful.

- **#ifneq** x y
  This begins a conditional block. Everything that follows is evaluated only if the results of the evaluations of x and y are not identical (even up to leading or trailing whitespace).

- **#else**
  This toggles the logical value of the current conditional block. What follows is evaluated if and only if the preceding input was commented out.

- **#endif**
  This ends a conditional block started by a *#if...* meta-macro.

- **#include** file
  This causes gpp to open the specified file and evaluate its contents, inserting the resulting text in the current output. All defined user macros are still available in the included file, and reciprocally all macros defined in the included file will be available in everything that follows. The include file is looked for first in the current directory, and then, if not found, in one of the directories specified by the *-I* command-line option (or */usr/include* if no directory was specified). Note that, for compatibility reasons, it is possible to put the file name between "" or <>.

  Upon including a file, gpp immediately saves a copy of the current operating mode onto the mode stack, and restores the operating mode at the end of the included file. The included file may override this behavior by starting with a *#mode restore* call and ending with a *#mode push* call. Additionally, when the *-m* command line option is specified, gpp will automatically switch to the cpp compatibility mode upon including a file whose name ends with either '.c' or '.h'.

- **#exec** command
  This causes gpp to execute the specified command line and include its standard output

in the current output. Note that this meta-macro is disabled unless the *-x* command line flag was specified, for security reasons. If use of *#exec* is not allowed, a warning message is printed and the output is left blank. Note that the specified command line is evaluated before being executed, thus allowing the use of macros in the command-line. However, the output of the command is included verbatim and not evaluated. If you need the output to be evaluated, you must use *#defeval* (see above) to cause a double evaluation.

- **#eval** expr
  The *#eval* meta-macro attempts to evaluate *expr* first by expanding macros (normal gpp evaluation) and then by performing arithmetic evaluation. The syntax and operator precedence for arithmetic expressions are the same as in C ; the only missing operators are <<, >>, ?: and assignment operators. If unable to assign a numerical value to the result, the returned text is simply the result of macro expansion without any arithmetic evaluation. The only exceptions to this rule are the == and != operators which, if one of the sides does not evaluate to a number, perform string comparison instead (ignoring trailing and leading spaces).

  Inside arithmetic expressions, the *defined(...)* special user macro is also available: it takes only one argument, which is not evaluated, and returns 1 if it is the name of a user macro and 0 otherwise.

- **#if** expr
  This meta-macro invokes the arithmetic evaluator in the same manner as *#eval*, and compares the result of evaluation with the string "0" in order to begin a conditional block. In particular note that the logical value of *expr* is always true when it cannot be evaluated to a number.

- **#mode** keyword ...
  This meta-macro controls gpp's operating mode. See below for a list of *#mode* commands.

The key to gpp's flexibility is the *#mode* meta-macro. Its first argument is always one of a list of available keywords (see below); its second argument is always a sequence of words separated by whitespace. Apart from possibly the first of them, each of these words is always a delimiter or syntax specifier, and should be provided as a C string delimited by double quotes (" "). The various special matching sequences listed in the section on syntax specification are available. Any *#mode* command is parsed in a mode where "..." is understood to be a C-style string, so it is safe to put any character inside these strings. Also note that the first argument of *#mode* (the keyword) is never evaluated, while the second argument is evaluated (except of course for the contents of C strings), so that the syntax specification may be obtained as the result of a macro evaluation.

The available *#mode* commands are:

- **#mode save / #mode push**
  Push the current mode specification onto the mode stack.

- **#mode restore / #mode pop**
  Pop mode specification from the mode stack.

- **#mode standard** name
  Select one of the standard modes. The only argument must be one of: default (default mode); cpp, C (cpp mode); tex, TeX (tex mode); html, HTML (html mode); prolog, Prolog (prolog mode). The mode name must be given directly, not as a C string.

- **#mode user** "s1" ... "s9"
  Specify user macro syntax. The 9 arguments, all of them C strings, are the mode specification for user macros (see the -U command-line option and the section on syntax specification). The meta-macro specification is not affected.

- **#mode meta** {user | "s1" ... "s7"}
  Specify meta-macro syntax. Either the only argument is *user* (not as a string), and the user-macro mode specifications are copied into the meta-macro mode specifications, or there must be 7 string arguments, whose significance is the same as for the -M command-line option (see section on syntax specification).

- **#mode quote** ["c"]
  With no argument or "" as argument, removes the quote character specification and disables the quoting functionality. With one string argument, the first character of the string is taken to be the new quote character. The quote character cannot be alphanumeric nor '_', and cannot be one of the special matching sequences either.

- **#mode comment** [xxx] "start" "end" ["c" ["c"]]
  Add a comment specification. Optionally a first argument consisting of three characters not enclosed in " " can be used to specify a comment/string modifier (see the section on syntax specification). The default modifier is *ccc*. The first two string arguments are used as comment start and end sequences respectively. The third string argument is optional and can be used to specify a string-quote character (if it is "" the functionality is disabled). The fourth string argument is optional and can be used to specify a string delimitation warning character (if it is "" the functionality is disabled).

- **#mode string** [xxx] "start" "end" ["c" ["c"]]
  Add a string specification. Identical to *#mode comment* except that the default modifier is *sss*.

- **#mode nocomment / #mode nostring** ["start"]
  With no argument, remove all comment/string specifications. With one string argument, delete the comment/string specification whose start sequence is the argument.

- **#mode preservelf** { on | off | 1 | 0 }
  Equivalent to the *-n* command-line switch. If the argument is *on* or *1*, any newline or whitespace character terminating a macro call or a comment/string is left in the input stream for further processing. If the argument is *off* or *0* this feature is disabled.

- **#mode charset** { id | op | par } "string"
  Specify the character sets to be used for matching the \o, \O and \i special sequences. The first argument must be one of *id* (the set matched by \i), *op* (the set matched by \o) or *par* (the set matched by \O in addition to the one matched by \o). *"string"* is a C string which lists all characters to put in the set. It may contain only the special matching sequences \a, \A, \b, \B, and \# (the other sequences and the negated sequences are not allowed). When a '-' is found in-between two non-special characters this adds all characters in-between (e.g. "A-Z" corresponds to all uppercase characters). To have '-' in the matched set, either put it in first or last position or place it next to a \x sequence.

A.7 Examples

Here is a basic self-explanatory example in standard or cpp mode:

```
#define FOO This is
#define BAR a message.
#define concat #1 #2
concat(FOO,BAR)
#ifeq (concat(foo,bar)) (foo bar)
This is output.
#else
This is not output.
#endif
```

Using argument naming, the *concat* macro could alternately be defined as

```
#define concat(x,y) x y
```

In TeX mode and using argument naming, the same example becomes:

```
\define{FOO}{This is}
\define{BAR}{a message.}
\define{\concat{x}{y}}{\x \y}
\concat{\FOO}{\BAR}
\ifeq{\concat{foo}{bar}}{foo bar}
This is output.
```

```
\else
This is not output.
\endif
```

In HTML mode and without argument naming, one gets similarly:

```
<#define FOO|This is>
<#define BAR|a message.>
<#define concat|#1 #2>
<#concat <#FOO>|<#BAR>>
<#ifeq <#concat foo|bar>|foo bar>
This is output.
<#else>
This is not output.
<#endif>
```

The following example (in standard mode) illustrates the use of the quote character:

```
#define FOO This is \
   a multiline definition.
#define BLAH(x) My argument is x
BLAH(urf)
\BLAH(urf)
```

Note that the multiline definition is also valid in cpp and Prolog modes despite the absence of quote character, because '\' followed by a newline is then interpreted as a comment and discarded.

In cpp mode, C strings and comments are understood as such, as illustrated by the following example:

```
#define BLAH foo
BLAH "BLAH" /* BLAH */
'It\'s a /*string*/ !'
```

The main difference between Prolog mode and cpp mode is the handling of strings and comments: in Prolog, a '...' string may not begin immediately after a digit, and a /*...*/ comment may not begin immediately after an operator character. Furthermore, comments are not removed from the output unless they occur in a #command.

The differences between cpp mode and default mode are deeper: in default mode #commands may start anywhere, while in cpp mode they must be at the beginning of a line; the default mode has no knowledge of comments and strings, but has a quote character ('\'),

while cpp mode has extensive comment/string specifications but no quote character. Moreover, the arguments to meta-macros need to be correctly parenthesized in default mode, while no such checking is performed in cpp mode.

This makes it easier to nest meta-macro calls in default mode than in cpp mode. For example, consider the following HTML mode input, which tests for the availability of the *#exec* command:

```
<#ifeq <#exec echo blah>|blah
> #exec allowed <#else> #exec not allowed <#endif>
```

There is no cpp mode equivalent, while in default mode it can be easily translated as

```
#ifeq (#exec echo blah
) (blah
)
\#exec allowed
#else
\#exec not allowed
#endif
```

In order to nest meta-macro calls in cpp mode it is necessary to modify the mode description, either by changing the meta-macro call syntax, or more elegantly by defining a silent string and using the fact that the context at the beginning of an evaluated string is a newline character:

```
#mode string QQQ "$" "$"
#ifeq $#exec echo blah
$ $blah
$
\#exec allowed
#else
\#exec not allowed
#endif
```

Note however that comments/strings cannot be nested ("..." inside $...$ would go undetected), so one needs to be careful about what to include inside such a silent evaluated string.

Remember that macros without arguments are actually understood to be aliases when they are called with arguments, as illustrated by the following example (default or cpp mode):

```
#define DUP(x) x x
```

```
#define FOO and I said: DUP
FOO(blah)
```

The usefulness of the *#defeval* meta-macro is shown by the following example in HTML mode:

```
<#define APPLY|<#defeval TEMP|<\##1 \#1>><#TEMP #2>>
<#define <#foo x>|<#x> and <#x>>
<#APPLY foo|BLAH>
```

The reason why *#defeval* is needed is that, since everything is evaluated in a single pass, the input that will result in the desired macro call needs to be generated by a first evaluation of the arguments passed to APPLY before being evaluated a second time.

To translate this example in default mode, one needs to resort to parenthesizing in order to nest the #defeval call inside the definition of APPLY, but need to do so without outputting the parentheses. The easiest solution is

```
#define BALANCE(x) x
#define APPLY(f,v) BALANCE(#defeval TEMP f
TEMP(v))
#define foo(x) x and x
APPLY(\foo,BLAH)
```

As explained above the simplest version in cpp mode relies on defining a silent evaluated string to play the role of the BALANCE macro.

The following example (default or cpp mode) demonstrates arithmetic evaluation:

```
#define x 4
The answer is:
#eval x*x + 2*(16-x) + 1998%x

#if defined(x)&&!(3*x+5>17)
This should be output.
#endif
```

To finish, here are some examples involving mode switching. The following example is self-explanatory (starting in default mode):

```
#mode push
#define f(x) x x
#mode standard TeX
```

```
\f{blah}
\mode{string}{"$" "$"}
\mode{comment}{"/*" "*/"}
$\f{urf}$ /* blah */
\define{FOO}{bar/* and some more */}
\mode{pop}
f($FOO$)
```

A good example where a user-defined mode becomes useful is the gpp source of this document (available with gpp's source code distribution).

Another interesting application is selectively forcing evaluation of macros in C strings when in cpp mode. For example, consider the following input:

```
#define blah(x) "and he said: x"
blah(foo)
```

Obviously one would want the parameter x to be expanded inside the string. There are several ways around this problem:

```
#mode push
#mode nostring "\""
#define blah(x) "and he said: x"
#mode pop

#mode quote "`"
#define blah(x) `"and he said: x`"

#mode string QQQ "$$" "$$"
#define blah(x) $$"and he said: x"$$
```

The first method is very natural, but has the inconvenient of being lengthy and neutralizing string semantics, so that having an unevaluated instance of 'x' in the string, or an occurrence of '/*', would be impossible without resorting to further contortions.

The second method is slightly more efficient, because the local presence of a quote character makes it easier to control what is evaluated and what isn't, but has the drawback that it is sometimes impossible to find a reasonable quote character without having to either significantly alter the source file or enclose it inside a *#mode push/pop* construct. For example any occurrence of '/*' in the string would have to be quoted.

The last method demonstrates the efficiency of evaluated strings in the context of selective evaluation: since comments/strings cannot be nested, any occurrence of '"' or '/*' inside the '$$' gets output as plain text, as expected inside a string, and only macro evaluation is

enabled. Also note that there is much more freedom in the choice of a string delimiter than in the choice of a quote character.

A.8 Advanced Examples

Here are some examples of advanced constructions using gpp. They tend to be pretty awkward and should be considered as evidence of gpp's limitations.

The first example is a recursive macro. The main problem is that, since gpp evaluates everything, a recursive macro must be very careful about the way in which recursion is terminated, in order to avoid undefined behavior (most of the time gpp will simply crash). In particular, relying on a *#if/#else/#endif* construct to end recursion is not possible and results in an infinite loop, because gpp scans user macro calls even in the unevaluated branch of the conditional block. A safe way to proceed is for example as follows (we give the example in TeX mode):

```
\define{countdown}{
  \if{#1}
  #1...
  \define{loop}{\countdown}
  \else
  Done.
  \define{loop}{}
  \endif
  \loop{\eval{#1-1}}
}
\countdown{10}
```

The following is an (unfortunately very weak) attempt at implementing functional abstraction in gpp (in standard mode). Understanding this example and why it can't be made much simpler is an exercise left to the curious reader.

```
#mode string "‘" "‘" "\\"
#define ASIS(x) x
#define SILENT(x) ASIS()
#define EVAL(x,f,v) SILENT(
  #mode string QQQ "‘" "‘" "\\"
  #defeval TEMP0 x
  #defeval TEMP1 (
    \#define \TEMP2(TEMP0) f
  )
  TEMP1
```

```
  )TEMP2(v)
#define LAMBDA(x,f,v) SILENT(
  #ifneq (v) ()
  #define TEMP3(a,b,c) EVAL(a,b,c)
  #else
  #define TEMP3(a,b,c) \LAMBDA(a,b)
  #endif
  )TEMP3(x,f,v)
#define EVALAMBDA(x,y) SILENT(
  #defeval TEMP4 x
  #defeval TEMP5 y
  )
#define APPLY(f,v) SILENT(
  #defeval TEMP6 ASIS(\EVA)f
  TEMP6
  )EVAL(TEMP4,TEMP5,v)
```

This yields the following results:

```
LAMBDA(z,z+z)
  => LAMBDA(z,z+z)

LAMBDA(z,z+z,2)
  => 2+2

#define f LAMBDA(y,y*y)
f
  => LAMBDA(y,y*y)

APPLY(f,blah)
  => blah*blah

APPLY(LAMBDA(t,t t),(t t))
  => (t t) (t t)

LAMBDA(x,APPLY(f,(x+x)),urf)
  => (urf+urf)*(urf+urf)

APPLY(APPLY(LAMBDA(x,LAMBDA(y,x*y)),foo),bar)
  => foo*bar

#define test LAMBDA(y,`#ifeq y urf
y is urf#else
```

```
y is not urf#endif
`)
APPLY(test,urf)
  => urf is urf

APPLY(test,foo)
  => foo is not urf
```

A.9 Author

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