Menhir Reference Manual
(version 20260209)

François Pottier Yann Régis-Gianas
INRIA
{Francois.Pottier, Yann.Regis-Gianas}@inria.fr

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1. Foreword

Menhir is a parser generator. It turns high-level grammar specifications, decorated with "semantic actions" (fragments of executable code), into parsers. It is based on Knuth's LR(1) parser construction technique [16]. It is strongly inspired by its precursors: `yacc` [12], `ML-Yacc` [29], and `ocamlyacc` [20], but offers a large number of minor and major improvements that make it a more modern tool.

This brief reference manual explains how to use Menhir. It does not attempt to explain context-free grammars, parsing, or the LR technique. Readers who have never used a parser generator are encouraged to read about these ideas first [1, 2, 9]. They are also invited to have a look at the `demos` directory in Menhir's distribution.

Back-ends Menhir currently offers a choice between several "back-ends":

- When the "code" back-end is used, the semantic actions are fragments of OCaml code, and the parser produced by Menhir is a stand-alone piece of OCaml code. The grammar is typically placed in a file whose name ends with `.mly`, such as `parser.mly`, and Menhir produces a parser whose implementation and interface are stored in the files `parser.ml` and `parser.mli`. The code back-end is the default back-end.
- When the "table" back-end is used, the semantic actions are fragments of OCaml code, and the parser produced by Menhir is a piece of OCaml code that needs to be linked with the library `MenhirLib`. The grammar is typically placed in a file whose name ends with `.mly`, such as `parser.mly`, and Menhir produces a parser whose implementation and interface are stored in the files `parser.ml` and `parser.mli`. The table back-end is selected by passing `--table` on the command line.
- When the "GLR" back-end is used, the semantic actions are fragments of OCaml code, and the parser produced by Menhir is a piece of OCaml code that needs to be linked with the library `MenhirGLR`. The grammar is typically placed in a file whose name ends with `.mly`, such as `parser.mly`, and Menhir produces a parser whose implementation and interface are stored in the files `parser.ml` and `parser.mli`. The GLR back-end is selected by passing `--GLR` on the command line.
- When the "Rocq" back-end is used, the semantic actions are fragments of Rocq code, and the parser produced by Menhir is a piece of Rocq code that contains not only a parser, but also a proof that this parser is correct and complete with respect to the grammar. The grammar is typically placed in a file whose name ends with `.vy`, such as `parser.vy`, and Menhir produces `parser.v`.

Caveat Potential users of Menhir should be warned that Menhir's feature set is not completely stable. There is a tension between preserving a measure of compatibility with `ocamlyacc`, on the one hand, and introducing new ideas, on the other hand. Some aspects of the tool are potentially subject to incompatible changes. For instance, the "traditional" error-handling mechanism (which is based on the **error** token, see §10) is now regarded as **deprecated** and is likely to be entirely removed in the future.

2. Usage

Menhir is invoked as follows:

`menhir` *option* ... *option filename* ... *filename*

Each of the file names must end with `.mly` (unless `--rocq` is used, in which case it must end with `.vy`) and denotes a partial grammar specification. These partial grammar specifications are joined (§5.1) to form a single, self-contained grammar specification, which is then processed. The following optional command line switches allow controlling many aspects of the process.

`--base` *basename*. This switch controls the base name of the `.ml` and `.mli` files that are produced. That is, the tool will produce files named *basename*`.ml` and *basename*`.mli`. Note that *basename* can contain occurrences of the `/` character, so it really specifies a path and a base name. When only one *filename* is provided on the command line, the default *basename* is obtained by depriving *filename* of its final `.mly` suffix. When multiple file names are provided on the command line, no default base name exists, so that the `--base` switch *must* be used.

`--cmly`. This switch causes Menhir to produce a `.cmly` file in addition to its normal operation. This file contains a (binary-form) representation of the grammar and automaton (see §14.1).

`--comment`. This switch causes a few comments to be inserted into the OCaml code that is written to the `.ml` file.

`--compare-errors` *filename1* `--compare-errors` *filename2*. Two such switches must always be used in conjunction so as to specify the names of two `.messages` files, *filename1* and *filename2*. Each file is read and internally translated to a mapping of states to messages. Menhir then checks that the left-hand mapping is a subset of the right-hand mapping. This feature is typically used in conjunction with `--list-errors` to check that *filename2* is complete (that is, covers all states where an error can occur). For more information, see §11.

`--compile-errors` *filename*. This switch causes Menhir to read the file *filename*, which must obey the `.messages` file format, and to compile it to an OCaml function that maps a state number to a message. The OCaml code is sent to the standard output channel. At the same time, Menhir checks that the collection of input sentences in the file *filename* is correct and irredundant. For more information, see §11.

`--rocq`. This switch causes Menhir to produce Rocq code. See §12.

`--rocq-lib-no-path`. This switch indicates that references to the Rocq library `MenhirLib` should *not* be qualified. This was the default behavior of Menhir prior to 2018/05/30. This switch is provided for compatibility, but normally should not be used.

`--rocq-lib-path` *path*. This switch allows specifying under what name (or path) the Rocq support library is known to Rocq. When Menhir runs in `--rocq` mode, the generated parser contains references to several modules in this library. This path is used to qualify these references. Its default value is `MenhirLib`.

`--rocq-no-actions`. (Used in conjunction with `--rocq`.) This switch causes the semantic actions present in the `.vy` file to be ignored and replaced with `tt`, the unique inhabitant of Rocq's `unit` type. This feature can be used to test the Rocq back-end with a standard grammar, that is, a grammar that contains OCaml semantic actions. Just rename the file from `.mly` to `.vy` and set this switch.

`--rocq-no-complete`. (Used in conjunction with `--rocq`.) This switch disables the generation of the proof of completeness of the parser (§12). This can be necessary because the proof of completeness is possible only if the grammar has no conflict (not even a benign one, in the sense of §6.1). This can be desirable also because, for a complex grammar, completeness may require a heavy certificate and its validation by Rocq may take time.

`--rocq-no-version-check`. (Used in conjunction with `--rocq`.) This switch prevents the generation of the check that verifies that the versions of Menhir and `MenhirLib` match.

`--depend`. See §15.

`--dump`. This switch causes a description of the automaton to be written to the file *basename*`.automaton`. This description is written after benign conflicts have been resolved, before severe conflicts are resolved (§6), and before extra reductions are introduced (§4.1.8).

`--dump-menhirLib` *directory*. This command causes Menhir to write the source code of the runtime library `MenhirLib` in the directory *directory*, and exit. The directory *directory* must exist already. Two files, named `menhirLib.ml` and `menhirLib.mli`, are created in it. This command can be useful to users with special needs who wish to use `MenhirLib` but do not want to rely on it being installed somewhere in the file system.

`--dump-resolved`. This command line switch causes a description of the automaton to be written to the file *basename*`.automaton.resolved`. This description is written after all conflicts have been resolved (§6) and after extra reductions have been introduced (§4.1.8).

`--echo-errors` *filename*. This switch causes Menhir to read the `.messages` file *filename* and to produce on the standard output channel just the input sentences. (That is, all messages, blank lines, and comments are filtered out.) For more information, see §11.

`--echo-errors-concrete` *filename*. This switch causes Menhir to read the `.messages` file *filename* and to produce on the standard output channel just the input sentences. Each sentence is followed with a comment of the form `## Concrete syntax: ...` that shows this sentence in concrete syntax. This comment is printed only if the user has defined an alias for every token (§4.1.3).

`--exn-carries-state`. This switch causes the exception `Error` to carry an integer parameter, as follows: `exception Error of int`. When the parser detects a syntax error, the number of the current state is reported in this way. This allows the caller to select a suitable syntax error message, along the lines described in §11. This switch is currently supported by the code back-end only. Thus, it is incompatible with `--table`. It is also incompatible with `--fixed-exception`.

`--explain`. This switch causes conflict explanations to be written to the file *basename*`.conflicts`. See also §6.

`--external-tokens` *T*. This switch causes the definition of the `token` type to be omitted in *basename*`.ml` and *basename*`.mli`. Instead, the generated parser relies on the type T`.token`, where T is an OCaml module name. It is up to the user to define module T and to make sure that it exports a suitable `token` type. Module T can be hand-written. It can also be automatically generated out of a grammar specification using the `--only-tokens` switch.

`--fixed-exception`. This switch causes the exception `Error` to be internally defined as a synonym for `Parsing.Parse_error`. This means that an exception handler that catches `Parsing.Parse_error` will also catch the generated parser's `Error`. This helps increase Menhir's compatibility with `ocamlyacc`. There is otherwise no reason to use this switch.

`--GLR`. This switch causes Menhir to use the GLR back-end. This back-end uses the GLR algorithm and supports non-deterministic parsing (§13).

`--infer`, `--infer-write-query`, `--infer-read-reply`. See §15.

`--inspection`. This switch requires `--table`. It causes Menhir to generate not only the monolithic and incremental APIs (§9.1, §9.2), but also the inspection API (§9.3). Activating this switch causes a few more tables to be produced, resulting in somewhat larger code size.

`--interpret`. This switch causes Menhir to act as an interpreter, rather than as a compiler. No OCaml code is generated. Instead, Menhir reads sentences off the standard input channel, parses them, and displays outcomes. This switch can be usefully combined with `--trace`. For more information, see §8.

`--interpret-error`. This switch is analogous to `--interpret`, except Menhir expects every sentence to cause an error on its last token, and displays information about the state in which the error is detected, in the `.messages` file format. For more information, see §11.

`--interpret-show-cst`. This switch, used in conjunction with `--interpret`, causes Menhir to display a concrete syntax tree when a sentence is successfully parsed. For more information, see §8.

`--list-errors`. This switch causes Menhir to produce (on the standard output channel) a complete list of input sentences that cause an error, in the `.messages` file format. For more information, see §11.

`--log-automaton` *level*. When *level* is nonzero, this switch causes some information about the automaton to be logged to the standard error channel.

`--log-code` *level*. When *level* is nonzero, this switch causes some information about the generated OCaml code to be logged to the standard error channel.

`--log-grammar` *level*. When *level* is nonzero, this switch causes some information about the grammar to be logged to the standard error channel. When *level* is 2, the *nullable*, *FIRST*, and *FOLLOW* tables are displayed.

`--merge-errors` *filename1* `--merge-errors` *filename2*. Two such switches must always be used in conjunction so as to specify the names of two `.messages` files, *filename1* and *filename2*. This command causes

Menhir to merge these two `.messages` files and print the result on the standard output channel. For more information, see §11.

`--no-code-generation`. This switch causes Menhir to stop without generating any code: in other words, no back-end is invoked. The analyses in Menhir's front-end are still performed. If requested via the command line switch `--cmly`, a `.cmly` file is written.

`--no-dollars`. This switch disallows the use of positional keywords of the form **$i**.

`--no-inline`. This switch causes all **%inline** keywords in the grammar specification to be ignored. This is especially useful in order to understand whether these keywords help solve any conflicts.

`--no-stdlib`. This switch instructs Menhir to *not* use its standard library (§5.4).

`--ocamlc` *command*. See §15.

`--ocamldep` *command*. See §15.

`--only-preprocess`. This switch causes the grammar specifications to be transformed up to the point where the automaton's construction can begin. The grammar specifications whose names are provided on the command line are joined (§5.1); all parameterized nonterminal symbols are expanded away (§5.2); type inference is performed, if `--infer` is enabled; all nonterminal symbols marked **%inline** are expanded away (§5.3). This yields a single, monolithic grammar specification, which is printed on the standard output channel.

`--only-tokens`. This switch causes the **%token** declarations in the grammar specification to be translated into a definition of the `token` type, which is written to the files *basename*`.ml` and *basename*`.mli`. No code is generated. This is useful when a single set of tokens is to be shared between several parsers. The directory `demos/calc-two` contains a demo that illustrates the use of this switch.

`--random-seed` *seed*. This switch allows the user to set a random seed. This seed influences the random sentence generator.

`--random-self-init`. This switch asks Menhir to choose a random seed in a nondeterministic (system-dependent) way. This seed influences the random sentence generator.

`--random-sentence-length` *length*. This switch allows the user to set a goal length for the random sentence generator. The generated sentences will normally have length at most *length*.

`--random-sentence` *symbol*. This switch asks Menhir to produce and display a random sentence that is generated by the nonterminal symbol *symbol*. The sentence is displayed as a sequence of terminal symbols, separated with spaces. Each terminal symbol is represented by its name.

The generated sentence is valid with respect to the grammar. If the grammar is in the class LR(1) (that is, if it has no conflicts at all), then the generated sentence is also accepted by the automaton. However, if the grammar has conflicts, then it may be the case that the sentence is rejected by the automaton.

The distribution of sentences is *not uniform*; some sentences (or fragments of sentences) may be more likely to appear than others.

The productions that involve the **error** pseudo-token are ignored by the random sentence generator.

`--random-sentence-concrete` *symbol*. This switch asks Menhir to produce and display a random sentence that is generated by the nonterminal symbol *symbol*. The sentence is displayed as a sequence of terminal symbols, separated with spaces. Each terminal symbol is represented by its token alias (§4.1.3). This assumes that a token alias has been defined for every token.

`--raw-depend`. See §15.

`--reference-graph`. This switch causes a description of the grammar's dependency graph to be written to the file *basename*`.dot`. The graph's vertices are the grammar's nonterminal symbols. There is a directed edge from vertex A to vertex B if the definition of A refers to B. The file is in a format that is suitable for processing by the *graphviz* toolkit.

`--require-aliases`. This switch causes Menhir to check that a token alias (§4.1.3) has been defined for every token. There is no requirement for this alias to be actually used; it must simply exist. A missing alias gives rise to a warning.

`--stdlib` *directory*. This switch exists only for backwards compatibility and is ignored. It may be removed in the future.

`--strategy` *strategy*. This switch selects an error-handling strategy, to be used by the code back-end, the table back-end, and the reference interpreter. The available strategies are `legacy` and simplified. When this switch is omitted, the `legacy` strategy is used, if it is available. (At the time of writing, the code back-end supports only the simplified strategy.) The choice of a strategy matters only if the grammar uses the **error** token. For more details, see §10.

`--strict`. This switch causes all warnings to be considered errors.

`--suggest-*`. See §15.

`--table`. This switch causes Menhir to use the table back-end, as opposed to the code back-end, which is the default. When `--table` is used, Menhir produces significantly more compact and somewhat slower parsers. See §17 for a speed comparison.

The table back-end produces rather compact tables, which are analogous to those produced by `yacc`, `bison`, or `ocamlyacc`. These tables are not quite stand-alone: they are exploited by an interpreter, which is shipped as part of the support library `MenhirLib`. For this reason, when `--table` is used, `MenhirLib` must be made visible to the OCaml compilers, and must be linked into your executable program. The `-suggest-*` switches, described above, help do this.

The code back-end compiles the LR automaton directly into a nest of mutually recursive OCaml functions. In that case, `MenhirLib` is not required.

The incremental API (§9.2) and the inspection API (§9.3) are made available only by the table back-end.

`--timings`. This switch causes internal timing information to be sent to the standard error channel.

`--timings-to` *filename*. This switch causes internal timing information to be written to the file *filename*.

`--trace`. This switch causes tracing code to be inserted into the generated parser, so that, when the parser is run, its actions are logged to the standard error channel. This is analogous to `ocamlrun`'s `p=1` parameter, except this switch must be enabled at compile time: one cannot selectively enable or disable tracing at runtime.

`--unparsing`. This switch requires `--table`. It causes Menhir to generate the unparsing API (§9.4). When this switch is enabled, the generated parser must be linked with the libraries `menhirLib` and `menhirCST`.

`--unused-precedence-levels`. This switch suppresses all warnings about useless **%left**, **%right**, **%nonassoc** and **%prec** declarations.

`--unused-token` *symbol*. This switch suppresses the warning that is normally emitted when Menhir finds that the terminal symbol *symbol* is unused.

`--unused-tokens`. This switch suppresses all of the warnings that are normally emitted when Menhir finds that some terminal symbols are unused.

`--update-errors` *filename*. This switch causes Menhir to read the `.messages` file *filename* and to produce on the standard output channel a new `.messages` file that is identical, except the auto-generated comments have been re-generated. For more information, see §11.

`--version`. This switch causes Menhir to print its own version number and exit.

3. Lexical conventions

A semicolon character (;) *may* appear after a declaration (§4.1).

An old-style rule (§4.2) *may* be terminated with a semicolon. Also, within an old-style rule, each producer (§4.2.3) *may* be terminated with a semicolon.

A new-style rule (§4.3) *must not* end with a semicolon. Within such a rule, the elements of a sequence *must* be separated with semicolons.

Semicolons are not allowed to appear anywhere except in the places mentioned above. This is in contrast with `ocamlyacc`, which views semicolons as insignificant, just like whitespace.

Identifiers (*id*) coincide with OCaml identifiers, except they are not allowed to contain the quote (') character. Following OCaml, identifiers that begin with a lowercase letter (*lid*) or with an uppercase letter (*uid*) are distinguished.

A quoted identifier *qid* is a string enclosed in double quotes. Such a string cannot contain a double quote or a backslash. Quoted identifiers are used as token aliases (§4.1.3).

Comments are C-style (surrounded with `/*` and `*/`, cannot be nested), C++-style (announced by `//` and extending until the end of the line), or OCaml-style (surrounded with `(*` and `*)`, can be nested). Of course, inside OCaml code, only OCaml-style comments are allowed.

OCaml type expressions are surrounded with $<$ and $>$. Within such expressions, all references to type constructors (other than the built-in *list*, *option*, etc.) must be fully qualified.

4. Syntax of grammar specifications

The syntax of grammar specifications appears in Figure 1. The places where attributes can be attached are not shown; they are documented separately (§14.2). A grammar specification begins with a sequence of declarations (§4.1), ended by a mandatory `%%` keyword. Following this keyword, a sequence of rules is expected. Each rule defines a nonterminal symbol *lid*, whose name must begin with a lowercase letter. A rule is expressed either in the "old syntax" (§4.2) or in the "new syntax" (§4.3), which is slightly more elegant and powerful.

4.1 Declarations

4.1.1 Headers

A header is a piece of OCaml code, surrounded with `%{` and `%}`. It is copied verbatim at the beginning of the `.ml` file. It typically contains OCaml `open` directives and function definitions for use by the semantic actions. If a single grammar specification file contains multiple headers, their order is preserved. However, when two headers originate in distinct grammar specification files, the order in which they are copied to the `.ml` file is unspecified.

It is important to note that the header is copied by Menhir only to the `.ml` file, *not* to the `.mli` file. Therefore, it should not contain declarations that affect the meaning of the types that appear in the `.mli` file. Here are two problems that people commonly run into:

- **Problem:** Placing an `open` directive that is required for a `%type` declaration to make sense. For instance, writing `open Foo` in the header and declaring `%type<t> bar`, where the type `t` is defined in the module `Foo`, will not work.
  Solution: Write `%type<Foo.t> bar`.
- **Problem:** Declaring a module alias that affects a (declared or inferred) type. For instance, placing the definition `module F = Foo` in the header can create a problem, because it allows OCaml to infer that the symbol `bar` has type `F.t`. Menhir relies on this information without realizing that `F` is a local name, so in the end, the `.mli` file contains a reference to `F.t` that does not make sense. The problem persists even if one declares `%type<Foo.t> bar`, because Menhir prefers the type inferred by OCaml over the type declared by the user.
  Solution: Wrap the module alias in an anonymous structure, like so: `open struct module F = Foo end`. (This requires OCaml 4.08 or newer.) This makes the name `F` available in your code, but forces OCaml to prefer the name `Foo` in the types that it infers.

4.1.2 Parameters

A declaration of the form:

specification ::= *declaration* ... *declaration* **%%** *rule* ... *rule* [**%%** *OCaml code*]
declaration ::= **%{** *OCaml code* **%}**
%parameter < *uid* : *OCaml module type* >
%token [< *OCaml type* >] *uid* [*qid*] ... *uid* [*qid*]
%nonassoc *uid* ... *uid*
%left *uid* ... *uid*
%right *uid* ... *uid*
%type < *OCaml type* > *lid* ... *lid*
%start [< *OCaml type* >] *lid* ... *lid*
%attribute *actual* ... *actual attribute* ... *attribute*
% *attribute*
%on_error_reduce *lid* ... *lid*
merge_function
attribute ::= **[@** *name payload* **]**
merge_function ::= **%merge {** *OCaml code* **}**

old syntax — rule ::= [**%public**] [**%inline**] *lid* [**(** *id*, ..., *id* **)**] : [|] *group* | ... | *group* [*merge_function*]
group ::= *production* | ... | *production* **{** *OCaml code* **}** [**%prec** *id*]
production ::= *producer* ... *producer* [**%prec** *id*]
producer ::= [*lid* =] *actual*
actual ::= *id* [**(** *actual*, ..., *actual* **)**]
actual (**?** | **+** | *****)
group | ... | *group*

new syntax — rule ::= [**%public**] **let** *lid* [**(** *id*, ..., *id* **)**] (**:=** | **==**) *expression* [*merge_function*]
expression ::= [|] *expression* | ... | *expression*
[*pattern* =] *expression* ; *expression*
id [**(** *expression*, ..., *expression* **)**]
expression (**?** | **+** | *****)
{ *OCaml code* **}** [**%prec** *id*]
< *OCaml id* > [**%prec** *id*]
pattern ::= *lid* | **_** | **~** | **(** *pattern*, ..., *pattern* **)**

Figure 1. Syntax of grammar specifications

%parameter < *uid* : *OCaml module type* >

causes the entire parser to become parameterized over the OCaml module *uid*, that is, to become an OCaml functor. The directory `demos/calc-param` contains a demo that illustrates the use of this switch.

If a single specification file contains multiple **%parameter** declarations, their order is preserved, so that the module name *uid* introduced by one declaration is effectively in scope in the declarations that follow. When two **%parameter** declarations originate in distinct grammar specification files, the order in which they are processed is unspecified. Last, **%parameter** declarations take effect before **%{** ... **%}**, **%token**, **%type**, or **%start** declarations are considered, so that the module name *uid* introduced by a **%parameter** declaration is effectively in scope in *all* **%{** ... **%}**, **%token**, **%type**, or **%start** declarations, regardless of whether they precede or follow the **%parameter** declaration. This means, in particular, that the side effects of an OCaml header are observed only when the functor is applied, not when it is defined.

4.1.3 Tokens

A declaration of the form:

%token [< *OCaml type* >] uid_1 [qid_1] ... uid_n [qid_n]

defines the identifiers $uid_1, \ldots, uid_n$ as tokens, that is, as terminal symbols in the grammar specification and as data constructors in the *token* type.

If an OCaml type t is present, then these tokens are considered to carry a semantic value of type t, otherwise they are considered to carry no semantic value.

If a quoted identifier qid_i is present, then it is considered an alias for the terminal symbol uid_i. (This feature, known as "token aliases", is borrowed from Bison.) Throughout the grammar, the quoted identifier qid_i is then synonymous with the identifier uid_i. For example, if one declares:

```
%token PLUS "+"
```

then the quoted identifier `"+"` stands for the terminal symbol `PLUS` throughout the grammar. An example of the use of token aliases appears in the directory `demos/calc-alias`. Token aliases can be used to improve the readability of a grammar. One must keep in mind, however, that they are just syntactic sugar: they are not interpreted in any way by Menhir or conveyed to tools like `ocamllex`. They could be considered confusing by a reader who mistakenly believes that they are interpreted as string literals.

4.1.4 Priority and associativity

A declaration of one of the following forms:

%nonassoc $uid_1 \ldots uid_n$
%left $uid_1 \ldots uid_n$
%right $uid_1 \ldots uid_n$

assigns both a *priority level* and an *associativity status* to the symbols $uid_1, \ldots, uid_n$. The priority level assigned to $uid_1, \ldots, uid_n$ is not defined explicitly: instead, it is defined to be higher than the priority level assigned by the previous **%nonassoc**, **%left**, or **%right** declaration, and lower than that assigned by the next **%nonassoc**, **%left**, or **%right** declaration. The symbols $uid_1, \ldots, uid_n$ can be tokens (defined elsewhere by a **%token** declaration) or dummies (not defined anywhere). Both can be referred to as part of **%prec** annotations. Associativity status and priority levels allow shift/reduce conflicts to be silently resolved (§6).

4.1.5 Types

A declaration of the form:

%type < *OCaml type* > $lid_1 \ldots lid_n$

assigns an OCaml type to each of the nonterminal symbols $lid_1, \ldots, lid_n$. For start symbols, providing an OCaml type is mandatory, but is usually done as part of the **%start** declaration. For other symbols, it is optional. Providing type information can improve the quality of OCaml's type error messages.

A **%type** declaration may concern not only a nonterminal symbol, such as, say, `expression`, but also a fully applied parameterized nonterminal symbol, such as `list(expression)` or `separated_list(COMMA, option(expression))`.

The types provided as part of **%type** declarations are copied verbatim to the `.ml` and `.mli` files. In contrast, headers (§4.1.1) are copied to the `.ml` file only. For this reason, the types provided as part of **%type** declarations must make sense both in the presence and in the absence of these headers. They should typically be fully qualified types.

4.1.6 Start symbols

A declaration of the form:

%start [< *OCaml type* >] $lid_1 \ldots lid_n$

declares the nonterminal symbols $lid_1, \ldots, lid_n$ to be start symbols. Each such symbol must be assigned an OCaml type either as part of the **%start** declaration or via separate **%type** declarations. Each of $lid_1, \ldots, lid_n$ becomes the name of a function whose signature is published in the `.mli` file and that can be used to invoke the parser.

4.1.7 Attribute declarations

Attribute declarations of the form **%attribute** *actual* ... *actual attribute* ... *attribute* and **%** *attribute* are explained in §14.2.

4.1.8 Extra reductions on error

A declaration of the form:

%on_error_reduce $lid_1 \ldots lid_n$

marks the nonterminal symbols $lid_1, \ldots, lid_n$ as potentially eligible for reduction when an invalid token is found. This may cause one or more extra reduction steps to be performed before the error is detected.

More precisely, this declaration affects the automaton as follows. Let us say that a production $lid \rightarrow \ldots$ is "reducible on error" if its left-hand symbol *lid* appears in a **%on_error_reduce** declaration. After the automaton has been constructed and after any conflicts have been resolved, in every state s, the following algorithm is applied:

1. Construct the set of all productions that are ready to be reduced in state s and are reducible on error;
2. Test if one of them, say p, has higher "on-error-reduce-priority" than every other production in this set;
3. If so, in state s, replace every error action with a reduction of the production p. (In other words, for every terminal symbol t, if the action table says: "in state s, when the next input symbol is t, fail", then this entry is replaced with: "in state s, when the next input symbol is t, reduce production p".)

If step 3 above is executed in state s, then an error can never be detected in state s, since all error actions in state s are replaced with reduce actions. Error detection is deferred: at least one reduction takes place before the error is detected. It is a "spurious" reduction: in a canonical LR(1) automaton, it would not take place.

An **%on_error_reduce** declaration does not affect the language that is accepted by the automaton. It does not affect the location where an error is detected. It is used to control in which state an error is detected. If used wisely, it can make errors easier to report, because they are detected in a state for which it is easier to write an accurate diagnostic message (§11.3).

Like a **%type** declaration, an **%on_error_reduce** declaration may concern not only a nonterminal symbol, such as, say, `expression`, but also a fully applied parameterized nonterminal symbol, such as `list(expression)` or `separated_list(COMMA, option(expression))`.

The "on-error-reduce-priority" of a production is that of its left-hand symbol. The "on-error-reduce-priority" of a nonterminal symbol is determined implicitly by the order of **%on_error_reduce** declarations. In the declaration **%on_error_reduce** $lid_1 \ldots lid_n$, the symbols $lid_1, \ldots, lid_n$ have the same "on-error-reduce-priority". They have higher "on-error-reduce-priority" than the symbols listed in previous **%on_error_reduce** declarations, and lower "on-error-reduce-priority" than those listed in later **%on_error_reduce** declarations.

4.2 Rules—old syntax

In its simplest form, a rule begins with the nonterminal symbol *lid*, followed by a colon character (:), and continues with a sequence of production groups (§4.2.1). Each production group is preceded with a vertical bar character (|); the very first bar is optional. The meaning of the bar is choice: the nonterminal symbol *id* develops to either of the production groups. We defer explanations of the keyword **%public** (§5.1), of the keyword **%inline** (§5.3), and of the optional formal parameters **(** *id*, ..., *id* **)** (§5.2).

4.2.1 Production groups

In its simplest form, a production group consists of a single production (§4.2.2), followed by an OCaml semantic action (§4.2.1) and an optional **%prec** annotation (§4.2.1). A production specifies a sequence of terminal and nonterminal symbols that should be recognized, and optionally binds identifiers to their semantic values.

Semantic actions A semantic action is a piece of OCaml code that is executed in order to assign a semantic value to the nonterminal symbol with which this production group is associated. A semantic action can refer to the (already computed) semantic values of the terminal or nonterminal symbols that appear in the production via the semantic value identifiers bound by the production.

For compatibility with `ocamlyacc`, semantic actions can also refer to unnamed semantic values via positional keywords of the form **$1**, **$2**, etc. This style is discouraged. (It is in fact forbidden if `--no-dollars` is turned on.) Furthermore, as a positional keyword of the form **$i** is internally rewritten as *_i*, the user should not use identifiers of the form *_i*.

%prec ***annotations*** An annotation of the form **%prec** *id* indicates that the precedence level of the production group is the level assigned to the symbol *id* via a previous **%nonassoc**, **%left**, or **%right** declaration (§4.1.4). In the absence of a **%prec** annotation, the precedence level assigned to each production is the level assigned to the rightmost terminal symbol that appears in it. It is undefined if the rightmost terminal symbol has an undefined precedence level or if the production mentions no terminal symbols at all. The precedence level assigned to a production is used when resolving shift/reduce conflicts (§6).

Multiple productions in a group If multiple productions are present in a single group, then the semantic action and precedence annotation are shared between them. This short-hand effectively allows several productions to share a semantic action and precedence annotation without requiring textual duplication. It is legal only when every production binds exactly the same set of semantic value identifiers and when no positional semantic value keywords (**$1**, etc.) are used.

4.2.2 Productions

A production is a sequence of producers (§4.2.3), optionally followed by a **%prec** annotation (§4.2.1). If a precedence annotation is present, it applies to this production alone, not to other productions in the production group. It is illegal for a production and its production group to both carry **%prec** annotations.

4.2.3 Producers

A producer is an actual (§4.2.4), optionally preceded with a binding of a semantic value identifier, of the form *lid* **=**. The actual specifies which construction should be recognized and how a semantic value should be computed for that construction. The identifier *lid*, if present, becomes bound to that semantic value in the semantic action that follows. Otherwise, the semantic value can be referred to via a positional keyword (**$1**, etc.).

4.2.4 Actuals

In its simplest form, an actual is just a terminal or nonterminal symbol *id*. If it is a parameterized nonterminal symbol (see §5.2), then it should be applied: *id***(** *actual*, ..., *actual* **)**.

An actual may be followed with a modifier (**?**, **+**, or *****). This is explained further on (see §5.2 and Figure 2).

An actual may also be an "anonymous rule". In that case, one writes just the rule's right-hand side, which takes the form *group* **|** ... **|** *group*. (This form is allowed only as an argument in an application.) This form is expanded on the fly to a definition of a fresh nonterminal symbol, which is declared **%inline**. For instance, providing an anonymous rule as an argument to *list*:

list **(** *e* **=** *expression*; *SEMICOLON* **{** *e* **}** **)**

is equivalent to writing this:

list **(** *expression_SEMICOLON* **)**

where the nonterminal symbol *expression_SEMICOLON* is chosen fresh and is defined as follows:

```
%inline expression_SEMICOLON:
  | e = expression; SEMICOLON { e }
```

4.3 Rules—new syntax

Please be warned that **the new syntax is considered experimental** and is subject to change in the future.

In its simplest form, a rule takes the form `let` *lid* `:=` *expression*. Its left-hand side *lid* is a nonterminal symbol; its right-hand side is an expression. Such a rule defines an ordinary nonterminal symbol, while the alternate form `let` *lid* `==` *expression* defines an `%inline` nonterminal symbol (§5.3), that is, a macro. A rule can be preceded with the keyword `%public` (§5.1) and can be parameterized with a tuple of formal parameters `(` *id*, ..., *id* `)` (§5.2). The various forms of expressions, listed in Figure 1, are:

- A **choice** between several expressions, [`|`] *expression*$_1$ `|` ... `|` *expression*$_n$. The leading bar is optional.
- A **sequence** of two expressions, *pattern* `=` *expression*$_1$ `;` *expression*$_2$. The semantic value produced by *expression*$_1$ is decomposed according to the pattern *pattern*. The OCaml variables introduced by *pattern* may appear in a semantic action that ends the sequence *expression*$_2$.
- A sequence `~` *id*$_1$ `;` *expression*$_2$, which is sugar for *id*$_1$ `=` *id*$_1$ `;` *expression*$_2$. This is a **pun**.
- A sequence *expression*$_1$ `;` *expression*$_2$, which is sugar for `_ =` *expression*$_1$ `;` *expression*$_2$.
- A **symbol** *id*, possibly applied to a tuple of expressions `(` *expression*$_1$, ..., *expression*$_n$ `)`. It is worth noting that such an expression *can* form the end of a sequence: *id* at the end of a sequence stands for *x* `=` *id* `;` `{` *x* `}` for some fresh variable *x*. Thus, a sequence need not end with a semantic action.
- An expression followed with `?`, `+`, or `*`. This is sugar for the previous form: see §5.2 and Figure 2.
- A **semantic action** `{` *OCaml code* `}`, possibly followed with a precedence annotation `%prec` *id*. This OCaml code can refer to the variables that have been bound earlier in the sequence that this semantic action ends. These include all variables named by the user as well as all variables introduced by a `~` pattern as part of a pun. The notation `$`i, where i is an integer, is forbidden.
- A **point-free semantic action** `<` *OCaml id* `>`, possibly followed with a precedence annotation `%prec` *id*. The OCaml identifier *id* must denote a function or a data constructor. It is applied to a tuple of the variables that have been bound earlier in the sequence that this semantic action ends. Thus, `<` *id* `>` is sugar for `{` *id* $(x_1, \ldots, x_n)$ `}`, where $x_1, \ldots, x_n$ are the variables bound earlier. These include all variables named by the user as well as all variables introduced by a `~` pattern.
- An identity semantic action `<>`. This is sugar for `<` *identity* `>`, where *identity* is OCaml's identity function. Therefore, it is sugar for `{` $(x_1, \ldots, x_n)$ `}`, where $x_1, \ldots, x_n$ are the variables bound earlier.

The syntax of expressions, as presented in Figure 1, seems more permissive than it really is. In reality, a choice cannot be nested inside a sequence; a sequence cannot be nested in the left-hand side of a sequence; a semantic action cannot appear in the left-hand side of a sequence. (Thus, there is a stratification in three levels: choice expressions, sequence expressions, and atomic expressions, which corresponds roughly to the stratification of rules, productions, and producers in the old syntax.) Furthermore, an expression between parentheses `(` *expression* `)` is *not* a valid expression. To surround an expression with parentheses, one must write either *midrule* `(` *expression* `)` or *endrule* `(` *expression* `)`; see §5.4 and Figure 3.

When a complex expression (e.g., a choice or a sequence) is placed in parentheses, as in *id* `(` *expression* `)`, this is equivalent to using *id* `(` *s* `)`, where the fresh symbol *s* is declared as a synonym for this expression, via the declaration `let` *s* `==` *expression*. This idiom is also known as an anonymous rule (§4.2.4).

Examples As an example of a rule in the new syntax, the parameterized nonterminal symbol *option*, which is part of Menhir's standard library (§5.4), can be defined as follows:

```
let option(x) :=
  |          { None }
  | x = x ; { Some x }
```

Using a pun, it can also be written as follows:

```
let option(x) :=
  |          { None }
  | ~ = x ; { Some x }
```

Using a pun and a point-free semantic action, it can also be expressed as follows:

```
let option(x) :=
  |          { None }
  | ~ = x ; < Some >
```

As another example, the parameterized symbol *delimited*, also part of Menhir's standard library (§5.4), can be defined in the new syntax as follows:

```
let delimited(opening, x, closing) ==
  opening ; ~ = x ; closing ; <>
```

The use of == indicates that this is a macro, i.e., an %inline nonterminal symbol (see §5.3). The identity semantic action <> is here synonymous with { *x* }.

Other illustrations of the new syntax can be found in the directories `demos/calc-new-syntax` and `demos/calc-ast`.

5. Advanced features

5.1 Splitting specifications over multiple files

Modules Grammar specifications can be split over multiple files. When Menhir is invoked with multiple argument file names, it considers each of these files as a *partial* grammar specification, and *joins* these partial specifications in order to obtain a single, complete specification.

This feature is intended to promote a form a modularity. It is hoped that, by splitting large grammar specifications into several "modules", they can be made more manageable. It is also hoped that this mechanism, in conjunction with parameterization (§5.2), will promote sharing and reuse. It should be noted, however, that this is only a weak form of modularity. Indeed, partial specifications cannot be independently processed (say, checked for conflicts). It is necessary to first join them, so as to form a complete grammar specification, before any kind of grammar analysis can be done.

This mechanism is, in fact, how Menhir's standard library (§5.4) is made available: even though its name does not appear on the command line, it is automatically joined with the user's explicitly-provided grammar specifications, making the standard library's definitions globally visible.

A partial grammar specification, or module, contains declarations and rules, just like a complete one: there is no visible difference. Of course, it can consist of only declarations, or only rules, if the user so chooses. (Don't forget the mandatory %% keyword that separates declarations and rules. It must be present, even if one of the two sections is empty.)

Private and public nonterminal symbols It should be noted that joining is *not* a purely textual process. If two modules happen to define a nonterminal symbol by the same name, then it is considered, by default, that this is an accidental name clash. In that case, each of the two nonterminal symbols is silently renamed so as to avoid the clash. In other words, by default, a nonterminal symbol defined in module A is considered *private*, and cannot be defined again, or referred to, in module B.

Naturally, it is sometimes desirable to define a nonterminal symbol N in module A and to refer to it in module B. This is permitted if N is public, that is, if either its definition carries the keyword %public or N is

declared to be a start symbol. A public nonterminal symbol is never renamed, so it can be referred to by modules other than its defining module.

In fact, it is permitted to split the definition of a *public* nonterminal symbol, over multiple modules and/or within a single module. That is, a public nonterminal symbol N can have multiple definitions, within one module and/or in distinct modules. All of these definitions are joined using the choice (|) operator. For instance, in the grammar of a programming language, the definition of the nonterminal symbol *expression* could be split into multiple modules, where one module groups the expression forms that have to do with arithmetic, one module groups those that concern function definitions and function calls, one module groups those that concern object definitions and method calls, and so on.

Tokens aside Another use of modularity consists in placing all `%token` declarations in one module, and the actual grammar specification in another module. The module that contains the token definitions can then be shared, making it easier to define multiple parsers that accept the same type of tokens. (On this topic, see `demos/calc-two`.)

5.2 Parameterizing rules

A rule (that is, the definition of a nonterminal symbol) can be parameterized over an arbitrary number of symbols, which are referred to as formal parameters.

Example For instance, here is the definition of the parameterized nonterminal symbol *option*, taken from the standard library (§5.4):

```
%public option(X):
  | { None }
  | x = X { Some x }
```

This definition states that *option*(*X*) expands to either the empty string, producing the semantic value *None*, or to the string *X*, producing the semantic value *Some x*, where *x* is the semantic value of *X*. In this definition, the symbol *X* is abstract: it stands for an arbitrary terminal or nonterminal symbol. The definition is made public, so *option* can be referred to within client modules.

A client who wishes to use *option* simply refers to it, together with an actual parameter – a symbol that is intended to replace *X*. For instance, here is how one might define a sequence of declarations, preceded with optional commas:

```
declarations:
  | { [] }
  | ds = declarations; option(COMMA); d = declaration { d :: ds }
```

This definition states that *declarations* expands either to the empty string or to *declarations* followed by an optional comma followed by *declaration*. (Here, *COMMA* is presumably a terminal symbol.) When this rule is encountered, the definition of *option* is instantiated: that is, a copy of the definition, where *COMMA* replaces *X*, is produced. Things behave exactly as if one had written:

```
optional_comma:
  | { None }
  | x = COMMA { Some x }
declarations:
  | { [] }
  | ds = declarations; optional_comma; d = declaration { d :: ds }
```

Note that, even though *COMMA* presumably has been declared as a token with no semantic value, writing *x* = *COMMA* is legal, and binds *x* to the unit value. This design choice ensures that the definition of *option* makes sense regardless of the nature of *X*: that is, *X* can be instantiated with a terminal symbol, with or without a semantic value, or with a nonterminal symbol.

actual?	is syntactic sugar for	*option*(*actual*)
actual+	is syntactic sugar for	*nonempty_list*(*actual*)
*actual**	is syntactic sugar for	*list*(*actual*)

Figure 2. Syntactic sugar for simulating regular expressions, also known as EBNF

Parameterization in general In general, the definition of a nonterminal symbol N can be parameterized with an arbitrary number of formal parameters. When N is referred to within a production, it must be applied to the same number of actuals. In general, an actual is:

- either a single symbol, which can be a terminal symbol, a nonterminal symbol, or a formal parameter;
- or an application of such a symbol to a number of actuals.

For instance, here is a rule whose single production consists of a single producer, which contains several, nested actuals. (This example is discussed again in §5.4.)

```
plist(X):
  | xs = loption(delimited(LPAREN, separated_nonempty_list(COMMA, X), RPAREN)) { xs }
```

Applications of the parameterized nonterminal symbols *option*, *nonempty_list*, and *list*, which are defined in the standard library (§5.4), can be written using a familiar, regular-expression like syntax (Figure 2).

Higher-order parameters A formal parameter can itself expect parameters. For instance, here is a rule that defines the syntax of procedures in an imaginary programming language:

```
procedure(list):
  | PROCEDURE ID list(formal) SEMICOLON block SEMICOLON { ... }
```

This rule states that the token *ID*, which represents the name of the procedure, should be followed with a list of formal parameters. (The definitions of the nonterminal symbols *formal* and *block* are not shown.) However, because *list* is a formal parameter, as opposed to a concrete nonterminal symbol defined elsewhere, this definition does not specify how the list is laid out: which token, if any, is used to separate, or terminate, list elements? is the list allowed to be empty? and so on. A more concrete notion of procedure is obtained by instantiating the formal parameter *list*: for instance, *procedure*(*plist*), where *plist* is the parameterized nonterminal symbol defined earlier, is a valid application.

Consistency Definitions and uses of parameterized nonterminal symbols are checked for consistency before they are expanded away. In short, it is checked that, wherever a nonterminal symbol is used, it is supplied with actual arguments in appropriate number and of appropriate nature. This guarantees that expansion of parameterized definitions terminates and produces a well-formed grammar as its outcome.

5.3 Inlining

It is well-known that the following grammar of arithmetic expressions does not work as expected: that is, in spite of the priority declarations, it has shift/reduce conflicts.

```
%token < int > INT
%token PLUS TIMES
%left PLUS
%left TIMES

%%

expression:
    | i = INT { i }
    | e = expression; o = op; f = expression { o e f }
op:
    | PLUS { ( + ) }
    | TIMES { ( * ) }
```

The trouble is, the precedence level of the production *expression* → *expression op expression* is undefined, and there is no sensible way of defining it via a %prec declaration, since the desired level really depends upon the symbol that was recognized by *op*: was it *PLUS* or *TIMES*?

The standard workaround is to abandon the definition of *op* as a separate nonterminal symbol, and to inline its definition into the definition of *expression*, like this:

```
expression:
    | i = INT { i }
    | e = expression; PLUS; f = expression { e + f }
    | e = expression; TIMES; f = expression { e * f }
```

This avoids the shift/reduce conflict, but gives up some of the original specification's structure, which, in realistic situations, can be damageable. Fortunately, Menhir offers a way of avoiding the conflict without manually transforming the grammar, by declaring that the nonterminal symbol *op* should be inlined:

```
expression:
    | i = INT { i }
    | e = expression; o = op; f = expression { o e f }
%inline op:
    | PLUS { ( + ) }
    | TIMES { ( * ) }
```

The %inline keyword causes all references to *op* to be replaced with its definition. In this example, the definition of *op* involves two productions, one that develops to *PLUS* and one that expands to *TIMES*, so every production that refers to *op* is effectively turned into two productions, one that refers to *PLUS* and one that refers to *TIMES*. After inlining, *op* disappears and *expression* has three productions: that is, the result of inlining is exactly the manual workaround shown above.

In some situations, inlining can also help recover a slight efficiency margin. For instance, the definition:

```
%inline plist(X):
    | xs = loption(delimited(LPAREN, separated_nonempty_list(COMMA, X), RPAREN)) { xs }
```

effectively makes *plist*(*X*) an alias for the right-hand side *loption*(...). Without the %inline keyword, the language recognized by the grammar would be the same, but the LR automaton would probably have one more state and would perform one more reduction at run time.

The %inline keyword does not affect the computation of positions (§7). The same positions are computed, regardless of where %inline keywords are placed.

If the semantic actions have side effects, the %inline keyword *can* affect the order in which these side effects take place. In the example of *op* and *expression* above, if for some reason the semantic action associated with *op*

Name	Recognizes	Produces	Comment
endrule(*X*)	*X*	α, if $X : \alpha$	(inlined)
midrule(*X*)	*X*	α, if $X : \alpha$	
option(*X*)	$\epsilon \mid X$	α *option*, if $X : \alpha$	(also *X*?)
ioption(*X*)	$\epsilon \mid X$	α *option*, if $X : \alpha$	(inlined)
boption(*X*)	$\epsilon \mid X$	*bool*	
loption(*X*)	$\epsilon \mid X$	α *list*, if $X : \alpha$ *list*	
pair(*X*, *Y*)	*X Y*	$\alpha \times \beta$, if $X : \alpha$ and $Y : \beta$	
separated_pair(*X*, *sep*, *Y*)	*X sep Y*	$\alpha \times \beta$, if $X : \alpha$ and $Y : \beta$	
preceded(*opening*, *X*)	*opening X*	α, if $X : \alpha$	
terminated(*X*, *closing*)	*X closing*	α, if $X : \alpha$	
delimited(*opening*, *X*, *closing*)	*opening X closing*	α, if $X : \alpha$	
list(*X*)	a possibly empty sequence of *X*'s	α *list*, if $X : \alpha$	(also *X**)
nonempty_list(*X*)	a nonempty sequence of *X*'s	α *list*, if $X : \alpha$	(also *X*+)
separated_list(*sep*, *X*)	a possibly empty sequence of *X*'s separated with *sep*'s	α *list*, if $X : \alpha$	
separated_nonempty_list(*sep*, *X*)	a nonempty sequence of *X*'s separated with *sep*'s	α *list*, if $X : \alpha$	
rev(*X*)	*X*	α *list*, if $X : \alpha$ *list*	(inlined)
flatten(*X*)	*X*	α *list*, if $X : \alpha$ *list list*	(inlined)
append(*X*, *Y*)	*X Y*	α *list*, if *X*, $Y : \alpha$ *list*	(inlined)

Figure 3. Summary of the standard library; see `standard.mly` for details

has a side effect (such as updating a global variable, or printing a message), then, by inlining *op*, we delay this side effect, which takes place *after* the second operand has been recognized, whereas in the absence of inlining it takes place as soon as the operator has been recognized.

5.4 The standard library

Once equipped with a rudimentary module system (§5.1), parameterization (§5.2), and inlining (§5.3), it is straightforward to propose a collection of commonly used definitions, such as options, sequences, lists, and so on. This *standard library* is joined, by default, with every grammar specification. A summary of the nonterminal symbols offered by the standard library appears in Figure 3. See also the short-hands documented in Figure 2.

By relying on the standard library, a client module can concisely define more elaborate notions. For instance, the following rule:

```
%inline plist(X):
  | xs = loption(delimited(LPAREN, separated_nonempty_list(COMMA, X), RPAREN)) { xs }
```

causes *plist*(*X*) to recognize a list of *X*'s, where the empty list is represented by the empty string, and a non-empty list is delimited with parentheses and comma-separated.

The standard library is stored in a file named `standard.mly`, which is embedded inside Menhir when it is built. The command line switch `--no-stdlib` instructs Menhir to *not* load the standard library.

The meaning of the symbols defined in the standard library (Figure 3) should be clear in most cases. Yet, the symbols *endrule*(*X*) and *midrule*(*X*) deserve an explanation. Both take an argument *X*, which typically will be

instantiated with an anonymous rule (§4.2.4). Both are defined as a synonym for *X*. In both cases, this allows placing an anonymous subrule in the middle of a rule.

For instance, the following is a well-formed production:

$$cat \quad endrule(dog \quad \{OCaml\ code_1\}) \quad cow \quad \{OCaml\ code_2\}$$

This production consists of three producers, namely *cat* and *endrule*(*dog* { *OCaml code*$_1$ }) and *cow*, and a semantic action { *OCaml code*$_2$ }. Because *endrule*(*X*) is declared as an %inline synonym for *X*, the expansion of anonymous rules (§4.2.4), followed with the expansion of %inline symbols (§5.3), transforms the above production into the following:

$$cat \quad dog \quad cow \quad \{OCaml\ code_1;\ OCaml\ code_2\}$$

Note that *OCaml code*$_1$ moves to the end of the rule, which means that this code is executed only after *cat*, *dog* and *cow* have been recognized. In this example, the use of *endrule* is rather pointless, as the expanded code is more concise and clearer than the original code. Still, *endrule* can be useful when its actual argument is an anonymous rule with multiple branches.

midrule is used in exactly the same way as *endrule*, but its expansion is different. For instance, the following is a well-formed production:

$$cat \quad midrule(\{OCaml\ code_1\}) \quad cow \quad \{OCaml\ code_2\}$$

(There is no *dog* in this example; this is intentional.) Because *midrule*(*X*) is a synonym for *X*, but is not declared %inline, the expansion of anonymous rules (§4.2.4), followed with the expansion of %inline symbols (§5.3), transforms the above production into the following:

$$cat \quad xxx \quad cow \quad \{OCaml\ code_2\}$$

where the fresh nonterminal symbol *xxx* is separately defined by the rule $xxx : \{OCaml\ code_1\}$. Thus, *xxx* recognizes the empty string, and as soon as it is recognized, *OCaml code*$_1$ is executed. This is known as a "mid-rule action".

6. Conflicts

When a shift/reduce or reduce/reduce conflict is detected, it is classified as either benign, if it can be resolved by consulting user-supplied precedence declarations, or severe, if it cannot. Benign conflicts are not reported. Severe conflicts are reported and, if the `--explain` switch is on, explained.

6.1 When is a conflict benign?

A shift/reduce conflict involves a single token (the one that one might wish to shift) and one or more productions (those that one might wish to reduce). When such a conflict is detected, the precedence level (§4.1.4, §4.2.1) of these entities are looked up and compared as follows:

1. if only one production is involved, and if it has higher priority than the token, then the conflict is resolved in favor of reduction.
2. if only one production is involved, and if it has the same priority as the token, then the associativity status of the token is looked up:
   (a) if the token was declared nonassociative, then the conflict is resolved in favor of neither action, that is, a syntax error will be signaled if this token shows up when this production is about to be reduced;
   (b) if the token was declared left-associative, then the conflict is resolved in favor of reduction;
   (c) if the token was declared right-associative, then the conflict is resolved in favor of shifting.

```
%token IF THEN ELSE
%start < expression > expression

%%

expression:
    | ...
    | IF b = expression THEN e = expression { ... }
    | IF b = expression THEN e = expression ELSE f = expression { ... }
    | ...
```

Figure 4. Basic example of a shift/reduce conflict

3. if multiple productions are involved, and if, considered one by one, they all cause the conflict to be resolved in the same way (that is, either in favor in shifting, or in favor of neither), then the conflict is resolved in that way.

In either of these cases, the conflict is considered benign. Otherwise, it is considered severe. Note that a reduce/reduce conflict is always considered severe, unless it happens to be subsumed by a benign multi-way shift/reduce conflict (item 3 above).

6.2 How are severe conflicts explained?

When the `--dump` switch is on, a description of the automaton is written to the `.automaton` file. Severe conflicts are shown as part of this description. Fortunately, there is also a way of understanding conflicts in terms of the grammar, rather than in terms of the automaton. When the `--explain` switch is on, a textual explanation is written to the `.conflicts` file.

Not all conflicts are explained in this file: instead, *only one conflict per automaton state is explained*. This is done partly in the interest of brevity, but also because Pager's algorithm can create artificial conflicts in a state that already contains a true LR(1) conflict; thus, one cannot hope in general to explain all of the conflicts that appear in the automaton. As a result of this policy, once all conflicts explained in the `.conflicts` file have been fixed, one might need to run Menhir again to produce yet more conflict explanations.

How the conflict state is reached Figure 4 shows a grammar specification with a typical shift/reduce conflict. When this specification is analyzed, the conflict is detected, and an explanation is written to the `.conflicts` file. The explanation first indicates in which state the conflict lies by showing how that state is reached. Here, it is reached after recognizing the following string of terminal and nonterminal symbols—the *conflict string*:

IF expression THEN IF expression THEN expression

Allowing the conflict string to contain both nonterminal and terminal symbols usually makes it shorter and more readable. If desired, a conflict string composed purely of terminal symbols could be obtained by replacing each occurrence of a nonterminal symbol N with an arbitrary N-sentence.

The conflict string can be thought of as a path that leads from one of the automaton's start states to the conflict state. When multiple such paths exist, the one that is displayed is chosen shortest. Nevertheless, it may sometimes be quite long. In that case, artificially (and temporarily) declaring some existing nonterminal symbols to be start symbols has the effect of adding new start states to the automaton and can help produce shorter conflict strings. Here, *expression* was declared to be a start symbol, which is why the conflict string is quite short.

In addition to the conflict string, the `.conflicts` file also states that the *conflict token* is *ELSE*. That is, when the automaton has recognized the conflict string and when the lookahead token (the next token on the input stream) is *ELSE*, a conflict arises. A conflict corresponds to a choice: the automaton is faced with several

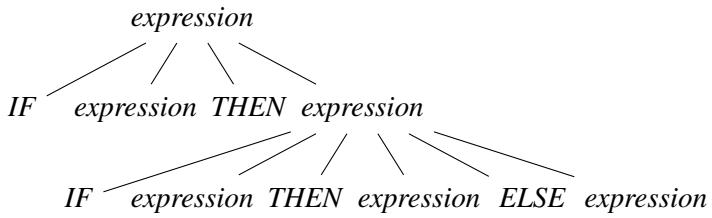


Figure 5. A partial derivation tree that justifies shifting

expression
IF expression THEN expression
IF expression THEN expression . ELSE expression

Figure 6. A textual version of the tree in Figure 5

possible actions, and does not know which one should be taken. This indicates that the grammar is not LR(1). The grammar may or may not be inherently ambiguous.

In our example, the conflict string and the conflict token are enough to understand why there is a conflict: when two *IF* constructs are nested, it is ambiguous which of the two constructs the *ELSE* branch should be associated with. Nevertheless, the `.conflicts` file provides further information: it explicitly shows that there exists a conflict, by proving that two distinct actions are possible. Here, one of these actions consists in *shifting*, while the other consists in *reducing*: this is a *shift/reduce* conflict.

A *proof* takes the form of a *partial derivation tree* whose *fringe* begins with the conflict string, followed by the conflict token. A derivation tree is a tree whose nodes are labeled with symbols. The root node carries a start symbol. A node that carries a terminal symbol is considered a leaf, and has no children. A node that carries a nonterminal symbol N either is considered a leaf, and has no children; or is not considered a leaf, and has n children, where $n \geq 0$, labeled $x_1, \ldots, x_n$, where $N \rightarrow x_1, \ldots, x_n$ is a production. The fringe of a partial derivation tree is the string of terminal and nonterminal symbols carried by the tree's leaves. A string of terminal and nonterminal symbols that is the fringe of some partial derivation tree is a *sentential form*.

Why shifting is legal In our example, the proof that shifting is possible is the derivation tree shown in Figures 5 and 6. At the root of the tree is the grammar's start symbol, *expression*. This symbol develops into the string *IF expression THEN expression*, which forms the tree's second level. The second occurrence of *expression* in that string develops into *IF expression THEN expression ELSE expression*, which forms the tree's last level. The tree's fringe, a sentential form, is the string *IF expression THEN IF expression THEN expression ELSE expression*. As announced earlier, it begins with the conflict string *IF expression THEN IF expression THEN expression*, followed with the conflict token *ELSE*.

In Figure 6, the end of the conflict string is materialized with a dot. Note that this dot does not occupy the rightmost position in the tree's last level. In other words, the conflict token (*ELSE*) itself occurs on the tree's last level. In practical terms, this means that, after the automaton has recognized the conflict string and peeked at the conflict token, it makes sense for it to *shift* that token.

Why reducing is legal In our example, the proof that reducing is possible is the derivation tree shown in Figures 7 and 8. Again, the sentential form found at the fringe of the tree begins with the conflict string, followed with the conflict token.

Again, in Figure 8, the end of the conflict string is materialized with a dot. Note that, this time, the dot occupies the rightmost position in the tree's last level. In other words, the conflict token (*ELSE*) appeared on an earlier level (here, on the second level). This fact is emphasized by the comment ***// lookahead token appears*** found at the second level. In practical terms, this means that, after the automaton has recognized the conflict string

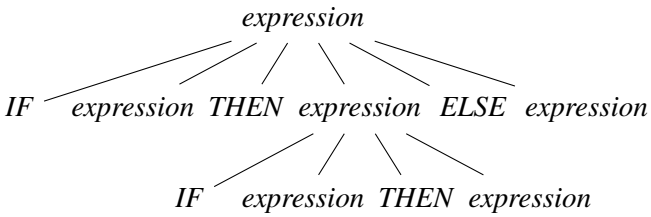


Figure 7. A partial derivation tree that justifies reducing

expression
IF expression THEN expression ELSE expression ***// lookahead token appears***
IF expression THEN expression .

Figure 8. A textual version of the tree in Figure 7

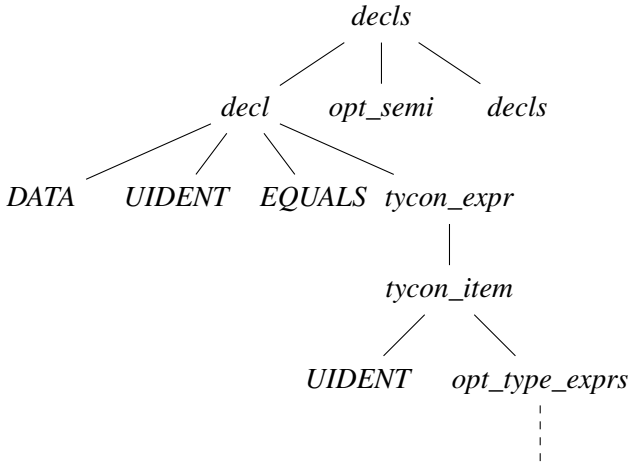


Figure 9. A partial derivation tree that justifies reducing

and peeked at the conflict token, it makes sense for it to *reduce* the production that corresponds to the tree's last level—here, the production is *expression* $\rightarrow$ *IF expression THEN expression*.

An example of a more complex derivation tree Figures 9 and 10 show a partial derivation tree that justifies reduction in a more complex situation. (This derivation tree is relative to a grammar that is not shown.) Here, the conflict string is *DATA UIDENT EQUALS UIDENT*; the conflict token is *LIDENT*. It is quite clear that the fringe of the tree begins with the conflict string. However, in this case, the fringe does not explicitly exhibit the conflict token. Let us examine the tree more closely and answer the question: following *UIDENT*, what's the next terminal symbol on the fringe?

First, note that *opt_type_exprs* is *not* a leaf node, even though it has no children. The grammar contains the production *opt_type_exprs* $\rightarrow \epsilon$: the nonterminal symbol *opt_type_exprs* develops to the empty string. (This is made clear in Figure 10, where a single dot appears immediately below *opt_type_exprs*.) Thus, *opt_type_exprs* is not part of the fringe.

Next, note that *opt_type_exprs* is the rightmost symbol within its level. Thus, in order to find the next symbol on the fringe, we have to look up one level. This is the meaning of the comment ***// lookahead token is inherited***. Similarly, *tycon_item* and *tycon_expr* appear rightmost within their level, so we again have to look further up.

decls
decl opt_semi decls ***// lookahead token appears because opt_semi can vanish and decls can begin with LIDENT***
DATA UIDENT EQUALS tycon_expr ***// lookahead token is inherited***
tycon_item ***// lookahead token is inherited***
UIDENT opt_type_exprs ***// lookahead token is inherited***
.

Figure 10. A textual version of the tree in Figure 9

This brings us back to the tree's second level. There, *decl* is *not* the rightmost symbol: next to it, we find *opt_semi* and *decls*. Does this mean that *opt_semi* is the next symbol on the fringe? Yes and no. *opt_semi* is a *nonterminal* symbol, but we are really interested in finding out what the next *terminal* symbol on the fringe could be. The partial derivation tree shown in Figures 9 and 10 does not explicitly answer this question. In order to answer it, we need to know more about *opt_semi* and *decls*.

Here, *opt_semi* stands (as one might have guessed) for an optional semicolon, so the grammar contains a production *opt_semi* $\rightarrow \epsilon$. This is indicated by the comment ***// opt_semi can vanish***. (Nonterminal symbols that generate ϵ are also said to be *nullable*.) Thus, one could choose to turn this partial derivation tree into a larger one by developing *opt_semi* into ϵ, making it a non-leaf node. That would yield a new partial derivation tree where the next symbol on the fringe, following *UIDENT*, is *decls*.

Now, what about *decls*? Again, it is a *nonterminal* symbol, and we are really interested in finding out what the next *terminal* symbol on the fringe could be. Again, we need to imagine how this partial derivation tree could be turned into a larger one by developing *decls*. Here, the grammar happens to contain a production of the form *decls* $\rightarrow$ *LIDENT* ... This is indicated by the comment ***// decls can begin with LIDENT***. Thus, by developing *decls*, it is possible to construct a partial derivation tree where the next symbol on the fringe, following *UIDENT*, is *LIDENT*. This is precisely the conflict token.

To sum up, there exists a partial derivation tree whose fringe begins with the conflict string, followed with the conflict token. Furthermore, in that derivation tree, the dot occupies the rightmost position in the last level. As in our previous example, this means that, after the automaton has recognized the conflict string and peeked at the conflict token, it makes sense for it to *reduce* the production that corresponds to the tree's last level—here, the production is *opt_type_exprs* $\rightarrow \epsilon$.

Greatest common factor among derivation trees Understanding conflicts requires comparing two (or more) derivation trees. It is frequent for these trees to exhibit a common factor, that is, to exhibit identical structure near the top of the tree, and to differ only below a specific node. Manual identification of that node can be tedious, so Menhir performs this work automatically. When explaining a n-way conflict, it first displays the greatest common factor of the n derivation trees. A question mark symbol *(?)* is used to identify the node where the trees begin to differ. Then, Menhir displays each of the n derivation trees, *without their common factor* – that is, it displays n sub-trees that actually begin to differ at the root. This should make visual comparisons significantly easier.

6.3 How are severe conflicts resolved in the end?

It is unspecified how severe conflicts are resolved. Menhir attempts to mimic `ocamlyacc`'s specification, that is, to resolve shift/reduce conflicts in favor of shifting, and to resolve reduce/reduce conflicts in favor of the production that textually appears earliest in the grammar specification. However, this specification is inconsistent in case of three-way conflicts, that is, conflicts that simultaneously involve a shift action and several reduction actions. Furthermore, textual precedence can be undefined when the grammar specification is split over multiple modules. In short, Menhir's philosophy is that

severe conflicts should not be tolerated,

so you should not care how they are resolved.

6.4 End-of-stream conflicts

Menhir's treatment of the end of the token stream is (believed to be) fully compatible with `ocamlyacc`'s. Yet, Menhir attempts to be more user-friendly by warning about a class of so-called "end-of-stream conflicts".

How the end of stream is handled In many textbooks on parsing, it is assumed that the lexical analyzer, which produces the token stream, produces a special token, written #, to signal that the end of the token stream has been reached. A parser generator can take advantage of this by transforming the grammar: for each start symbol *S* in the original grammar, a new start symbol *S'* is defined, together with the production $S' \rightarrow S\#$. The symbol S is no longer a start symbol in the new grammar. This means that the parser will accept a sentence derived from S only if it is immediately followed by the end of the token stream.

This approach has the advantage of simplicity. However, `ocamlyacc` and Menhir do not follow it, for several reasons. Perhaps the most convincing one is that it is not flexible enough: sometimes, it is desirable to recognize a sentence derived from S, *without* requiring that it be followed by the end of the token stream: this is the case, for instance, when reading commands, one by one, on the standard input channel. In that case, there is no end of stream: the token stream is conceptually infinite. Furthermore, after a command has been recognized, we do *not* wish to examine the next token, because doing so might cause the program to block, waiting for more input.

In short, `ocamlyacc` and Menhir's approach is to recognize a sentence derived from S and to *not look*, if possible, at what follows. However, this is possible only if the definition of S is such that the end of an S-sentence is identifiable without knowledge of the lookahead token. When the definition of S does not satisfy this criterion, and *end-of-stream conflict* arises: after a potential S-sentence has been read, there can be a tension between consulting the next token, in order to determine whether the sentence is continued, and *not* consulting the next token, because the sentence might be over and whatever follows should not be read. Menhir warns about end-of-stream conflicts, whereas `ocamlyacc` does not.

A definition of end-of-stream conflicts Technically, Menhir proceeds as follows. A # symbol is introduced. It is, however, only a *pseudo*-token: it is never produced by the lexical analyzer. For each start symbol *S* in the original grammar, a new start symbol *S'* is defined, together with the production $S' \rightarrow S$. The corresponding start state of the LR(1) automaton is composed of the LR(1) item $S' \rightarrow . \ S \ [\#]$. That is, the pseudo-token # initially appears in the lookahead set, indicating that we expect to be done after recognizing an S-sentence. During the construction of the LR(1) automaton, this lookahead set is inherited by other items, with the effect that, in the end, the automaton has:

- *shift* actions only on physical tokens; and
- *reduce* actions either on physical tokens or on the pseudo-token #.

A state of the automaton has a reduce action on # if, in that state, an S-sentence has been read, so that the job is potentially finished. A state has a shift or reduce action on a physical token if, in that state, more tokens potentially need to be read before an S-sentence is recognized. If a state has a reduce action on #, then that action should be taken *without* requesting the next token from the lexical analyzer. On the other hand, if a state has a shift or reduce action on a physical token, then the lookahead token *must* be consulted in order to determine if that action should be taken.

An end-of-stream conflict arises when a state has distinct actions on # and on at least one physical token. In short, this means that the end of an S-sentence cannot be unambiguously identified without examining one extra token. Menhir's default behavior, in that case, is to suppress the action on #, so that more input is *always* requested.

Example Figure 11 shows a grammar that has end-of-stream conflicts. When this grammar is processed, Menhir warns about these conflicts, and further warns that *expr* is never accepted. Let us explain.

Part of the corresponding automaton, as described in the `.automaton` file, is shown in Figure 12. Explanations at the end of the `.automaton` file (not shown) point out that states 6 and 2 have an end-of-stream conflict.

```
%token < int > INT
%token PLUS TIMES
%left PLUS
%left TIMES
%start < int > expr
%%
expr:
      | i = INT { i }
      | e1 = expr PLUS e2 = expr { e1 + e2 }
      | e1 = expr TIMES e2 = expr { e1 * e2 }
```

Figure 11. Basic example of an end-of-stream conflict

```
State 6:
expr -> expr . PLUS expr [ # TIMES PLUS ]
expr -> expr PLUS expr . [ # TIMES PLUS ]
expr -> expr . TIMES expr [ # TIMES PLUS ]
-- On TIMES shift to state 3
-- On # PLUS reduce production expr -> expr PLUS expr

State 4:
expr -> expr . PLUS expr [ # TIMES PLUS ]
expr -> expr . TIMES expr [ # TIMES PLUS ]
expr -> expr TIMES expr . [ # TIMES PLUS ]
-- On # TIMES PLUS reduce production expr -> expr TIMES expr

State 2:
expr' -> expr . [ # ]
expr -> expr . PLUS expr [ # TIMES PLUS ]
expr -> expr . TIMES expr [ # TIMES PLUS ]
-- On TIMES shift to state 3
-- On PLUS shift to state 5
-- On # accept expr
```

Figure 12. Part of an LR automaton for the grammar in Figure 11

```
...
%token END
%start < int > main          // instead of expr
%%
main:
      | e = expr END { e }
expr:
      | ...
```

Figure 13. Fixing the grammar specification in Figure 11

`$startpos`	start position of the first symbol in the production's right-hand side, if there is one; end position of the most recently parsed symbol, otherwise
`$endpos`	end position of the last symbol in the production's right-hand side, if there is one; end position of the most recently parsed symbol, otherwise
`$startpos(` $\$i \mid id$ `)`	start position of the symbol named $\$i$ or *id*
`$endpos(` $\$i \mid id$ `)`	end position of the symbol named $\$i$ or *id*
`$symbolstartpos`	start position of the leftmost symbol *id* such that `$startpos(`*id*`) != $endpos(`*id*`)`; if there is no such symbol, `$endpos`
`$startofs`	
`$endofs`	
`$startofs(` $\$i \mid id$ `)`	same as above, but produce an integer offset instead of a position
`$endofs(` $\$i \mid id$ `)`	
`$symbolstartofs`	
`$loc`	stands for the pair `($startpos, $endpos)`
`$loc(` *id* `)`	stands for the pair `($startpos(` *id* `), $endpos(` *id* `))`
`$sloc`	stands for the pair `($symbolstartpos, $endpos)`

Figure 14. Position-related keywords

Indeed, both states have distinct actions on # and on the physical token *TIMES*. It is interesting to note that, even though state 4 has actions on # and on physical tokens, it does not have an end-of-stream conflict. This is because the action taken in state 4 is always to reduce the production *expr* → *expr TIMES expr*, regardless of the lookahead token.

By default, Menhir produces a parser where end-of-stream conflicts are resolved in favor of looking ahead: that is, the problematic reduce actions on # are suppressed. This means, in particular, that the *accept* action in state 2, which corresponds to reducing the production *expr* → *expr'*, is suppressed. This explains why the symbol *expr* is never accepted: because expressions do not have an unambiguous end marker, the parser will always request one more token and will never stop.

In order to avoid this end-of-stream conflict, the standard solution is to introduce a new token, say *END*, and to use it as an end marker for expressions. The *END* token could be generated by the lexical analyzer when it encounters the actual end of stream, or it could correspond to a piece of concrete syntax, say, a line feed character, a semicolon, or an `end` keyword. The solution is shown in Figure 13.

7. Positions

When an `ocamllex`-generated lexical analyzer produces a token, it updates two fields, named `lex_start_p` and `lex_curr_p`, in its environment record, whose type is `Lexing.lexbuf`. Each of these fields holds a value of type `Lexing.position`. Together, they represent the token's start and end positions within the text that is being scanned. These fields are read by Menhir after calling the lexical analyzer, so **it is the lexical analyzer's responsibility** to correctly set these fields.

A position consists mainly of an offset (the position's `pos_cnum` field), but also holds information about the current file name, the current line number, and the current offset within the current line. (Not all `ocamllex`-generated analyzers keep this extra information up to date. This must be explicitly programmed by the author of the lexical analyzer.)

This mechanism allows associating pairs of positions with terminal symbols. If desired, Menhir automatically extends it to nonterminal symbols as well. That is, it offers a mechanism for associating pairs of positions with terminal or nonterminal symbols. This is done by making a set of keywords available to semantic actions

`symbol_start_pos()`	`$symbolstartpos`	
`symbol_end_pos()`	`$endpos`	
`rhs_start_pos i`	`$startpos($i)`	$(1 \leq i \leq n)$
`rhs_end_pos i`	`$endpos($i)`	$(1 \leq i \leq n)$
`symbol_start()`	`$symbolstartofs`	
`symbol_end()`	`$endofs`	
`rhs_start i`	`$startofs($i)`	$(1 \leq i \leq n)$
`rhs_end i`	`$endofs($i)`	$(1 \leq i \leq n)$

Figure 15. Translating position-related incantations from `ocamlyacc` to Menhir

(Figure 14). These keywords are *not* available outside of a semantic action: in particular, they cannot be used within an OCaml header.

OCaml's standard library module `Parsing` is deprecated. The functions that it offers *can* be called, but will return dummy positions.

We remark that, if the current production has an empty right-hand side, then `$startpos` and `$endpos` are equal, and (by convention) are the end position of the most recently parsed symbol (that is, the symbol that happens to be on top of the automaton's stack when this production is reduced). If the current production has a nonempty right-hand side, then `$startpos` is the same as `$startpos($1)` and `$endpos` is the same as `$endpos($`n`)`, where n is the length of the right-hand side.

More generally, if the current production has matched a sentence of length zero, then `$startpos` and `$endpos` will be equal, and conversely.

The position `$startpos` is sometimes "further towards the left" than one would like. For example, in the following production:

```
declaration: modifier? variable { $startpos }
```

the keyword `$startpos` represents the start position of the optional modifier `modifier?`. If this modifier turns out to be absent, then its start position is (by definition) the end position of the most recently parsed symbol. This may not be what is desired: perhaps the user would prefer in this case to use the start position of the symbol `variable`. This is achieved by using `$symbolstartpos` instead of `$startpos`. By definition, `$symbolstartpos` is the start position of the leftmost symbol whose start and end positions differ. In this example, the computation of `$symbolstartpos` skips the absent `modifier`, whose start and end positions coincide, and returns the start position of the symbol `variable` (assuming this symbol has distinct start and end positions).

There is no keyword `$symbolendpos`. Indeed, the problem with `$startpos` is due to the asymmetry in the definition of `$startpos` and `$endpos` in the case of an empty right-hand side, and does not affect `$endpos`.

The positions computed by Menhir are exactly the same as those computed by `ocamlyacc`[1]. More precisely, Figure 15 sums up how to translate a call to the `Parsing` module, as used in an `ocamlyacc` grammar, to a Menhir keyword.

We note that Menhir's `$startpos` does not appear in the right-hand column in Figure 15. In other words, Menhir's `$startpos` does not correspond exactly to any of the `ocamlyacc` function calls. An exact `ocamlyacc` equivalent of `$startpos` is `rhs_start_pos 1` if the current production has a nonempty right-hand side and `symbol_start_pos()` if it has an empty right-hand side.

Finally, we remark that Menhir's **%inline** keyword (§5.3) does not affect the computation of positions. The same positions are computed, regardless of where **%inline** keywords are placed.

[1] The computation of `$symbolstartpos` is optimized by Menhir under two assumptions about the lexer. First, Menhir assumes that the lexer never produces a token whose start and end positions are equal. Second, Menhir assumes that two positions produced by the lexer are equal if and only if they are physically equal. If the lexer violates either of these assumptions, the computation of `$symbolstartpos` could produce a result that differs from `Parsing.symbol_start_pos()`.

8. Using Menhir as an interpreter

When `--interpret` is set, Menhir no longer behaves as a compiler. Instead, it acts as an interpreter. That is, it repeatedly:

- reads a sentence off the standard input channel;
- parses this sentence, according to the grammar;
- displays an outcome.

This process stops when the end of the input channel is reached.

8.1 Sentences

The syntax of sentences is as follows:

$$\mathit{sentence} ::= [\, \mathit{lid} :]\ \mathit{uid}\ \ldots\ \mathit{uid}\ \backslash\mathsf{n}$$

Less formally, a sentence is a sequence of zero or more terminal symbols (*uid*'s), separated with whitespace, terminated with a newline character, and optionally preceded with a nonterminal start symbol (*lid*). This nonterminal symbol can be omitted if, and only if, the grammar only has one start symbol.

For instance, here are four valid sentences for the grammar of arithmetic expressions found in the directory `demos/calc`:

```
main: INT PLUS INT EOL
INT PLUS INT
INT PLUS PLUS INT EOL
INT PLUS PLUS
```

In the first sentence, the start symbol `main` was explicitly specified. In the other sentences, it was omitted, which is permitted, because this grammar has no start symbol other than `main`. The first sentence is a stream of four terminal symbols, namely `INT`, `PLUS`, `INT`, and `EOL`. These terminal symbols must be provided under their symbolic names. Writing, say, "`12+32\n`" instead of `INT PLUS INT EOL` is not permitted. Menhir would not be able to make sense of such a concrete notation, since it does not have a lexer for it.

8.2 Outcomes

As soon as Menhir is able to read a complete sentence off the standard input channel (that is, as soon as it finds the newline character that ends the sentence), it parses the sentence according to whichever grammar was specified on the command line, and displays an outcome.

An outcome is one of the following:

- `ACCEPT`: a prefix of the sentence was successfully parsed; a parser generated by Menhir would successfully stop and produce a semantic value;
- `OVERSHOOT`: the end of the sentence was reached before it could be accepted; a parser generated by Menhir would request a non-existent "next token" from the lexer, causing it to fail or block;
- `REJECT`: the sentence was not accepted; a parser generated by Menhir would raise the exception `Error`.

When `--interpret-show-cst` is set, each `ACCEPT` outcome is followed with a concrete syntax tree. A concrete syntax tree is either a leaf or a node. A leaf is either a terminal symbol or **error**. A node is annotated with a nonterminal symbol, and carries a sequence of immediate descendants that correspond to a valid expansion of this nonterminal symbol. Menhir's notation for concrete syntax trees is as follows:

$$\begin{array}{rl} \mathit{cst} ::= & \mathit{uid} \\ & \mathsf{error} \\ & [\ \mathit{lid} : \mathit{cst}\ \ldots\ \mathit{cst}\ ] \end{array}$$

For instance, if one wished to parse the example sentences of §8.1 using the grammar of arithmetic expressions in `demos/calc`, one could invoke Menhir as follows:

```
$ menhir --interpret --interpret-show-cst demos/calc/parser.mly
main: INT PLUS INT EOL
ACCEPT
[main: [expr: [expr: INT] PLUS [expr: INT]] EOL]
INT PLUS INT
OVERSHOOT
INT PLUS PLUS INT EOL
REJECT
INT PLUS PLUS
REJECT
```

(Here, Menhir's input—the sentences provided by the user on the standard input channel— is shown intermixed with Menhir's output—the outcomes printed by Menhir on the standard output channel.) The first sentence is valid, and accepted; a concrete syntax tree is displayed. The second sentence is incomplete, because the grammar specifies that a valid expansion of `main` ends with the terminal symbol `EOL`; hence, the outcome is `OVERSHOOT`. The third sentence is invalid, because of the repeated occurrence of the terminal symbol `PLUS`; the outcome is `REJECT`. The fourth sentence, a prefix of the third one, is rejected for the same reason.

8.3 Remarks

Using Menhir as an interpreter offers an easy way of debugging your grammar. For instance, if one wished to check that addition is considered left-associative, as requested by the **%left** directive found in the file demos/calc/parser.mly, one could submit the following sentence:

```
$ ./menhir --interpret --interpret-show-cst ../demos/calc/parser.mly
INT PLUS INT PLUS INT EOL
ACCEPT
[main:
  [expr: [expr: [expr: INT] PLUS [expr: INT]] PLUS [expr: INT]]
  EOL
]
```

The concrete syntax tree displayed by Menhir is skewed towards the left, as desired.

The switches `--interpret` and `--trace` can be used in conjunction. When `--trace` is set, the interpreter logs its actions to the standard error channel.

9. Generated API

When Menhir processes a grammar specification, say `parser.mly`, it produces one OCaml module, `Parser`, whose code resides in the file `parser.ml` and whose signature resides in the file `parser.mli`. We now review this signature. For simplicity, we assume that the grammar specification has just one start symbol `main`, whose OCaml type is `thing`.

9.1 Monolithic API

The monolithic API defines the type `token`, the exception `Error`, and the parsing function `main`, named after the start symbol of the grammar.

The type `token` is an algebraic data type. A value of type `token` represents a terminal symbol and its semantic value. For instance, if the grammar contains the declarations `%token A` and `%token<int> B`, then the generated file `parser.mli` contains the following definition:

```
type token =
| A
| B of int
```

If `--only-tokens` is specified on the command line, the type `token` is generated, and the rest is omitted. On the contrary, if `--external-tokens` is used, the type `token` is omitted, but the rest (described below) is generated.

The exception `Error` carries no argument. It is raised by the parsing function `main` (described below) when a syntax error is detected.

```
exception Error
```

Next comes one parsing function for each start symbol of the grammar. Here, we have assumed that there is one start symbol, named `main`, so the generated file `parser.mli` contains the following declaration:

```
val main: (Lexing.lexbuf -> token) -> Lexing.lexbuf -> thing
```

This function expects two arguments, namely: a lexer, which typically is produced by `ocamllex` and has type `Lexing.lexbuf -> token`; and a lexing buffer, which has type `Lexing.lexbuf`. This API is compatible with `ocamlyacc`. (For information on using Menhir without `ocamllex`, please consult §17.) This API is "monolithic" in the sense that there is just one function, which does everything: it pulls tokens from the lexer, parses, and eventually returns a semantic value (or fails by throwing the exception `Error`).

9.2 Incremental API

If `--table` is set, Menhir offers an incremental API in addition to the monolithic API. In this API, control is inverted. The parser does not have access to the lexer. Instead, when the parser needs the next token, it stops and returns its current state to the user. The user is then responsible for obtaining this token (typically by invoking the lexer) and resuming the parser from that state. The directory `demos/calc-incremental` contains a demo that illustrates the use of the incremental API.

This API is "incremental" in the sense that the user has access to a sequence of the intermediate states of the parser. Assuming that semantic values are immutable, a parser state is a persistent data structure: it can be stored and used multiple times, if desired. This enables applications such as "live parsing", where a buffer is continuously parsed while it is being edited. The parser can be re-started in the middle of the buffer whenever the user edits a character. Because two successive parser states share most of their data in memory, a list of n successive parser states occupies only $O(n)$ space in memory.

9.2.1 Starting the parser

In this API, the parser is started by invoking `Incremental.main`. (Recall that we assume that `main` is the name of the start symbol.) The generated file `parser.mli` contains the following declaration:

```
module Incremental : sig
  val main: position -> thing MenhirInterpreter.checkpoint
end
```

The argument is the initial position. If the lexer is based on an OCaml lexing buffer, this argument should be `lexbuf.lex_curr_p`. In §9.2 and §9.3, the type `position` is a synonym for `Lexing.position`.

We emphasize that the function `Incremental.main` does not parse anything. It constructs a checkpoint which serves as a *starting* point. The functions `offer` and `resume`, described below, are used to drive the parser.

9.2.2 Driving the parser

The sub-module `MenhirInterpreter` is also part of the incremental API. Its declaration, which appears in the generated file `parser.mli`, is as follows:

```
module MenhirInterpreter : MenhirLib.IncrementalEngine.INCREMENTAL_ENGINE
  with type token = token
```

The signature `INCREMENTAL_ENGINE`, defined in the module `MenhirLib.IncrementalEngine`, contains many types and functions, which are described in the rest of this section (§9.2.2) and in the following sections (§9.2.3, §9.2.4).

Please keep in mind that, from the outside, these types and functions should be referred to with an appropriate prefix. For instance, the type `checkpoint` should be referred to as `MenhirInterpreter.checkpoint`, or `Parser.MenhirInterpreter.checkpoint`, depending on which modules the user chooses to open.

```
type 'a env
```

The abstract type `'a env` represents the current state of the parser. (That is, it contains the current state and stack of the LR automaton.) Assuming that semantic values are immutable, it is a persistent data structure: it can be stored and used multiple times, if desired. The parameter `'a` is the type of the semantic value that will eventually be produced if the parser succeeds.

```
type production
```

The abstract type `production` represents a production of the grammar. The "start productions" (which do not exist in an `.mly` file, but are constructed by Menhir internally) are *not* part of this type.

```
type 'a checkpoint = private
  | InputNeeded of 'a env
  | Shifting of 'a env * 'a env * bool
  | AboutToReduce of 'a env * production
  | HandlingError of 'a env
  | Accepted of 'a
  | Rejected
```

The type `'a checkpoint` represents an intermediate or final state of the parser. An intermediate checkpoint is a suspension: it records the parser's current state, and allows parsing to be resumed. The parameter `'a` is the type of the semantic value that will eventually be produced if the parser succeeds.

`Accepted` and `Rejected` are final checkpoints. `Accepted` carries a semantic value.

`InputNeeded` is an intermediate checkpoint. It means that the parser wishes to read one token before continuing.

`Shifting` is an intermediate checkpoint. It means that the parser is taking a shift transition. It exposes the state of the parser before and after the transition. The Boolean parameter tells whether the parser intends to request a new token after this transition. (It always does, except when it is about to accept.)

`AboutToReduce` is an intermediate checkpoint: it means that the parser is about to perform a reduction step. `HandlingError` is also an intermediate checkpoint: it means that the parser has detected an error and is about to handle it. (Error handling is typically performed in several steps, so the next checkpoint is likely to be `HandlingError` again.) In these two cases, the parser does not need more input. The parser suspends itself at this point only in order to give the user an opportunity to observe the parser's transitions and possibly handle errors in a different manner, if desired.

```
val offer:
  'a checkpoint ->
  token * position * position ->
  'a checkpoint
```

The function `offer` allows the user to resume the parser after the parser has suspended itself with a checkpoint of the form `InputNeeded env`. This function expects the previous checkpoint `checkpoint` as well as a new token (together with the start and end positions of this token). It produces a new checkpoint, which again can be an intermediate checkpoint or a final checkpoint. It does not raise any exception. (The exception `Error` is used only in the monolithic API.)

```
val resume:
```

```
  ?strategy:[ `Legacy | `Simplified ] ->
  'a checkpoint ->
  'a checkpoint
```

The function `resume` allows the user to resume the parser after the parser has suspended itself with a checkpoint of the form `Shifting _` or `AboutToReduce _` or `HandlingError _`. This function expects just the previous checkpoint `checkpoint`. It produces a new checkpoint. It does not raise any exception. The optional argument `strategy` influences the manner in which `resume` deals with checkpoints of the form `HandlingError _`. Its default value is `` `Legacy ``. For more details, see §10.

The incremental API subsumes the monolithic API. Indeed, `main` can be (and is in fact) implemented by first using `Incremental.main`, then calling `offer` and `resume` in a loop, until a final checkpoint is obtained.

```
type supplier =
  unit -> token * position * position
```

A token supplier is a function of no arguments which delivers a new token (together with its start and end positions) every time it is called. The function `loop` and its variants, described below, expect a supplier as an argument.

```
val lexer_lexbuf_to_supplier:
  (Lexing.lexbuf -> token) -> Lexing.lexbuf -> supplier
```

The function `lexer_lexbuf_to_supplier`, applied to a lexer and to a lexing buffer, produces a fresh supplier.

The functions `offer` and `resume`, documented above, are sufficient to write a parser loop. One can imagine many variations of such a loop, which is why we expose `offer` and `resume` in the first place. Nevertheless, some variations are so common that it is worth providing them, ready for use. The following functions are implemented on top of `offer` and `resume`.

```
val loop:
  ?strategy:[ `Legacy | `Simplified ] ->
  supplier -> 'a checkpoint -> 'a
```

`loop supplier checkpoint` begins parsing from `checkpoint`, reading tokens from `supplier`. It continues parsing until it reaches a checkpoint of the form `Accepted v` or `Rejected`. In the former case, it returns `v`. In the latter case, it raises the exception `Error`. (By the way, this is how we implement the monolithic API on top of the incremental API.) The optional argument `strategy` influences the manner in which `loop` deals with checkpoints of the form `HandlingError _`. Its default value is `` `Legacy ``. For more details, see §10.

```
val loop_handle:
  ('a -> 'answer) ->
  ('a checkpoint -> 'answer) ->
  supplier -> 'a checkpoint -> 'answer
```

`loop_handle succeed fail supplier checkpoint` begins parsing from `checkpoint`, reading tokens from `supplier`. It continues until it reaches a checkpoint of the form `Accepted v` or `HandlingError _` (or `Rejected`, but that should not happen, as `HandlingError _` will be observed first). In the former case, it calls `succeed v`. In the latter case, it calls `fail` with this checkpoint. It cannot raise `Error`.

This means that Menhir's traditional error-handling procedure (which pops the stack until a state that can act on the **error** token is found) does not get a chance to run. Instead, the user can implement her own error-handling code, in the `fail` continuation.

```
val loop_handle_undo:
```

```
('a -> 'answer) ->
('a checkpoint -> 'a checkpoint -> 'answer) ->
supplier -> 'a checkpoint -> 'answer
```

`loop_handle_undo` is analogous to `loop_handle`, but passes a pair of checkpoints (instead of a single checkpoint) to the failure continuation. The first (and oldest) checkpoint that is passed to the failure continuation is the last `InputNeeded` checkpoint that was encountered before the error was detected. The second (and newest) checkpoint is where the error was detected. (This is the same checkpoint that `loop_handle` would pass to its failure continuation.) Going back to the first checkpoint can be thought of as undoing any reductions that were performed after seeing the problematic token. (These reductions must be default reductions or spurious reductions.) This can be useful to someone who wishes to implement an error explanation or error recovery mechanism.

`loop_handle_undo` must be applied to an `InputNeeded` checkpoint. The initial checkpoint produced by `Incremental.main` is of this form.

```
val shifts: 'a checkpoint -> 'a env option
```

`shifts checkpoint` assumes that `checkpoint` has been obtained by submitting a token to the parser. It runs the parser from `checkpoint`, through an arbitrary number of reductions, until the parser either accepts this token (i.e., shifts) or rejects it (i.e., signals an error). If the parser decides to shift, then `Some env` is returned, where `env` is the parser's state just before shifting. Otherwise, `None` is returned. This can be used to test whether the parser is willing to accept a certain token. This function should be used with caution, though, as it causes semantic actions to be executed. It is desirable that all semantic actions be side-effect-free, or that their side-effects be harmless.

```
val acceptable: 'a checkpoint -> token -> position -> bool
```

`acceptable checkpoint token pos` requires `checkpoint` to be an `InputNeeded` checkpoint. It returns `true` iff the parser is willing to shift this token. This can be used to test, after an error has been detected, which tokens would have been accepted at this point. To do this, one would typically use `loop_handle_undo` to get access to the last `InputNeeded` checkpoint that was encountered before the error was detected, and apply `acceptable` to that checkpoint.

`acceptable` is implemented using `shifts`, so, like `shifts`, it causes certain semantic actions to be executed. It is desirable that all semantic actions be side-effect-free, or that their side-effects be harmless.

9.2.3 Inspecting the parser's state

Although the type `env` is opaque, a parser state can be inspected via a few accessor functions, which are described in this section. The following types and functions are contained in the `MenhirInterpreter` submodule.

```
type 'a lr1state
```

The abstract type `'a lr1state` describes a (non-initial) state of the LR(1) automaton. If `s` is such a state, then `s` should have at least one incoming transition, and all of its incoming transitions carry the same (terminal or nonterminal) symbol, say A. We say that A is the *incoming symbol* of the state `s`. The index `'a` is the type of the semantic values associated with A. The role played by `'a` is clarified in the definition of the type `element`, which appears further on.

```
val number: _ lr1state -> int
```

The states of the LR(1) automaton are numbered (from 0 and up). The function `number` maps a state to its number.

```
val production_index: production -> int
val find_production: int -> production
```

Productions are numbered. (The set of indices of all productions forms an interval, which does *not* necessarily begin at 0.) The function `production_index` converts a production to an integer number, whereas the function `find_production` carries out the reverse conversion. It is an error to apply `find_production` to an invalid index.

```
type element =
  | Element: 'a lr1state * 'a * position * position -> element
```

The type `element` describes one entry in the stack of the LR(1) automaton. In a stack element of the form `Element (s, v, startp, endp)`, `s` is a (non-initial) state and `v` is a semantic value. The value `v` is associated with the incoming symbol A of the state `s`. In other words, the value `v` was pushed onto the stack just before the state `s` was entered. Thus, for some type `'a`, the state `s` has type `'a lr1state` and the value `v` has type `'a`. The positions `startp` and `endp` delimit the fragment of the input text that was reduced to the symbol A.

In order to do anything useful with the value `v`, one must gain information about the type `'a`, by inspection of the state `s`. So far, the type `'a lr1state` is abstract, so there is no way of inspecting `s`. The inspection API (§9.3) offers further tools for this purpose.

```
val top: 'a env -> element option
```

`top env` returns the parser's top stack element. The state contained in this stack element is the current state of the automaton. If the stack is empty, `None` is returned. In that case, the current state of the automaton must be an initial state.

```
val pop_many: int -> 'a env -> 'a env option
```

`pop_many i env` pops `i` elements off the automaton's stack. This is done via `i` successive invocations of `pop`. Thus, `pop_many 1` is `pop`. The index `i` must be nonnegative. The time complexity is $O(i)$.

```
val get: int -> 'a env -> element option
```

`get i env` returns the parser's `i`-th stack element. The index `i` is 0-based: thus, `get 0` is `top`. If `i` is greater than or equal to the number of elements in the stack, `None` is returned. `get` is implemented using `pop_many` and `top`: its time complexity is $O(i)$.

```
val current_state_number: 'a env -> int
```

`current_state_number env` is the integer number of the automaton's current state. Although this number might conceivably be obtained via the functions `top` and `number`, using `current_state_number` is preferable, because this method works even when the automaton's stack is empty (in which case the current state is an initial state, and `top` returns `None`). This number can be passed as an argument to a `message` function generated by `menhir --compile-errors`.

```
val equal: 'a env -> 'a env -> bool
```

`equal env1 env2` tells whether the parser configurations `env1` and `env2` are equal in the sense that the automaton's current state is the same in `env1` and `env2` and the stack is *physically* the same in `env1` and `env2`. If `equal env1 env2` is `true`, then the sequence of the stack elements, as observed via `pop` and `top`, must be the same in `env1` and `env2`. Also, if `equal env1 env2` holds, then the checkpoints `input_needed env1` and `input_needed env2` must be equivalent. (The function `input_needed` is documented in §9.2.4.) The function `equal` has time complexity $O(1)$.

```
val positions: 'a env -> position * position
```

The function `positions` returns the start and end positions of the current lookahead token. If invoked in an initial state, this function returns a pair of twice the initial position that was passed as an argument to `main`.

```
val env_has_default_reduction: 'a env -> bool
val state_has_default_reduction: _ lr1state -> bool
```

When applied to an environment `env` taken from a checkpoint of the form `AboutToReduce (env, prod)`, the function `env_has_default_reduction` tells whether the reduction that is about to take place is a default reduction.

`state_has_default_reduction s` tells whether the state `s` has a default reduction. This includes the case where `s` is an accepting state.

9.2.4 Updating the parser's state

The functions presented in the previous section (§9.2.3) allow inspecting parser states of type `'a checkpoint` and `'a env`. However, so far, there are no functions for manufacturing new parser states, except `offer` and `resume`, which create new checkpoints by feeding tokens, one by one, to the parser.

In this section, a small number of functions are provided for manufacturing new parser states of type `'a env` and `'a checkpoint`. These functions allow going far back into the past and jumping ahead into the future, so to speak. In other words, they allow driving the parser in other ways than by feeding tokens into it. The functions `pop`, `force_reduction` and `feed` (part of the inspection API; see §9.3) construct values of type `'a env`. The function `input_needed` constructs values of type `'a checkpoint` and thereby allows resuming parsing in normal mode (via `offer`). Together, these functions can be used to implement error handling and error recovery strategies.

```
val pop: 'a env -> 'a env option
```

`pop env` returns a new environment, where the parser's top stack cell has been popped off. (If the stack is empty, `None` is returned.) This amounts to pretending that the (terminal or nonterminal) symbol that corresponds to this stack cell has not been read.

```
val force_reduction: production -> 'a env -> 'a env
```

`force_reduction prod env` can be called only if in the state `env` the parser is capable of reducing the production `prod`. If this condition is satisfied, then this production is reduced, which means that its semantic action is executed (this can have side effects!) and the automaton makes a goto (nonterminal) transition. If this condition is not satisfied, an `Invalid_argument` exception is raised.

```
val input_needed: 'a env -> 'a checkpoint
```

`input_needed env` returns `InputNeeded env`. Thus, out of a parser state that might have been obtained via a series of calls to the functions `pop`, `force_reduction`, `feed`, and so on, it produces a checkpoint, which can be used to resume normal parsing, by supplying this checkpoint as an argument to `offer`.

This function should be used with some care. It could "mess up the lookahead" in the sense that it allows parsing to resume in an arbitrary state `s` with an arbitrary lookahead symbol `t`, even though Menhir's reachability analysis (which is carried out via the `--list-errors` switch) might well think that it is impossible to reach this particular configuration. If one is using Menhir's new error reporting facility (§11), this could cause the parser to reach an error state for which no error message has been prepared.

9.3 Inspection API

If `--inspection` is set, Menhir offers an inspection API in addition to the monolithic and incremental APIs. (The reason why this is not done by default is that this requires more tables to be generated, thus

making the generated parser larger.) Like the incremental API, the inspection API is found in the sub-module `MenhirInterpreter`. It offers the following types and functions.

The type `'a terminal` is a generalized algebraic data type (GADT). A value of type `'a terminal` represents a terminal symbol (without a semantic value). The index `'a` is the type of the semantic values associated with this symbol. For instance, if the grammar contains the declarations `%token A` and `%token<int> B`, then the generated module `MenhirInterpreter` contains the following definition:

```
type _ terminal =
| T_A : unit terminal
| T_B : int terminal
```

The data constructors are named after the terminal symbols, prefixed with "`T_`".

The type `'a nonterminal` is also a GADT. A value of type `'a nonterminal` represents a nonterminal symbol (without a semantic value). The index `'a` is the type of the semantic values associated with this symbol. For instance, if `main` is the only nonterminal symbol, then the generated module `MenhirInterpreter` contains the following definition:

```
type _ nonterminal =
| N_main : thing nonterminal
```

The data constructors are named after the nonterminal symbols, prefixed with "`N_`".

The type `'a symbol` is the disjoint union of the types `'a terminal` and `'a nonterminal`. In other words, a value of type `'a symbol` represents a terminal or nonterminal symbol (without a semantic value). This type is (always) defined as follows:

```
type 'a symbol =
  | T : 'a terminal -> 'a symbol
  | N : 'a nonterminal -> 'a symbol
```

The type `xsymbol` is an existentially quantified version of the type `'a symbol`. It is useful in situations where the index `'a` is not statically known. It is (always) defined as follows:

```
type xsymbol =
  | X : 'a symbol -> xsymbol
```

The type `item` describes an LR(0) item, that is, a pair of a production `prod` and an index `i` into the right-hand side of this production. If the length of the right-hand side is `n`, then `i` is comprised between 0 and `n`, inclusive.

```
type item =
    production * int
```

The following functions implement total orderings on the types `_ terminal`, `_ nonterminal`, `xsymbol`, `production`, and `item`.

```
val compare_terminals: _ terminal -> _ terminal -> int
val compare_nonterminals: _ nonterminal -> _ nonterminal -> int
val compare_symbols: xsymbol -> xsymbol -> int
val compare_productions: production -> production -> int
val compare_items: item -> item -> int
```

The function `incoming_symbol` maps a (non-initial) LR(1) state `s` to its incoming symbol, that is, the symbol that the parser must recognize before it enters the state `s`.

```
val incoming_symbol: 'a lr1state -> 'a symbol
```

This function can be used to gain access to the semantic value `v` in a stack element `Element (s, v, _, _)`. Indeed, by case analysis on the symbol `incoming_symbol s`, one gains information about the type `'a`, hence one obtains the ability to do something useful with the value `v`.

The function `items` maps a (non-initial) LR(1) state `s` to its LR(0) *core*, that is, to the underlying set of LR(0) items. This set is represented as a list, whose elements appear in an arbitrary order. This set is *not* closed under ϵ-transitions.

```
val items: _ lr1state -> item list
```

The functions `lhs` and `rhs` map a production `prod` to its left-hand side and right-hand side, respectively. The left-hand side is always a nonterminal symbol, hence always of the form `N _`. The right-hand side is a (possibly empty) sequence of (terminal or nonterminal) symbols.

```
val lhs: production -> xsymbol
val rhs: production -> xsymbol list
```

The function `nullable`, applied to a nonterminal symbol, tells whether this symbol is nullable. A nonterminal symbol is nullable if and only if it produces the empty word ϵ.

```
val nullable: _ nonterminal -> bool
```

The function call `first nt t` tells whether the *FIRST* set of the nonterminal symbol `nt` contains the terminal symbol `t`. That is, it returns `true` if and only if `nt` produces a word that begins with `t`. The function `xfirst` is identical to `first`, except it expects a first argument of type `xsymbol` instead of `_ terminal`.

```
val first: _ nonterminal -> _ terminal -> bool
val xfirst: xsymbol -> _ terminal -> bool
```

The function `foreach_terminal` enumerates the terminal symbols, including the special symbol **error**. The function `foreach_terminal_but_error` enumerates the terminal symbols, excluding **error**.

```
val foreach_terminal:           (xsymbol -> 'a -> 'a) -> 'a -> 'a
val foreach_terminal_but_error: (xsymbol -> 'a -> 'a) -> 'a -> 'a
```

`feed symbol startp semv endp env` causes the parser to consume the (terminal or nonterminal) symbol `symbol`, accompanied with the semantic value `semv` and with the start and end positions `startp` and `endp`. Thus, the automaton makes a transition, and reaches a new state. The stack grows by one cell. This operation is permitted only if the current state (as determined by `env`) has an outgoing transition labeled with `symbol`. Otherwise, an `Invalid_argument` exception is raised.

```
val feed: 'a symbol -> position -> 'a -> position -> 'b env -> 'b env
```

9.4 Unparsing API

The purpose of parsing is to transform a sequence of characters, or a sequence of tokens, into a semantic value, which typically is some kind of syntax tree. The purpose of *unparsing* is to perform the reverse transformation, that is, to transform a syntax tree back into a sequence of tokens or characters.

Although unparsing may not seem conceptually very challenging, writing an unparser by hand can require a significant amount of work. Furthermore, ensuring that an unparser is correct can be difficult. An unparser is correct if its output can be parsed and if this gives rise to the same syntax tree that one started with. In other words, it is correct if the composition $unparse; parse$ is the identity. Intuitively, this means that the unparser must produce syntactically correct output and must insert enough parentheses (or other disambiguation symbols) to ensure that its output is correctly interpreted. If the grammar involves priority or precedence declarations (§4.1.4, §4.2.1), enforcing this property can be tricky.

When the switch `--unparsing` is supplied on the command line, Menhir generates code that helps implement a correct unparser. In this reference manual, we give a brief overview of the generated code; for more

details, the reader is referred to the paper "Correct, Fast LR(1) Unparsing" [26]. Furthermore, the directory `demos/calc-unparsing` contains a demo that illustrates the use of the unparsing API. In this directory, the command `make api` shows the file `parser.mli` generated by Menhir.

The unparsing API involves two distinct data structures, namely *disjunctive concrete syntax trees* and *concrete syntax trees*.

- A *concrete syntax tree* (CST) is a tree where every node is either a *terminal node*, labeled with a token, or a *nonterminal node*, labeled with a production. A terminal node has no children. A nonterminal node has children whose number and types must match the right-hand side of the production.
- A *disjunctive concrete syntax tree* (DCST) contains terminal nodes, nonterminal nodes, and *disjunction nodes*. A disjunction node has two children. It represents a choice between two possible descriptions of a subtree: for example, without or with surrounding parentheses.

The unparsing API expects the unparsing process to be performed in three steps, as follows:

1. an abstract syntax tree (or, more generally, a semantic value) is transformed into a DCST;
2. the DCST is transformed into a CST;
3. the CST is transformed into text, either directly, or by going through some form of structured document.

The facilities provided by the unparsing API are:

- a DCST construction API (a set of constructor functions) ;
- a *settlement* algorithm, which converts a DCST to a CST;
- a CST deconstruction API (a visitor class).

The settlement algorithm performs step 2 automatically. It is up to you, the user, to implement steps 1 and 2. In step 2, you use the DCST construction API. In step 3, you use the CST deconstruction API.

9.4.1 DCST construction API

The DST construction API is found in the sub-module `DCST`. It offers a set of constructor functions that you can use to construct DCSTs. OCaml's type discipline ensures that only well-formed DCSTs can be constructed; this rules out a class of mistakes that would lead to syntactically incorrect output.

- For each nonterminal symbol, say `expr`, there is an abstract type of DCSTs, also named `expr`.

  ```
  type expr
  ```

- For each production, there is a constructor function, whose name is determined by the production's `@name` attribute. This constructor function takes parameters whose number and types match the right-hand side of the production. If a parameter corresponds to a terminal symbol that does not carry a semantic value, then this parameter is omitted. For instance, if the grammar includes a production of the form

  ```
  expr:
    LPAREN; e = expr; RPAREN { e } [@name paren]
  ```

  then the sub-module `DCST` includes a constructor function

  ```
  val paren: expr -> expr
  ```

- For each nonterminal symbol, say `expr`, there is a constructor function, named `expr_choice`, that constructs a disjunction node.

  ```
  val expr_choice: expr -> expr -> expr
  ```

9.4.2 Settlement

For each start nonterminal symbol, say `main`, there is a function, named `Settle.main`, which transforms a DCST to a CST.

```
val main: DCST.main -> CST.main option
```

This transformation eliminates all disjunction nodes. In other words, whenever there is a choice between several ways of displaying a subtree (for example, without or with surrounding parentheses), this choice is resolved. The settlement algorithm is left-biased: if the left-hand alternative leads to a viable tree (that is, a tree that can be printed and parsed again, without confusion) then this alternative is chosen; otherwise, the right-hand alternative is chosen.

If the algorithm is unable to find a viable tree, then it fails: it returns `None`. If you encounter this situation, first make sure that in the previous step (step 1) you have inserted enough parentheses, or constructed enough disjunction nodes that offer a possibility of inserting parentheses. If you think that you have done so, and if the algorithm still fails, please contact Menhir's developers. As explained in the paper [26], the settlement algorithm is fast but incomplete. When faced with a disjunction node, it commits early to the left-hand alternative. If this alternative later turns out to fail, then the algorithm does not backtrack; the right-hand alternative is never tried.

9.4.3 CST deconstruction API

The CST deconstruction API is found in the sub-module `CST`. It offers a visitor class, named `reduce`, which allows traversing a CST and transforming it into a printable form. This printable form could be text, or could be a document in a a structured document description language; it is up to the user to choose it.

For each nonterminal symbol, say `expr`, there is an abstract type of CSTs, also named `expr`.

```
type expr
```

Then, there is a single visitor class:

```
class virtual ['r] reduce : object
  method virtual zero : 'r
  method virtual cat : 'r -> 'r -> 'r
  method virtual text : string -> 'r
  (* one method per terminal symbol *)
  (* one method per nonterminal symbol *)
  (* one method per production *)
end
```

This class is parameterized by a type `'r`, which is the result type of every method: it is the type of the printable form to which every tree must be reduced.

The user is expected to provide implementations for the three virtual methods `zero`, `cat`, and `text`. In short, `zero` is the empty printable thing; `cat` concatenates two printable things; and `text` converts a string to a printable thing.

Furthermore, the following methods exist:

- For each terminal symbol, there is a visitor method. For example, if the token `INT` has been declared by `%token<int> INT` then the following method exists:

  ```
  method virtual visit_INT : int -> 'r
  ```

  This method is normally virtual. However, if the terminal symbol carries no semantic value and if a token alias (§4.1.3) has been provided by the user for this symbol then a default implementation of this method is generated by Menhir; the method is then non-virtual. For example, if the token `LPAREN` has been declared by `%token LPAREN "("` then the following non-virtual method exists:

  ```
  method visit_LPAREN : 'r
  ```

- For each nonterminal symbol, say `expr`, there is a visitor method, named `visit_expr`. This method is not virtual: Menhir generates code for it. This method expects a CST of type `expr` as an argument, performs a case analysis of the root node, and applies a suitable `case` method to the children of the root node.

```
method visit_expr : expr -> 'r
```

- For each production, there is a visitor method. This method is not virtual: Menhir generates code for it. This method expects zero, one, or more arguments. First, each argument is reduced to a printable thing via recursive calls to suitable `visit` methods; then these printable things are concatenated using `zero` and `cat`. For instance, if the grammar includes a production of the form

```
expr:
  LPAREN; e = expr; RPAREN { e } [@name paren]
```

then the following method exists:

```
method case_paren : expr -> 'r
```

10. Error handling: the traditional way

Menhir's traditional error-handling mechanism is considered deprecated: although it is still supported for the time being, it is likely to be removed in the future. We recommend setting up an error-handling mechanism using the new tools offered by Menhir (§11).

Error handling Menhir's error traditional handling mechanism is inspired by that of `yacc` and `ocamlyacc`, but is not identical. A special **error** token is made available for use within productions. The LR automaton is constructed exactly as if **error** was a regular terminal symbol. However, **error** is never produced by the lexical analyzer. Instead, when an error is detected, the current lookahead token is discarded and replaced with the **error** token, which becomes the current lookahead token. At this point, the parser enters *error handling* mode. In error-handling mode, the parser behaves as follows:

- If the current state has a shift action on the **error** token, then this action takes place. Under the `legacy` strategy, the parser then reads the next token and returns to normal mode. Under the simplified strategy, it does *not* request the next token, so the current token remains **error**, and the parser remains in error-handling mode.[2]
- If the current state has a reduce action on the **error** token, then this action takes place. (This behavior differs from that of `yacc` and `ocamlyacc`, which do not reduce on **error**. It is somewhat unclear why not.) The current token remains **error** and the parser remains in error-handling mode.
- If the current state has no action on the **error** token, then, under the simplified strategy, the parser rejects the input. Under the `legacy` strategy, the parser pops a cell off its stack and remains in error-handling mode. If the stack is empty, then the parser rejects the input.

In the monolithic API, the parser rejects the input by raising the exception `Error`. This exception carries no information. The position of the error can be obtained by reading the lexical analyzer's environment record. In the incremental API, the parser rejects the input by returning the checkpoint `Rejected`.

Which strategy should one choose? First, let us note that the difference between the strategies `legacy` and `simplified` matters only if the grammar uses the **error** token. The following rule of thumb can be used to select between them:

- If the **error** token is used only to catch an error and stop, then the `simplified` strategy should be preferred. When this strategy is selected, the **error** token should always appear at the end of a production, whose semantic action should abort the parser by raising an exception. (Menhir checks that the **error** token is used only at the end of productions. It cannot statically check that the semantic action raises an exception, but it may insert a runtime check.)
- If the **error** token is used to survive an error and continue parsing, then the legacy strategy should be selected.

[2] In the simplified strategy, once the parser enters error-handling mode, it remains in error-handling mode forever. Thus, the input stream is effectively discarded and replaced with an infinite stream of **error** tokens.

Error recovery `ocamlyacc` offers an error recovery mode, which is entered immediately after an **error** token was successfully shifted. In this mode, tokens are repeatedly taken off the input stream and discarded until an acceptable token is found. This feature is no longer offered by Menhir.

11. Error handling: the new way

Menhir's incremental API (§9.2) allows taking control when an error is detected. Indeed, as soon as an invalid token is detected, the parser produces a checkpoint of the form `HandlingError _`. At this point, if one decides to let the parser proceed, by just calling `resume`, then Menhir enters its traditional error-handling mode (§10). Instead, however, one can decide to take control and perform error handling or error recovery in any way one pleases. One can, for instance, build and display a diagnostic message, based on the automaton's current stack and/or state. Or, one could modify the input stream, by inserting or deleting tokens, so as to suppress the error, and resume normal parsing. In principle, the possibilities are endless.

An apparently simple-minded approach to error reporting, proposed by Jeffery [11] and further explored by Pottier [25], consists in selecting a diagnostic message (or a template for a diagnostic message) based purely on the current state of the automaton.

In this approach, one determines, ahead of time, which are the "error states" (that is, the states in which an error can be detected), and one prepares, for each error state, a diagnostic message. Because state numbers are fragile (they change when the grammar evolves), an error state is identified not by its number, but by an input sentence that leads to it: more precisely, by an input sentence which causes an error to be detected in this state. Thus, one maintains a set of pairs of an erroneous input sentence and a diagnostic message.

Menhir defines a file format, the `.messages` file format, for representing this information (§11.1), and offers a set of tools for creating, maintaining, and exploiting `.messages` files (§11.2). Once one understands these tools, there remains to write a collection of diagnostic messages, a more subtle task than one might think (§11.3), and to glue everything together (§11.4).

In this approach to error handling, as in any other approach, one must understand exactly when (that is, in which states) errors are detected. This in turn requires understanding how the automaton is constructed. Menhir's construction technique is not Knuth's canonical LR(1) technique [16], which is usually too expensive to be practical. Instead, Menhir *merges* states [24] and introduces so-called *default reductions*. These techniques *defer* error detection by allowing extra reductions to take place before an error is detected. The impact of these alterations must be taken into account when writing diagnostic messages (§11.3).

In this approach to error handling, the special **error** token is not used. It should not appear in the grammar.

11.1 The `.messages` file format

Definition A `.messages` file is a text file. It is composed of a list of entries. Each entry consists of one or more input sentences, followed with one or more blank lines, followed with a message. Two entries are separated by one or more blank lines. The syntax of an input sentence is described in §8.1. A message is an arbitrary piece of text, but cannot cannot a blank line.

Blank lines are significant: they are used as separators, both between entries, and (within an entry) between the sentences and the message. Thus, there cannot be a blank line between two sentences. (If there is one, Menhir becomes confused and may complain about some word not being "a known nonterminal symbol"). There also cannot be a blank line inside a message.

As an example, Figure 16 shows a valid entry, taken from Menhir's own `.messages` file. This entry contains two input sentences, which lead to errors in two distinct states. A single message is associated with these two error states.

Comments Comment lines, which begin with a `#` character, are ignored everywhere. However, users who wish to take advantage of Menhir's facility for merging two `.messages` files (§11.2) should follow certain conventions regarding the placement of comments:

```
grammar: TYPE UID
# This hand-written comment concerns just the sentence above.
grammar: TYPE OCAMLTYPE UID PREC
# This hand-written comment concerns just the sentence above.

# This hand-written comment concerns both sentences above.

Ill-formed declaration.
Examples of well-formed declarations:
  %type <Syntax.expression> expression
  %type <int> date time
```

Figure 16. An entry in a `.messages` file

```
grammar: TYPE UID
##
## Ends in an error in state: 1.
##
## declaration -> TYPE . OCAMLTYPE separated_nonempty_list(option(COMMA),
##   strict_actual) [ TYPE TOKEN START RIGHT PUBLIC PERCENTPERCENT PARAMETER
##   ON_ERROR_REDUCE NONASSOC LEFT INLINE HEADER EOF COLON ]
##
## The known suffix of the stack is as follows:
## TYPE
##
# This hand-written comment concerns just the sentence above.
#
grammar: TYPE OCAMLTYPE UID PREC
##
## Ends in an error in state: 5.
##
## strict_actual -> symbol . loption(delimited(LPAREN,separated_nonempty_list
##   (COMMA,strict_actual),RPAREN)) [ UID TYPE TOKEN START STAR RIGHT QUESTION
##   PUBLIC PLUS PERCENTPERCENT PARAMETER ON_ERROR_REDUCE NONASSOC LID LEFT
##   INLINE HEADER EOF COMMA COLON ]
##
## The known suffix of the stack is as follows:
## symbol
##
# This hand-written comment concerns just the sentence above.

# This hand-written comment concerns both sentences above.

Ill-formed declaration.
Examples of well-formed declarations:
  %type <Syntax.expression> expression
  %type <int> date time
```

Figure 17. An entry in a `.messages` file, decorated with auto-generated comments

- If a comment concerns a specific sentence and should remain attached to this sentence, then it must immediately follow this sentence (without a blank line in between).
- If a comment concerns all sentences in an entry, then it should appear between the sentences and the message, with blank lines in between.
- One should avoid placing comments between two entries, as the merging algorithm will not be able to handle them in a satisfactory way.

Auto-generated comments Several commands, described next (§11.2), produce `.messages` files where each input sentence is followed with an auto-generated comment, marked with `##`. This special comment indicates in which state the error is detected, and is supposed to help the reader understand what it means to be in this state: What has been read so far? What is expected next?

As an example, the previous entry, decorated with auto-generated comments, is shown in Figure 17. (We have manually wrapped the lines that did not fit in this document.)

An auto-generated comment begins with the number of the error state that is reached via this input sentence.

Then, the auto-generated comment shows the LR(1) items that compose this state, in the same format as in an `.automaton` file. these items offer a description of the past (that is, what has been read so far) and the future (that is, which terminal symbols are allowed next).

Finally, the auto-generated comment shows what is known about the stack when the automaton is in this state. (This can be deduced from the LR(1) items, but is more readable if shown separately.)

In a canonical LR(1) automaton, the LR(1) items offer an exact description of the past and future. However, in a noncanonical automaton, which is by default what Menhir produces, the situation is more subtle. The lookahead sets can be over-approximated, so the automaton can perform one or more "spurious reductions" before an error is detected. As a result, the LR(1) items in the error state offer a description of the future that may be both incorrect (that is, a terminal symbol that appears in a lookahead set is not necessarily a valid continuation) and incomplete (that is, a terminal symbol that does not appear in any lookahead set may nevertheless be a valid continuation). More details appear further on (§11.3).

In order to attract the user's attention to this issue, if an input sentence causes one or more spurious reductions, then the auto-generated comment contains a warning about this fact. This mechanism is not completely foolproof, though, as it may be the case that one particular sentence does not cause any spurious reductions (hence, no warning appears), yet leads to an error state that can be reached via other sentences that do involve spurious reductions.

11.2 Maintaining `.messages` files

Ideally, the set of input sentences in a `.messages` file should be correct (that is, every sentence causes an error on its last token), irredundant (that is, no two sentences lead to the same error state), and complete (that is, every error state is reached by some sentence).

Verifying correctness and irredundancy The correctness and irredundancy of a `.messages` file are checked by supplying `--compile-errors` *filename* on the command line, where *filename* is the name of the `.messages` file. (These arguments must be supplied in addition to the other usual arguments, such as the name of the `.mly` file.) This command fails if a sentence does not cause an error at all, or causes an error too early. It also fails if two sentences lead to the same error state. If the file is correct and irredundant, then (as its name suggests) this command compiles the `.messages` file down to an OCaml function, whose code is printed on the standard output channel. This function, named `message`, has type `int -> string`, and maps a state number to a message. It raises the exception `Not_found` if its argument is not the number of a state for which a message has been defined. If the set of input sentences is complete, then it cannot raise `Not_found`.

Verifying completeness The completeness of a `.messages` file is checked via the commands `--list-errors` and `--compare-errors`. The former produces, from scratch, a complete set of input sentences, that is, a set of

input sentences that reaches all error states. The latter compares two sets of sentences (more precisely, the two underlying sets of error states) for inclusion.

The command `--list-errors` first computes all possible ways of causing an error. From this information, it deduces a list of all error states, that is, all states where an error can be detected. For each of these states, it computes a (minimal) input sentence that causes an error in this state. Finally, it prints these sentences, in the `.messages` file format, on the standard output channel. Each sentence is followed with an auto-generated comment and with a dummy diagnostic message. The user should be warned that this algorithm may require large amounts of time (typically in the tens of seconds, possibly more) and memory (typically in the gigabytes, possibly more). It requires a 64-bit machine. (On a 32-bit machine, it works, but quickly hits a built-in size limit.) At the verbosity level `--log-automaton 2`, it displays some progress information and internal statistics on the standard error channel.

The command `--compare-errors` *filename1* `--compare-errors` *filename2* compares the `.messages` files *filename1* and *filename2*. Each file is read and internally translated to a mapping of states to messages. Menhir then checks that the left-hand mapping is a subset of the right-hand mapping. That is, if a state s is reached by some sentence in *filename1*, then it should also be reached by some sentence in *filename2*. Furthermore, if the message associated with s in *filename1* is not a dummy message, then the same message should be associated with s in *filename2*.

To check that the sentences in *filename2* cover all error states, it suffices to (1) use `--list-errors` to produce a complete set of sentences, which one stores in *filename1*, then (2) use `--compare-errors` to compare *filename1* and *filename2*.

In the case of a grammar that evolves fairly often, it can take significant human time and effort to update the `.messages` file and ensure correctness, irredundancy, and completeness. A tempting way of reducing this effort is to abandon completeness. This implies that the auto-generated `message` function can raise `Not_found` and that a generic "syntax error" message must be produced in that case. We prefer to discourage this approach, as it implies that the end user is exposed to a mixture of specific and generic syntax error messages, and there is no guarantee that the specific (hand-written) messages will appear in *all* situations where they are expected to appear. Instead, we recommend waiting for the grammar to become stable and enforcing completeness.

Merging `.messages` ***files*** The command `--merge-errors` *filename1* `--merge-errors` *filename2* attempts to merge the `.messages` files *filename1* and *filename2*, and prints the result on the standard output channel. This command can be useful if two users have worked independently and each of them has produced a `.messages` file that covers a subset of all error states. The merging algorithm works roughly as follows:

- All entries in *filename2* are preserved literally.
- An entry in *filename1* that contains the dummy message `<YOUR SYNTAX ERROR MESSAGE HERE>` is ignored.
- An entry in *filename1* that leads to a state for which there is no entry in *filename2* is copied to *filename2*.
- An entry in *filename1* that leads to a state for which there is also an entry in *filename2*, with a distinct message, gives rise to a conflict. It is inserted into *filename2* together with a comment that signals the conflict.

The algorithm is asymmetric: the content of *filename1* is inserted into or appended to *filename2*. For this reason, if one of the files is a large "reference" file and the other file is a small "delta", then it is recommended to provide the "delta" as *filename1* and the "reference" as *filename2*.

Other commands The command `--update-errors` *filename* is used to update the auto-generated comments in the `.messages` file *filename*. It is typically used after a change in the grammar (or in the command line options that affect the construction of the automaton). A new `.messages` file is produced on the standard output channel. It is identical to *filename*, except the auto-generated comments, identified by `##`, have been removed and re-generated.

The command `--echo-errors` *filename* is used to filter out all comments, blank lines, and messages from the `.messages` file *filename*. The input sentences, and nothing else, are echoed on the standard output channel.

```
%token ID ARROW LPAREN RPAREN COLON SEMICOLON
%start<unit> program
%%
typ0: ID | LPAREN typ1 RPAREN {}
typ1: typ0 | typ0 ARROW typ1  {}
declaration: ID COLON typ1    {}
program:
| LPAREN declaration RPAREN
| declaration SEMICOLON       {}
```

Figure 18. A grammar where one error state is difficult to explain

```
program: ID COLON ID LPAREN
##
## Ends in an error in state: 8.
##
## typ1 -> typ0 . [ SEMICOLON RPAREN ]
## typ1 -> typ0 . ARROW typ1 [ SEMICOLON RPAREN ]
##
## The known suffix of the stack is as follows:
## typ0
##
```

Figure 19. A problematic error state in the grammar of Figure 18, due to over-approximation

As an example application, one could then translate the sentences to concrete syntax and create a collection of source files that trigger every possible syntax error.

The command `--interpret-error` is analogous to `--interpret`. It causes Menhir to act as an interpreter. Menhir reads sentences off the standard input channel, parses them, and displays the outcome. This switch can be usefully combined with `--trace`. The main difference between `--interpret` and `--interpret-error` is that, when the latter command is used, Menhir expects the input sentence to cause an error on its last token, and displays information about the state in which the error is detected, in the form of a `.messages` file entry. This can be used to quickly find out exactly what error is caused by one particular input sentence.

11.3 Writing accurate diagnostic messages

One might think that writing a diagnostic message for each error state is a straightforward (if lengthy) task. In reality, it is not so simple.

A state, not a sentence The first thing to keep in mind is that a diagnostic message is associated with a *state* s, as opposed to a sentence. An entry in a `.messages` file contains a sentence w that leads to an error in state s. This sentence is just one way of causing an error in state s; there may exist many other sentences that also cause an error in this state. The diagnostic message should not be specific of the sentence w: it should make sense regardless of how the state s is reached.

As a rule of thumb, when writing a diagnostic message, one should (as much as possible) ignore the example sentence w altogether, and concentrate on the description of the state s, which appears as part of the auto-generated comment.

The LR(1) items that compose the state s offer a description of the past (that is, what has been read so far) and the future (that is, which terminal symbols are allowed next). A diagnostic message should be designed based on this description.

```
%token ID ARROW LPAREN RPAREN COLON SEMICOLON
%start<unit> program
%%
typ0: ID | LPAREN typ1(RPAREN) RPAREN          {}
typ1(phantom): typ0 | typ0 ARROW typ1(phantom) {}
declaration(phantom): ID COLON typ1(phantom)   {}
program:
| LPAREN declaration(RPAREN) RPAREN
| declaration(SEMICOLON)  SEMICOLON            {}
```

Figure 20. Splitting the problematic state of Figure 19 via selective duplication

The problem of over-approximated lookahead sets As pointed out earlier (§11.1), in a noncanonical automaton, the lookahead sets in the LR(1) items can be both over- and under-approximated. One must be aware of this phenomenon, otherwise one runs the risk of writing a diagnostic message that proposes too many or too few continuations.

As an example, let us consider the grammar in Figure 18. According to this grammar, a "program" is either a declaration between parentheses or a declaration followed with a semicolon. A "declaration" is an identifier, followed with a colon, followed with a type. A "type" is an identifier, a type between parentheses, or a function type in the style of OCaml.

The (noncanonical) automaton produced by Menhir for this grammar has 17 states. Using `--list-errors`, we find that an error can be detected in 10 of these 17 states. By manual inspection of the auto-generated comments, we find that for 9 out of these 10 states, writing an accurate diagnostic message is easy. However, one problematic state remains, namely state 8, shown in Figure 19.

In this state, a (level-0) type has just been read. One valid continuation, which corresponds to the second LR(1) item in Figure 19, is to continue this type: the terminal symbol `ARROW`, followed with a (level-1) type, is a valid continuation. Now, the question is, what other valid continuations are there? By examining the first LR(1) item in Figure 19, it may look as if both `SEMICOLON` and `RPAREN` are valid continuations. However, this cannot be the case. A moment's thought reveals that *either* we have seen an opening parenthesis `LPAREN` at the very beginning of the program, in which case we definitely expect a closing parenthesis `RPAREN`; *or* we have not seen one, in which case we definitely expect a semicolon `SEMICOLON`. It is *never* the case that *both* `SEMICOLON` and `RPAREN` are valid continuations!

In fact, the lookahead set in the first LR(1) item in Figure 19 is over-approximated. State 8 in the noncanonical automaton results from merging two states in the canonical automaton.

In such a situation, one cannot write an accurate diagnostic message. Knowing that the automaton is in state 8 does not give us a precise view of the valid continuations. Some valuable information (that is, whether we have seen an opening parenthesis `LPAREN` at the very beginning of the program) is buried in the automaton's stack.

How can one work around this problem? Let us suggest three options.

Blind duplication of states One option would be to build a canonical automaton by using the `--canonical` switch. In this example, one would obtain a 27-state automaton, where the problem has disappeared. However, this option is rarely viable, as it duplicates many states without good reason.

Selective duplication of states A second option is to manually cause just enough duplication to remove the problematic over-approximation. In our example, we wish to distinguish two kinds of types and declarations, namely those that must be followed with a closing parenthesis, and those that must be followed with a semicolon. We create such a distinction by parameterizing `typ1` and `declaration` with a phantom parameter. The modified grammar is shown in Figure 20. The phantom parameter does not affect the language that is accepted: for instance, the nonterminal symbols `declaration(SEMICOLON)` and `declaration(RPAREN)` generate the same language as `declaration` in the grammar of Figure 18. Yet, by giving distinct names to these two symbols, we

```
%token ID ARROW LPAREN RPAREN COLON SEMICOLON
%start<unit> program
%on_error_reduce typ1
%%
typ0: ID | LPAREN typ1 RPAREN {}
typ1: typ0 | typ0 ARROW typ1  {}
declaration: ID COLON typ1    {}
program:
| LPAREN declaration RPAREN
| declaration SEMICOLON       {}
```

Figure 21. Avoiding the problematic state of Figure 19 via reductions on error

```
program: ID COLON ID LPAREN
##
## Ends in an error in state: 15.
##
## program -> declaration . SEMICOLON [ # ]
##
## The known suffix of the stack is as follows:
## declaration
##
## WARNING: This example involves spurious reductions.
## This implies that, although the LR(1) items shown above provide an
## accurate view of the past (what has been recognized so far), they
## may provide an INCOMPLETE view of the future (what was expected next).
## In state 8, spurious reduction of production typ1 -> typ0
## In state 11, spurious reduction of production declaration -> ID COLON typ1
##
```

Figure 22. A problematic error state in the grammar of Figure 21, due to under-approximation

force the construction of an automaton where more states are distinguished. In this example, Menhir produces a 23-state automaton. Using `--list-errors`, we find that an error can be detected in 11 of these 23 states, and by manual inspection of the auto-generated comments, we find that for each of these 11 states, writing an accurate diagnostic message is easy. In summary, we have selectively duplicated just enough states so as to split the problematic error state into two non-problematic error states.

Reductions on error A third and last option is to introduce an `%on_error_reduce` declaration (§4.1.8) so as to prevent the detection of an error in the problematic state 8. We see in Figure 19 that, in state 8, the production `typ1` → `typ0` is ready to be reduced. If we could force this reduction to take place, then the automaton would move to some other state where it would be clear which of `SEMICOLON` and `RPAREN` is expected. We achieve this by marking `typ1` as "reducible on error". The modified grammar is shown in Figure 21. For this grammar, Menhir produces a 17-state automaton. (This is the exact same automaton as for the grammar of Figure 18, except 2 of the 17 states have received extra reduction actions.) Using `--list-errors`, we find that an error can be detected in 9 of these 17 states. The problematic state, namely state 8, is no longer an error state! The problem has vanished.

The problem of under-approximated lookahead sets The third option seems by far the simplest of all, and is recommended in many situations. However, it comes with a caveat. There may now exist states whose lookahead

sets are under-approximated, in a certain sense. Because of this, there is a danger of writing an incomplete diagnostic message, one that does not list all valid continuations.

To see this, let us look again at the sentence `ID COLON ID LPAREN`. In the grammar and automaton of Figure 18, this sentence takes us to the problematic state 8, shown in Figure 19. In the grammar and automaton of Figure 21, because more reduction actions are carried out before the error is detected, this sentence takes us to state 15, shown in Figure 22.

When writing a diagnostic message for state 15, one might be tempted to write: "Up to this point, a declaration has been recognized. At this point, a semicolon is expected". Indeed, by examining the sole LR(1) item in state 15, it looks as if `SEMICOLON` is the only permitted continuation. However, this is not the case. Another valid continuation is `ARROW`: indeed, the sentence `ID COLON ID ARROW ID SEMICOLON` forms a valid program. In fact, if the first token following `ID COLON ID` is `ARROW`, then in state 8 this token is shifted, so the two reductions that take us from state 8 through state 11 to state 15 never take place. This is why, even though `ARROW` does not appear in state 15 as a valid continuation, it nevertheless is a valid continuation of `ID COLON ID`. The warning produced by Menhir, shown in Figure 22, is supposed to attract attention to this issue.

Another way to explain this issue is to point out that, by declaring `%on_error_reduce typ1`, we make a choice. When the parser reads a type and finds an invalid token, it decides that this type is finished, even though, in reality, this type could be continued with `ARROW` .... This in turn causes the parser to perform another reduction and consider the current declaration finished, even though, in reality, this declaration could be continued with `ARROW` ....

In summary, when writing a diagnostic message for state 15, one should take into account the fact that this state can be reached via spurious reductions and (therefore) `SEMICOLON` may not be the only permitted continuation. One way of doing this, without explicitly listing all permitted continuations, is to write: "Up to this point, a declaration has been recognized. If this declaration is complete, then at this point, a semicolon is expected".

11.4 A working example

The demo `demos/calc-syntax-errors` illustrates this approach to error handling. It is based on the demo `demos/calc`, which involves a very simple grammar of arithmetic expressions. Compared with `demos/calc`, one **%on_error_reduce** declaration is added so as to reduce the number of error states. There remain just 9 error states, for which we write 5 distinct syntax error messages. These messages are stored in the file `demos/calc-syntax-errors/parserMessages.messages`. The file `demos/calc-syntax-errors/dune` instructs the build system to check this file for correctness, irredundancy and completeness and to compile this file into an OCaml module `parserMessages.ml`. This OCaml module contains a single function, `ParserMessages.messages`, which maps a state number to a diagnostic message. It is called from the main module, `demos/calc-syntax-errors/calc.ml`. There, we use the facilities offered by the module `MenhirLib.ErrorReports` to print a full syntax error message, which includes the precise location of the error as well as the diagnostic message returned by the function `ParserMessages.messages`. As icing on the cake, we allow the diagnostic message to contain placeholders of the form `$i`, where `i` is an integer constant, understood as a 0-based index into the parser's stack. We replace such a placeholder with the fragment of the source text that corresponds to this stack entry. A number of expected-output files demonstrate the kind of syntax error messages that we produce; see for instance `demos/calc-syntax-errors/calc03.exp` and `demos/calc-syntax-errors/calc07.exp`.

The CompCert verified compiler offers another real-world example. The "pre-parser" is where syntax errors are detected: see `cparser/pre_parser.mly`. A database of erroneous input sentences and (templates for) diagnostic messages is stored in `cparser/handcrafted.messages`.

As a final remark, it is worth noting that this approach to producing syntax error messages does *not* require using Menhir's incremental API and table back-end. One can instead use Menhir's code back-end with

`--exn-carries-state`. In that case, the exception `Error` carries a state number, which can be used to select a syntax error message. Menhir uses this method in its own parser; see `src/stage2/Driver.ml`.

12. Rocq back-end

Menhir is able to generate a parser that whose correctness can be formally verified using the Rocq proof assistant [14]. This feature is used to construct the parser of the CompCert verified compiler [19].

Setting the `--rocq` switch on the command line enables the Rocq back-end. When this switch is set, Menhir expects an input file whose name ends in `.vy` and generates a Rocq file whose name ends in `.v`.

Like a `.mly` file, a `.vy` file is a grammar specification, with embedded semantic actions. The only difference is that the semantic actions in a `.vy` file are expressed in Rocq instead of OCaml. A `.vy` file otherwise uses the same syntax as a `.mly` file. CompCert's `cparser/Parser.vy` serves as an example.

Several restrictions are imposed when Menhir is used in `--rocq` mode:

- The error-handling mechanism (§10) is absent. The **error** token is not supported.
- Location information is not propagated. The `$start*` and `$end*` keywords (Figure 14) are not supported.
- **%parameter** (§4.1.2) is not supported.
- **%inline** (§5.3) is not supported.
- The standard library (§5.4) is not supported, of course, because its semantic actions are expressed in OCaml. If desired, the user can define an analogous library, whose semantic actions are expressed in Rocq.
- Because Rocq's type inference algorithm is rather unpredictable, the Rocq type of every nonterminal symbol must be provided via a **%type** or **%start** declaration (§4.1.5, §4.1.6).
- Unless the proof of completeness has been deactivated using `--rocq-no-complete`, the grammar must not have a conflict (not even a benign one, in the sense of §6.1). That is, the grammar must be LR(1). Conflict resolution via priority and associativity declarations (§4.1.4) is not supported. The reason is that there is no simple formal specification of how conflict resolution should work.

The generated file contains several modules:

- The module `Gram` defines the terminal and nonterminal symbols, the grammar, and the semantic actions.
- The module `Aut` contains the automaton generated by Menhir, together with a certificate that is checked by Rocq while establishing the soundness and completeness of the parser.

The type `terminal` of the terminal symbols is an inductive type, with one constructor for each terminal symbol. A terminal symbol named `Foo` in the `.vy` file is named `Foo't` in Rocq. A terminal symbol per se does not carry a the semantic value.

We also define the type `token` of tokens, that is, dependent pairs of a terminal symbol and a semantic value of an appropriate type for this symbol. We model the lexer as an object of type `Streams.Stream token`, that is, an infinite stream of tokens.

The type `nonterminal` of the nonterminal symbols is an inductive type, with one constructor for each nonterminal symbol. A nonterminal symbol named `Bar` in the `.vy` file is named `Bar'nt` in Rocq.

The proof of termination of an LR(1) parser in the case of invalid input seems far from obvious. We did not find such a proof in the literature. In an application such as CompCert [19], this question is not considered crucial. For this reason, we did not formally establish the termination of the parser. Instead, in order to satisfy Rocq's termination requirements, we use the "fuel" technique: the parser takes an additional parameter `log_fuel` of type `nat` such that $2^{\texttt{log_fuel}}$ is the maximum number of steps the parser is allowed to perform. In practice, one can use a value of e.g., 40 or 50 to make sure the parser will never run out of fuel in a reasonable time.

Parsing can have three different outcomes, represented by the type `parse_result`. (This definition is implicitly parameterized over the initial state `init`. We omit the details here.)

```
Inductive parse_result :=
| Fail_pr_full: state -> token -> parse_result
| Timeout_pr: parse_result
| Parsed_pr:
    symbol_semantic_type (NT (start_nt init)) ->
    Stream token ->
    parse_result.
```

The outcome `Fail_pr_full` means that parsing has failed because of a syntax error. (If the completeness of the parser with respect to the grammar has been proved, this implies that the input is invalid). It contains two pieces of information: the state of the parser and the token which caused the error. These are provided for error reporting, if desired. It is important to note that, even though they should be correct, the validity of these two pieces of information is not certified by either the correctness or the completeness theorem. For more discussion on this, see §12.1. The outcome `Timeout_pr` means that the fuel has been exhausted. Of course, this cannot happen if the parser was given an infinite amount of fuel, as suggested above. The outcome `Parsed_pr` means that the parser has succeeded in parsing a prefix of the input stream. It carries the semantic value that has been constructed for this prefix, as well as the remainder of the input stream.

For each entry point `entry` of the grammar, Menhir generates a parsing function `entry`, whose type is `nat -> Stream token -> parse_result`.

Two theorems are provided, named `entry_point_correct` and `entry_point_complete`. The correctness theorem states that, if a word (a prefix of the input stream) is accepted, then this word is valid (with respect to the grammar) and the semantic value that is constructed by the parser is valid as well (with respect to the grammar). The completeness theorem states that if a word (a prefix of the input stream) is valid (with respect to the grammar), then (given sufficient fuel) it is accepted by the parser.

These results imply that the grammar is unambiguous: for every input, there is at most one valid interpretation. This is proved by another generated theorem, named `Parser.unambiguous`.

The parsers produced by Menhir's Rocq back-end must be linked with a Rocq library. This library can be installed via the command `opam install coq-menhirlib`.[3] The Rocq sources of this library can be found in the directory `coq-menhirlib` inside Menhir's repository.

The directory `demos/rocq-minicalc` contains a minimal example that shows how to set things up.

The CompCert verified compiler [19, 18] offers a real-world example. There, see in particular the directory `cparser`.

12.1 Error messaging options for Rocq mode

Users of the Rocq mode have several options for providing error messages from the parser. If they wish, they can follow the pattern of CompCert and use Menhir's incremental mode for a *non-verified* separate parser (§11.4). This may also aid in parsing languages (such as C) that need a lexical feedback loop for correct parsing.

A similar option is available in `demos/calc-syntax-errors`, where a second parser is used after the first to determine errors.

The parse result `Fail_pr_full` provides the third and simplest option. As it carries state and token information, it allows constructing meaningful error messages with a small amount of work. The generated function `Aut.N_of_state` converts a state to a state number. While this is not as powerful as the advanced error-handling possibilities afforded by the incremental API for non-verified parsers, this does allow interoperability with the existing `.messages` files and tooling, described in §11.1 and §11.2. This allows error messaging without a second parser. An example is provided in `demos/rocq-syntax-errors`.

[3] This assumes that you have installed `opam`, the OCaml package manager, and that you have run the command `opam repo add rocq-released https://rocq-prover.org/opam/released`.

Note that the extra information carried by the data constructor `Fail_pr_full` (and by the related data constructor `Fail_sr_full` that is used internally) is not verified. This extra information is provided for convenience, but there is no proof of its correctness.

Users who wish to ignore this extra information can use the abbreviated notation `Fail_pr` and `Fail_sr`. This notation is used in the statements of the theorems about the parser. It is available only in Rocq code, such as in `demos/rocq-minicalc`, not in extracted OCaml code.

13. GLR Parsing

13.1 LR versus GLR

Menhir traditionally constructs LR parsers, which are *deterministic* parsers. Whenever a parser might need to decide between several actions, this decision is made ahead of time, when the parser is constructed; so, at runtime, when the parser runs, it never needs to make a choice or to explore several possibilities.

When Menhir does not know what decision to make, it asks for help from the user by reporting a *conflict*. There are three types of conflicts:

1. a *shift/reduce* conflict represents a choice between consuming the next input token and reducing a production;
2. a *reduce/reduce* conflict represents a choice between reducing several productions;
3. an *end-of-stream* conflict represents a choice between querying the lexer for the next input token and performing a default reduction without querying the lexer.

A deterministic parser does not tolerate ambiguity: it either rejects the input or accepts the input and constructs a single parse tree, that is, a unique witness of the fact that the input is syntactically correct. A deterministic parser runs in linear time, that is, in time $O(n)$, where n is the length of the input. In summary, the strengths of deterministic parsers are guaranteed unambiguity and efficiency.

In contrast, a *non-deterministic parser* does not require resolving conflicts at parser construction time. At runtime, when a non-deterministic parser encounters several possibilities, it explores all of them in parallel. The upside of this approach is that there is no need to statically decide, once and for all, which way a conflict should be resolved. The main downsides, of course, are the need to face ambiguity at runtime and a possibly catastrophic loss of efficiency. A non-deterministic parser does not build a single parse tree: instead, it usually builds a parse forest, which contains disjunction nodes; it is then up to the user to somehow deal with these disjunctions, which represent multiple possible interpretations of the input. A non-deterministic parser does not always run in linear time: in the presence of ambiguity, it time complexity can be polynomial (§13.7).

The Generalized LR (GLR) algorithm, first described by Lang [17] and independently discovered by Tomita [31], is a non-deterministic parsing algorithm. In short, when a GLR parser encounters a choice between several actions, it creates several distinct "threads" of computation so as to explore the consequences of each action in parallel. Furthermore, if it determines that two threads, after performing a number of unrelated actions, have reached a common state, then it merges them back into a single thread. Thus, a small ambiguous segment inside a large, mostly unambiguous input has limited cost.

GLR parsing has been studied and improved over the years by many researchers. Menhir's implementation of this algorithm is inspired by McPeak's presentation [21, 22], with several key improvements in efficiency. Following McPeak's approach, Menhir's GLR parser executes user-provided semantic actions and user-provided "merge functions" to build semantic values. Semantic values are typically abstract syntax trees, which may have shared subtrees, and which may contain disjunction nodes, reflecting the presence of ambiguous input segments. These abstract syntax "trees" are really abstract syntax DAGs (directed acyclic graphs), but, out of habit, we will often keep saying "trees".

13.2 GLR parsing using Menhir

Here is a brief introduction to GLR parsing with Menhir.

1. Write your grammar in an `.mly` file as you normally would.

2. As far as possible, avoid conflicts altogether, or resolve conflicts by providing priority and associativity declarations (§4.1.4) and %prec annotations (§4.2.1) as you normally would. If a conflict cannot be avoided or resolved, then leave it. In GLR mode, Menhir does *not* resolve severe conflicts in an arbitrary way, as it normally would (§6.3). Instead, it tolerates ambiguity.
3. If you believe that a nonterminal symbol is ambiguous (§13.5) then you should provide a *merge function* (§13.4) for this symbol, in the `.mly` file, following the definition of this symbol. A merge function is an OCaml function, between curly braces, preceded with the keyword %merge.
4. Unless you have provided a merge function for every nonterminal symbol, you must also provide a *default merge function* (§13.5). A default merge function is an OCaml function, between curly braces, preceded with the keyword %merge. Its declaration must appear in the first section of the `.mly` file, before %%.
5. Invoke Menhir with the command-line switch `--GLR`.
6. Link your program with the library `MenhirGLR`.
7. Invoke the generated parser in the same way as usual. At this time, in GLR mode, only the monolithic API (§9.1) is supported. The incremental API, the inspection API, and the unparsing API are not supported.

The following subsections provide more information about semantic actions (§13.3), merge functions (§13.4, §13.5), and technical details and current limitations (§13.6). We also discuss how to understand and analyze the time complexity of a GLR parser (§13.7) and offer a comparison between Elkhound and Menhir (§13.8).

13.3 Semantic actions

Semantic actions in GLR mode work essentially in the same way as they do in LR mode (§4.2.1). If $A \rightarrow \alpha$ is a production, then, once the components of the right-hand side α have been recognized, the production $A \rightarrow \alpha$ is *reduced*: that is, the semantic action that is associated with this production is invoked. The semantic action has access to the semantic value of each symbol in the right-hand side α and must construct and return the semantic value of the left-hand side A.

The following remarks about semantic actions may be useful:

1. Semantic actions have access to the position keywords (§7), but the manner in which positions are computed differs in LR mode and in GLR mode (§13.6).
2. Semantic actions should be cheap: they should have time complexity $O(1)$.
3. Semantic actions can have side effects: that is, they can use mutable state. It is recommended to avoid this feature. Using a mutable counter to assign unique identifiers to abstract syntax DAG nodes is a reasonable use.
4. The execution of semantic actions is *not* delayed in any way: semantic actions are executed during parsing. Their execution obeys a left-to-right discipline, based on the *right* ends of the input segments that they cover. That is, if j and j' are two input indices such that $j < j'$, then a production whose right-hand side covers the interval $[i, j)$ will be reduced *before* a production whose right-hand side covers the interval $[i', j')$.
5. The parser can appear to execute several "threads" in parallel, each of which executes a distinct sequence of semantic actions. The execution of these "threads" is in in fact sequential; the operations of the various "threads" are interleaved, so the execution of a semantic action is atomic. Sometimes a "thread" reaches a dead end and dies. This event is not observable. In such an event, some of the semantic values that this thread has constructed may become unused and may be reclaimed by the garbage collector.
6. In a semantic action, if for some reason you are able to determine that the reduction that is currently taking place is "wrong" (that is, this reduction represents an incorrect interpretation of the input) then you can kill the current parser "thread" via the function call `MenhirGLR.GLR.reject()`, which does not return.

Using `MenhirGLR.GLR.reject()` lets you eliminate some ambiguity, that is, throw away certain abstract syntax subtrees and (eventually) build abstract syntax trees that contain fewer disjunction nodes. Contrary to what one might expect, this does not necessarily lead to a savings in time. If, for some A, i, and j, *all* of

the parser threads that would have recognized the nonterminal symbol A in the input segment $[i, j)$ are killed by this mechanism, *then* some work is saved, as the consequences of recognizing A in the segment $[i, j)$ are not explored. However, if any of these threads survives then the symbol A is recognized in the segment $[i, j)$, the consequences of this event must be explored, and no work is saved.

In LR mode, a semantic value is used (passed to a semantic action) exactly once. In GLR mode, this is no longer true: a semantic value may be never used, used once, or used several times. As a result, if the semantic actions build abstract syntax trees, then these trees can have shared subtrees: they are really abstract syntax DAGs. Traversing such a DAG requires some care: a naive tree traversal, which traverses a shared subtree more than once, has exponential time complexity.

Both in LR mode and in GLR mode, semantic actions are executed in a bottom-up manner. That is to say, when a semantic action is executed, the semantic values to which this semantic action has access have already been computed.

13.4 Merge functions

Whenever the parser determines that the nonterminal symbol A can be recognized in the input segment $[i, j)$, it constructs a semantic value, which can be viewed as a witness of the fact that A can be recognized over $[i, j)$. There are sometimes several reasons why A can be recognized over $[i, j)$. In other words, there can exist several ways of interpreting the input fragment delimited by the indices i and j as an instance of the symbol A. In this case, several semantic values are built. These semantic values must then be *merged*, that is, combined, so as to obtain a single semantic value.

In the typical scenario where a semantic value is an abstract syntax DAG, a merge function should typically build a *disjunction node*. Such a node reflects the existence of an ambiguity: there is more than one proof of the fact that the symbol A can be recognized in the segment $[i, j)$. Each child of the disjunction node represents one such proof. As usual, it is up to you, the user, to define the algebraic data type of abstract syntax DAGs. Therefore, it is also up to you to equip this type with a constructor for disjunction nodes. This constructor might have exactly two children, or might carry a list of children; this is up to you. It is also up to you to write merge functions.

Every nonterminal symbol needs a merge function. (This constraint can be relaxed by providing a default merge function; see §13.5.) To provide a merge function for the symbol A, after the definition of this symbol, use the keyword `%merge`, followed with the merge function itself, between curly braces. The merge function should be an OCaml function of type $[\![A]\!] \to [\![A]\!] \to [\![A]\!]$, where we write $[\![A]\!]$ to mean "the type of the semantic values associated with the symbol A". In other words, a merge function expects two semantic values and returns a semantic value.

One may distinguish two kinds of semantic values: a "plain" value is one that is produced by a semantic action; a "composite" value is one that is produced by a merge function. A merge function is asymmetric: whereas its first argument may be a plain value or a composite value, its second argument is a plain value.

A merge function should have time complexity $O(1)$. Its main purpose should be to build a disjunction node. Although one could imagine other strategies, such as returning one of the two arguments and discarding the other one, these strategies would not speed up parsing. Therefore, attempting to perform disambiguation inside a merge function is pointless.

A merge function can use the position keywords `$startpos` and `$endpos` (§13.6) to obtain the start position and end position of the interval $[i, j)$. At this time, a merge function does not have access to the input indices i and j.

A parameterized nonterminal symbol (§5.2) can have a merge function, and (if it is ambiguous) should have a merge function. When this symbol is instantiated, each instance inherits a copy of the merge function. A nonterminal symbol that is marked `%inline` (§5.3) does not need and cannot have a merge function.

13.5 Default merge functions

In principle, every nonterminal symbol needs a merge function (§13.4). If, for some symbol, no merge function is provided, then, for this symbol, the *default merge function* is used instead. To declare a default merge function, use the keyword **%merge**, followed with the default merge function itself, between curly braces. This declaration must appear in the first section of the `.mly` file, before the delimiter **%%**.

A default merge function serves the same purpose as a merge function, and works in the same way. Compared with a merge function, it receives one more argument, which is the name of a nonterminal symbol A whose semantic values must be merged. Because the dependent type $(A : \mathit{string}) \to [\![A]\!] \to [\![A]\!] \to [\![A]\!]$ cannot be expressed in OCaml, a default merge function must be polymorphic: its type must be $\forall v.\ \mathit{string} \to v \to v \to v$. Therefore, the two semantic values must be considered as opaque by the default merge function.

Let us say that a symbol A is *ambiguous* if it is possible to construct two distinct reasons why A can be recognized in an input segment $[i, j)$. Otherwise, let us say that A is *unambiguous*. If A is unambiguous then its merge function is dead: the need to merge two semantic values associated with this symbol never arises. It would be pleasant if Menhir would require a merge function for each ambiguous symbol, and would require no merge function for unambiguous symbols. Unfortunately, Menhir cannot tell whether a symbol is ambiguous; this property is undecidable. Therefore Menhir requires that every nonterminal symbol be covered, either by its own merge function, or by the default merge function. If you believe that a merge function is dead then you can let this function print an error message and either die or return one of the semantic values that it has received as arguments.

13.6 Technical details

Cyclic grammars A grammar is *cyclic* if there exists a nonterminal symbol *A* and *B* such that $A \longrightarrow^+ A$, that is, in one or more steps, *A* generates *A*. Under the assumption that the symbol *A* is reachable from a start symbol, such a grammar is infinitely ambiguous: for some input sentences, there exist an infinite number of parse trees. Menhir forbids cyclic grammars, both in LR mode and in GLR mode. In LR mode, this restriction seems natural, since ambiguity is considered undesirable. In GLR mode, this restriction ensures that semantic actions can be applied bottom-up (§13.3). It exists also in Elkhound (§13.8).

Hidden left recursion A grammar has *hidden left recursion* if there exists a nonterminal symbol *A* such that $A \longrightarrow^+ \alpha A \beta$ where α is a nonempty string of nonterminal symbols and α is nullable, that is, $\alpha \longrightarrow^+ \epsilon$. Under the assumption that the symbol *A* is reachable from a start symbol, such a grammar is not in the class LR(k); either it is infinitely ambiguous or it requires unbounded lookahead. Menhir forbids hidden left recursion, both in LR mode and in GLR mode. In LR mode, this restriction seems natural. In GLR mode, this restriction ensures that the graph-structured stack (GSS) remains acyclic. This property is in fact not essential: the GLR algorithm does not rely on it. Therefore, in the future, this restriction may be removed.

Expansion of nullable suffixes If one or more nullable nonterminal symbols appear at the end of a production, we say that this production exhibits *a nullable suffix*. The presence of a nullable suffix in a production introduces an inefficiency (§13.7). To avoid this problem, Menhir transforms the grammar so that, in the transformed grammar, no production has a nullable suffix.

Roughly speaking, if the nonterminal symbol *A* is nullable and participates in a nullable suffix then it is transformed into a disjunction *empty_A* | *nonempty_A*, where the new nonterminal symbol *empty_A* groups the productions that generate the empty word ϵ and the new nonterminal symbol *nonempty_A* groups the productions that generate nonempty words. Furthermore, the symbol *empty_A* is marked **%inline**, so it is expanded away and disappears.

For example, suppose that the grammar contains the production

$$\mathit{expr} \quad \to \quad \mathit{expr}\ \mathsf{where}\ \mathit{list}(\mathit{decl})$$

where where is a terminal symbol and where the symbol $\mathit{list}(\mathit{decl})$ is defined by $\mathit{list}(\mathit{decl}) \to \epsilon \mid \mathit{decl}\ \mathit{list}(\mathit{decl})$. Because $\mathit{list}(\mathit{decl})$ is nullable, this production has a nullable suffix. Once the grammar is transformed, this

production is replaced with two productions:

$$\begin{array}{lcl} \mathit{expr} & \rightarrow & \mathit{expr}\ \mathsf{where} \\ \mathit{expr} & \rightarrow & \mathit{expr}\ \mathsf{where}\ \mathit{nonempty_list}(\mathit{decl}) \end{array}$$

where the symbol $\mathit{nonempty_list}(\mathit{decl})$ is defined by $\mathit{nonempty_list}(\mathit{decl}) \rightarrow \mathit{decl} \mid \mathit{decl}\ \mathit{nonempty_list}(\mathit{decl})$.

This example involves a right-recursive list, but the transformation applies equally well to left-recursive symbols and to non-recursive symbols (such as options). In the worst case, this transformation could cause an exponential blowup in the size of the grammar. To avoid such a blowup, as a rule of thumb, it is recommended to avoid sequences of nullable symbols: for example, instead of $A?\ B?\ C?\ D?$ (which, after expansion, would give rise to 16 productions), it is recommended to write $\mathit{llist}(A \mid B \mid C \mid D)$ and to check for well-formedness in a later stage.

The grammar is transformed by Menhir before it explains conflicts. Therefore, the conflict explanations produced by Menhir refer to the transformed grammar. We believe that the transformation itself cannot create new conflicts.

Failure As explained earlier (§13.1), a GLR parser conceptually runs several parsing "threads" in parallel. When such a thread reaches a state where no action is permitted, it dies silently. If all threads have died then the GLR parser itself dies by raising the exception `Error`. The type of this exception in GLR mode is not the same as in LR mode. In GLR mode, the exception `Error` carries a parameter, which is a list of GSS nodes:

```
exception Error of (int, Obj.t) MenhirGLR.GSS.node list
```

This aspect should be considered unstable and may change in the future.

In GLR mode, the command line switches `--exn-carries-state` and `--fixed-exception` are not supported. The special token **error** is also not supported.

Successful termination As explained earlier (§13.1), a GLR parser conceptually runs several parsing "threads" in parallel. A GLR parser produced by Menhir terminates as soon as one thread declares success, that is, as soon as one thread recognizes the start symbol.

It is up to the user to avoid end-of-stream conflicts, which are situations where both recognizing the start symbol *and* querying the lexer for the next token are valid actions. If there is an end-of-stream conflict then one thread might declare success while one or more other threads want to continue parsing. In this case, a GLR parser generated by Menhir terminates successfully, discarding all of the unfinished threads. Therefore, an ambiguity is silently ignored.

Lexical feedback *Lexical feedback* refers to the use of mutable state that is shared between the lexer and the parser, allowing the parser to influence the lexer through side effects. This technique is also known, more trivially, as a "lexer hack". To perform lexical feedback in a correct manner, it is necessary to understand *at what times* the parser invokes the lexer to request the next token. In other words, it is necessary to understand exactly in what order the execution of the semantic actions and the invocations of the lexer are interleaved. This is difficult, therefore highly discouraged.

The times at which the lexer is invoked are currently undocumented. We draw the reader's attention to the fact that they are not the same in LR mode and in GLR mode.

Positions In GLR mode, the position keywords (§7) can be used in semantic actions, in the same way as in LR mode. However, the manner in which positions are computed differs slightly. In other words, simply enabling `--GLR` can cause different positions to be computed.

The fundamental reason why there can be a disagreement and a difficulty is that there are several ways of thinking about "positions" in the input:

1. One way is to consider the input as a stream of tokens and to define a *date* as an index into the input. In this view, a date represents a position between two tokens. If the input stream has length n then the set of all dates is the interval $[0, n]$. Thus, in total, there exist $n + 1$ dates.

2. Another way is to consider the input as a string of characters and to reason directly in terms of the *positions* returned by the lexer, whose type is `Lexing.position`. Each invocation of the lexer returns one token and *two* positions: the start position and the end position of this token. If the input stream has length n then the lexer produces $2n$ positions in total.

The existence of these two systems creates a tension. In short, in LR mode, Menhir works directly with the second system, that is, the positions produced by the lexer. This creates difficulties with productions whose right-hand side is empty; certain conventions are used in this case (§7). In GLR mode, instead, Menhir works with dates internally, and translates dates to positions in the following manner:

- If the date i must be translated to a start position, then the start position of the token that follows the input index i is used. In the special case where i is n, instead of the start position of the token at index i, which does not exist, the date i is translated to an end position, as per the next item.
- If the date i must be translated to an end position, then the end position of the token that precedes the input index i is used. In the special case where i is 0, instead of the end position of the token at index -1, which does not exist, the initial position is used.

In the case of a production with an empty right-hand side, this translation produces a possibly counter-intuitive result. Such a production spans an empty date interval, of the form $[i, i]$. In this case, the start position `$startpos` is obtained by translating the date i to a start position, while the end position `$endpos` is obtained by translating the date i to an end position. As a result, assuming $0 < i < n$, `$startpos` is the start position of the token at index i, whereas `$endpos` is the end position of the token at index $i - 1$. Therefore the position `$endpos` comes *earlier* in the text than the position `$startpos`. Then, the fragment of input text between `$endpos` and `$startpos` is whitespace (or whatever the lexer considers whitespace).

Tolerating known conflicts When using Menhir in GLR mode, it is important to study the conflicts reported by Menhir (§6) and to eliminate as many conflicts as possible, either by changing the grammar or by introducing priority declarations (§4.1.4). As a general rule, conflicts should be eliminated because they are costly. In particular, end-of-stream conflicts should be eliminated because a GLR cannot deal with them properly (see "Successful termination" above).

If a conflict cannot be eliminated, then it is acceptable to keep it: after all, the point of using a GLR parser is to tolerate some conflicts. Unfortunately, there is currently no way of marking a specific conflict (or a group of conflicts) as "tolerated", so that Menhir stops warning about this conflict. We intend to remedy this shortcoming in the future.

13.7 Time complexity

The time complexity of GLR parsing critically depends on the amount of ambiguity that exists in the grammar, in the automaton, and in the input. At one extreme, if at compile-time ambiguity is absent (there are no conflicts) or is eliminated (all conflicts are resolved) then a deterministic automaton is constructed and GLR parsing has linear time complexity, just like LR parsing. (In such a scenario, Menhir's GLR parser can be roughly 50% slower than Menhir's table-based LR parser.) Once ambiguity appears, the time complexity of GLR parsing degrades and becomes polynomial in the length of the input. In the worst case, it is $O(n^{p+1})$, where p is the maximum length of a production. (We ignore a logarithmic factor that exists in our implementation.)

How is this worst-case bound obtained? The total cost of the "shift" actions of a GLR parser is $O(n)$. It is therefore dominated by the cost of the reductions. Furthermore, still ignoring a logarithmic factor, the cost of the reductions is $O(1)$ per reduction. Therefore, to understand the time complexity of GLR parsing, it suffices to assess how many reductions may take place in the worst case. Let us consider a production $A \rightarrow x_1 x_2 \ldots x_k$. Its right-hand side is a sequence of terminal or nonterminal symbols x_i, where i ranges over $[1, k]$. This production can be reduced only when the parser finds a *match*, that is, a sequence of $k + 1$ input indices $i_0 \leq i_1 \leq i_2 \leq \ldots \leq i_k$ such that the symbol x_1 is recognized in the input segment $[i_0, i_1]$, the symbol x_2 is recognized in the input segment $[i_1, i_2]$, and so on. How many matches can there be? Because a match is a tuple

of $k+1$ input indices, the answer is, $O(n^{k+1})$. How large can k be? The answer, k is at most equal to p, the maximum length of a production. This explains the bound $O(n^{p+1})$.

In reality, this bound is pessimistic, for at least two reasons: first, it does not account for rigid symbols; second, it assumes that every match gives rise to a reduction. Let us explain these two points in turn.

First, consider, for example, a production of length three, $A \to x_1 x_2 x_3$, and suppose that x_2 is a terminal symbol. How many matches for this production might exist? By the previous reasoning, the answer would be $O(n^4)$, because a match involves four indices i_0, i_1, i_2, i_3. However, upon second thought, these indices are not independent: for the terminal symbol x_2 to be recognized in the segment $[i_1, i_2]$, the equation $i_1 + 1 = i_2$ must hold. Thus, at most $O(n^3)$ matches can exist. This reasoning applies not just to terminal symbols, but to all *rigid* symbols.[4] Thus, in reality, the worst-case time complexity of GLR parsing is $O(n^{p+1})$ where p is the maximum number of *non-rigid* symbols in a right-hand side.

Second, in our analysis so far, we have pessimistically assumed that every match may give rise to a reduction. However, in reality, this is not the case: a match that does not follow a suitable *left context* is ignored by a GLR parser. In other words, a GLR parser attempts to recognize a symbol A at input offset i_0 only if such an attempt is warranted by the partial input that has been read so far. For example, let GL_1 be the grammar $S \to \mathit{llist}(a)\ b$ where a and b are terminal symbols and where $\mathit{llist}(a)$ is a left-recursive list of a's: $\mathit{llist}(a) \to \epsilon \mid \mathit{llist}(a)\ a$. This grammar is in fact deterministic; it is in the class LR(1). Suppose that the input is $a^n\ b$. How many matches for the symbol $\mathit{llist}(a)$ exist in this input? The answer is $O(n^2)$: there is a quadratic number of runs of a's. How many matches will actually cause a reduction? The answer is $O(n)$: only the matches that begin at offset 0 will be detected by an LR or GLR parser. Indeed, there is no reason for such a parser to look for a match at any offset other than 0. This example shows that counting matches can yield a pessimistic worst-case bound.

To continue this discussion, let us consider three more example grammars.

First, let us examine the grammar GR_1, defined by $S \to \mathit{rlist}(a)\ b$ where $\mathit{rlist}(a)$ is a right-recursive list: $\mathit{rlist}(a) \to \epsilon \mid a\ \mathit{rlist}(a)$. This grammar is also in the class LR(1). Suppose that the input is $a^n\ b$. How many matches for the symbol $\mathit{rlist}(a)$ exist in this input? The answer is still $O(n^2)$: there is a quadratic number of runs of a's. How many matches will actually cause a reduction? The answer is still $O(n)$: only the matches that end at offset n will be reduced. (These matches can begin at an arbitrary offset i.) Indeed, the lookahead symbol is exploited: an LR or GLR parser for this grammar will reduce a run of a's to $\mathit{rlist}(a)$ only if this run is followed by the symbol b.

Next, let us look at the grammar GR_2 defined by $S \to \mathit{rlist}(a)\ a\ b$. This grammar is unambiguous, but is *not* in the class LR(1). There is a shift-reduce conflict: every time an LR or GLR parser looks ahead at a new symbol a, it cannot know whether this is the last a. So, a GLR parser for this grammar will both shift (which is the correct action if this is not the last a) and reduce $\mathit{rlist}(a)$ (which is the correct action if this is the last a). Suppose that the input is $a^n\ a\ b$. How many matches for the symbol $\mathit{rlist}(a)$ exist in this input? The answer is still $O(n^2)$. How many matches will actually cause a reduction? This time, the answer is $O(n^2)$: for every pair of indices i and j such that $0 \le i \le j \le n$, a GLR parser will recognize $\mathit{rlist}(a)$ in the interval $[i, j)$. A comparison of the grammars GR_1 and GR_1' shows that the cost of introducing a single source of ambiguity can be huge: allowing the symbol a to follow a (right-recursive) list of a's changes the time complexity of GLR parsing from linear to quadratic.

As a last example, let us look at the grammar GL_2 defined by $S \to \mathit{llist}(a)\ a\ b$. Like GR_2, this grammar is unambiguous but is not in the class LR(1). Suppose that the input is $a^n\ a\ b$. How many matches for the symbol $\mathit{llist}(a)$ exist in this input? The answer is still $O(n^2)$. How many matches will actually cause a reduction? The answer is $O(n)$, because, as in the case of the grammar GL_1, only the matches that begin at offset 0 are considered by a GLR parser. A comparison of the grammars GR_2 and GL_2 shows that the choice between a left-recursive list and a right-recursive list can make a huge difference: in this case, using a right-recursive

[4] A symbol x is *rigid* if and only if for all words $w_1, w_2 \in \mathcal{L}(x)$, if w_1 is a prefix of w_2, then $w_1 = w_2$. In other words, x is rigid if and only if two words generated by x cannot be in the strict prefix relation. All terminal symbols are rigid.

list changes the time complexity of GLR parsing from linear to quadratic. As a general rule, with GLR parsing, it seems advisable to prefer left-recursive definitions.

We warn the reader that the list-like symbols defined in Menhir's standard library (§5.4), including *list*, *nonempty_list*, and *separated_nonempty_list*, are right-recursive. In situations where the end of a list is not unambiguously announced by the lookahead symbol, one should avoid using these symbols and introduce left-recursive symbols instead.

To conclude this section, let us formulate two final remarks about the worst-case time complexity of GLR parsing. We have indicated that it is $O(n^{p+1})$ where n is the length of the input and p is the maximum number of non-rigid symbols in a right-hand side. Our first remark is, in realistic scenarios, an input typically contains ambiguous input fragments, separated with non-ambiguous parts. In such a scenario, one can think of the parameter n as the length of the ambiguous input fragments, as opposed to the length of the whole input. In other words, the complexity of GLR parsing is kept in check if in practice the input does not contain long ambiguous fragments: It is important to *keep ambiguity local*. Our second remark is that Menhir applies several transformations to the grammar: it expands away the symbols that are marked `%inline` and (in GLR mode) expands away the nullable symbols that appear at the end of a production (§13.6). When assessing the value of p, one should take these transformations into account.

13.8 Comparison with Elkhound

Menhir's implementation of GLR parsing is inspired by Elkhound [21, 22], and makes a significant number of improvements over Elkhound. McPeak's technical report [21] explains GLR very well, and provides very clear pseudo-code, although one must be aware that it contains an omission, as acknowledged by McPeak. The main common points and differences between Elkhound and Menhir are as follows:

- Following Elkhound, Menhir requires the grammar to be acyclic (§13.6), and performs reductions in a bottom-up manner (§13.3): when a semantic action is invoked, the semantic values to which this semantic action has access have already been computed.
- An important source of inefficiency exists in Elkhound as well as in earlier GLR algorithms by Nozohoor-Farshi [23] and by Rekers [28]. When a pre-existing top node receives a new edge, these algorithms must search every top node for reduction paths that exploit this new edge. The cost of this search, if properly implemented, should be only $O(1)$, because the number of top nodes is $O(1)$. Nevertheless, in practice, we believe that this search can create significant overhead. This search is needed only if some productions end with a nullable symbol. To remove the need for this search, Menhir transforms the grammar at compile-time. The nullable nonterminal symbols that appear at the end of a production are expanded away (§13.6), so that, in the transformed grammar, no production ends with a nullable nonterminal symbol.
- Following Elkhound, Menhir stores the pending reductions in a priority queue. Whereas Elkhound's priority queue is a doubly-linked list, where insertion requires linear time, Menhir uses an efficient priority queue, where insertion and extraction require logarithmic time.
- Whereas Elkhound stores the outgoing edges of a node is a linked list, whose membership test requires linear time, Menhir stores them in a set, where insertion and membership testing require logarithmic time.
- Like Elkhound, Menhir implements a hybrid of the LR and GLR algorithms, so as to achieve greater speed when parsing unambiguous input fragments. We find this feature less crucial than McPeak does: in our setting, the LR/GLR hybrid is, at best, roughly twice faster than pure GLR.
- The LR/GLR hybrid algorithm requires maintaining the *deterministic depth* of each node. For this purpose, McPeak's technique exploits reference counts, which Menhir does not maintain, and sometimes involves expensive re-computations. Menhir uses a different, more efficient way of computing deterministic depths.

Whereas McPeak reports that Elkhound's performance on the grammar $E \rightarrow E + E \mid b$ is $O(n^4)$, Menhir's performance on this grammar is $O(n^3)$. Menhir's performance is consistent with our time complexity analysis (§13.7): it is $O(n^{p+1})$ where p, the maximum number of non-rigid symbols in a right-hand side, is 2.

14. Building grammarware on top of Menhir

It is possible to build a variety of grammar-processing tools, also known as "grammarware" [15], on top of Menhir's front-end. Indeed, Menhir offers a facility for dumping a `.cmly` file, which contains a (binary-form) representation of the grammar and automaton, as well as a library, `MenhirSdk`, for (programmatically) reading and exploiting a `.cmly` file. These facilities are described in §14.1. Furthermore, Menhir allows decorating a grammar with "attributes", which are ignored by Menhir's back-ends, yet are written to the `.cmly` file, thus can be exploited by other tools, via `MenhirSdk`. Attributes are described in §14.2.

14.1 Menhir's SDK

The command line option `--cmly` causes Menhir to produce a `.cmly` file in addition to its normal operation. This file contains a (binary-form) representation of the grammar and automaton. This is the grammar that is obtained after the following steps have been carried out:

- joining multiple `.mly` files, if necessary;
- eliminating anonymous rules;
- expanding away parameterized nonterminal symbols;
- removing unreachable nonterminal symbols;
- performing OCaml type inference, if the `--infer` switch is used;
- inlining away nonterminal symbols that are decorated with `%inline`.

The library `MenhirSdk` offers an API for reading a `.cmly` file. The functor `MenhirSdk.Cmly_read.Read` reads such a file and produces a module whose signature is `MenhirSdk.Cmly_api.GRAMMAR`. This API is not explained in this document; for details, the reader is expected to follow the above links.

14.2 Attributes

Attributes are decorations that can be placed in `.mly` files. They are ignored by Menhir's back-ends, but are written to `.cmly` files, thus can be exploited by other tools, via `MenhirSdk`.

14.2.1 Attribute structure

An attribute consists of a label and a payload. An attribute label is an OCaml identifier, such as `cost`, or a list of OCaml identifiers, separated with dots, such as `my.label`. An attribute payload is an OCaml expression of arbitrary type, such as `1` or `"&&"` or `print_int`. (The payload is not parsed or type-checked, but must be well-formed according to OCaml's lexical conventions: that is, inside it, braces, parentheses, single and double quotes, and comment delimiters must be balanced.) Following the syntax of OCaml's attributes, an attribute's label and payload are separated with one or more spaces, and are delimited by `[@` and `]`. Thus, `[@name foo]` and `[@cost 1]` and `[@printer print_int]` are examples of attributes.

14.2.2 Attribute placement

An attribute can be attached at one of five levels:

1. An attribute can be attached with the grammar. Such an attribute must be preceded with a `%` sign and must appear in the declarations section (§4.1). For example, the following is a valid declaration:

   ```
   %[@trace true]
   ```

2. An attribute can be attached with a terminal symbol. Such an attribute must follow the declaration of this symbol. For example, the following is a valid declaration of the terminal symbol `INT`:

   ```
   %token<int> INT [@cost 0] [@printer print_int]
   ```

3. An attribute can be attached with a nonterminal symbol. Such an attribute must appear inside the rule that defines this symbol, immediately after the name of this symbol. For instance, the following is a valid definition of the nonterminal symbol `expr`:

```
expr [@default EConst 0]:
  i = INT                   { EConst i }
| e1 = expr PLUS e2 = expr { EAdd (e1, e2) }
```

An attribute can be attached with a parameterized nonterminal symbol:

```
option [@default None] (X):
        { None }
| x = X { Some x }
```

An attribute cannot be attached with a nonterminal symbol that is decorated with the %inline keyword.

4. An attribute can be attached with a producer (§4.2.3), that is, with an occurrence of a terminal or nonterminal symbol in the right-hand side of a production. Such an attribute must appear immediately after the producer. For instance, in the following rule, an attribute is attached with the producer `expr*`:

```
exprs:
  LPAREN es = expr* [@list true] RPAREN { es }
```

5. An attribute can be attached with a production. Such an attribute must appear after the semantic action and after the %prec annotation, if there is one (§4.2.1). If a production group contains several productions, then its attributes are shared by all productions. For instance, in the following definition, each of the two productions carries an attribute whose label is `name`:

```
option(X):
    { None   } [@name none]
| x = X
    { Some x } [@name some]
```

If a nonterminal symbol is marked %inline then it cannot carry an attribute, and a use of it cannot carry an attribute.

14.2.3 Syntactic sugar

As a convenience, it is possible to attach many attributes with many (terminal and nonterminal) symbols in one go, via an %attribute declaration, which must be placed in the declarations section (§4.1). For instance, the following declaration attaches both of the attributes `[@cost 0]` and `[@precious false]` with each of the symbols `INT` and `id`:

```
%attribute INT id [@cost 0] [@precious false]
```

An %attribute declaration can be considered syntactic sugar: it is desugared away in terms of the five forms of attributes presented earlier (§14.2.2). The command line switch `--only-preprocess` can be used to see how it is desugared.

14.2.4 Attribute propagation

Symbol attributes / parameterized symbol expansion If an attribute is attached with a parameterized nonterminal symbol, then, when this symbol is expanded away (§5.2), the attribute is transmitted to every instance. For instance, in an earlier example, the attribute `[@default None]` was attached with the parameterized symbol `option`. Then, every instance of `option`, such as `option(expr)`, `option(COMMA)`, and so on, inherits this attribute. To attach an attribute with one specific instance only, one can use an %attribute declaration. For instance, the declaration `%attribute option(expr) [@cost 10]` attaches an attribute with the nonterminal symbol `option(expr)`, but not with the symbol `option(COMMA)`.

Production attributes / parameterized symbol expansion If an attribute is attached with a production for a parameterized nonterminal symbol, then, when this symbol is expanded away (§5.2), this attribute is transmitted to every instance of this production.

As an exception to this general rule, `@name` attributes receive special treatment: their payload is specialized. For instance, assuming that the parameterized symbol `option(X)` is defined as follows:

```
option(X):
    { None   } [@name none]
| x = X
    { Some x } [@name some]
```

then instantiating the parameter `X` with `expr` results in the following definition:

```
option(expr):
    { None   } [@name none_expr]
| x = expr
    { Some x } [@name some_expr]
```

The payload of each `@name` attribute has been extended with an underscore character `_` followed with the actual parameter `expr`. (If the actual parameter contains parentheses or commas, they are replaced with underscore characters.) This special behavior is intended to allow each production to receive a unique name.

Production attributes / inlining When a production whose left-hand side is marked `%inline` (the *callee*) is inlined (§5.3) into another production (the *caller*), the attributes of the caller are transmitted to the new production, while the attributes of the callee are lost. (This policy may change in the future.)

As an exception to this general rule, `@name` attributes receive special treatment: the `@name` attributes of the callee and caller are combined, as follows. If the caller and the callee both carry a `@name` attribute, then the attribute payloads are concatenated, and an underscore character `_` is inserted between them. If only the caller or only the callee carries a `@name` attribute, then this attribute is preserved. For example, after inlining, the following definitions:

```
expr:
| e1 = expr; op = binop; e2 = expr
    { EBinOp (e1, op, e2) } [@name binop]
%inline binop:
| ADD { BAdd } [@name add]
| SUB { BSub } [@name sub]
```

give rise to the following result:

```
expr:
| e1 = expr; op = ADD; e2 = expr
    { let op = BAdd in EBinOp (e1, op, e2) }
    [@name binop_add]
| e1 = expr; op = SUB; e2 = expr
    { let op = BSub in EBinOp (e1, op, e2) }
    [@name binop_sub]
```

This special behavior is intended to allow each production to receive a unique name.

15. Interaction with build systems

This section explains some details of the compilation workflow, including OCaml type inference and its repercussions on dependency analysis (§15.1) and compilation flags (§15.2). This material should be of interest only to authors of build systems who wish to build support for Menhir into their system. Ordinary users should skip this section and use a build system that knows about Menhir, such as `dune` (preferred; §17) or `ocamlbuild`.

15.1 OCaml type inference and dependency analysis

In an ideal world, the semantic actions in a `.mly` file should be well-typed according to the OCaml type discipline, and their types should be known to Menhir, which may need this knowledge. (When `--inspection` is set, Menhir needs to know the OCaml type of every nonterminal symbol.) To address this problem, three approaches exist:

1. Ignore the problem and let Menhir run without OCaml type information (§15.1.1).
2. Let Menhir obtain OCaml type information by invoking the OCaml compiler (§15.1.2).
3. Let Menhir request and receive OCaml type information without invoking the OCaml compiler (§15.1.3).

`dune` follows the third approach behind the scenes.

15.1.1 Running without OCaml type information

The simplest thing to do is to run Menhir *without* any of the flags described in the following (§15.1.2, §15.1.3). Then, the semantic actions are *not* type-checked, and their OCaml type is *not* inferred. (This is analogous to using `ocamlyacc`.) The drawbacks of this approach are as follows:

- A type error in a semantic action is detected only when the `.ml` file produced by Menhir is type-checked. The location of the type error, as reported by the OCaml compiler, can be suboptimal.
- Unless the type of every nonterminal symbol is given (via a `%type` declaration), some features of Menhir are disabled. The main features that require type information are the code back-end and the inspection API.

15.1.2 Obtaining OCaml type information by calling the OCaml compiler

The second approach is to let Menhir invoke the OCaml compiler so as to type-check the semantic actions and infer their types. This is done by invoking Menhir with the `--infer` switch, as follows.

`--infer`. This switch causes the semantic actions to be checked for type consistency *before* the parser is generated. To do so, Menhir generates a mock `.ml` file, which contains just the semantic actions, and invokes the OCaml compiler, under the form `ocamlc -i`, so as to type-check this file and infer the types of the semantic actions. Menhir then reads this information and produces real `.ml` and `.mli` files.

`--ocamlc` *command*. This switch controls how `ocamlc` is invoked. It allows setting both the name of the executable and the command line options that are passed to it.

One difficulty with this approach is that the OCaml compiler usually needs to consult a few `.cm[iox]` files. Indeed, if the `.mly` file contains a reference to an external OCaml module, say `A`, then the OCaml compiler typically needs to read one or more files named `A.cm[iox]`.

This implies that these files must have been created first. But how is one supposed to know, exactly, which files should be created first? One must scan the `.mly` file so as to find out which external modules it depends upon. In other words, a dependency analysis is required. This analysis can be carried out by invoking Menhir with the `--depend` switch, as follows.

`--depend`. This switch causes Menhir to generate dependency information for use in conjunction with `make`. When invoked in this mode, Menhir does not generate a parser. Instead, it examines the grammar specification and prints a list of prerequisites for the targets *basename*`.cm[iox]`, *basename*`.ml`, and *basename*`.mli`. This list is intended to be textually included within a `Makefile`. To produce this list, Menhir generates a mock `.ml` file, which contains just the semantic actions, invokes `ocamldep`, and postprocesses its output.

`--raw-depend`. This switch is analogous to `--depend`. However, in this case, `ocamldep`'s output is *not* postprocessed by Menhir: it is echoed without change. This switch is not suitable for direct use with `make`; it is intended for use with `omake` or `ocamlbuild`, which perform their own postprocessing.

`--ocamldep` *command*. This switch controls how `ocamldep` is invoked. It allows setting both the name of the executable and the command line options that are passed to it.

15.1.3 Obtaining OCaml type information without calling the OCaml compiler

The third approach is to let Menhir request and receive OCaml type information *without* allowing Menhir to invoke the OCaml compiler. There is nothing magic about this: to achieve this, Menhir must be invoked twice, and the OCaml compiler must be invoked (by the user, or by the build system) in between. This is done as follows.

`--infer-write-query` *mockfilename*. When invoked in this mode, Menhir does not generate a parser. Instead, generates a mock `.ml` file, named *mockfilename*, which contains just the semantic actions. Then, it stops.

It is then up to the user (or to the build system) to invoke `ocamlc -i` so as to type-check the mock `.ml` file and infer its signature. The output of this command should be redirected to some file *sigfilename*. Then, Menhir can be invoked again, as follows.

`--infer-read-reply` *sigfilename*. When invoked in this mode, Menhir assumes that the file *sigfilename* contains the result of running `ocamlc -i` on the file *mockfilename*. It reads and parses this file, so as to obtain the OCaml type of every semantic action, then proceeds normally to generate a parser.

This protocol was introduced on 2018/05/23; earlier versions of Menhir do not support it. Its existence can be tested as follows:

`--infer-protocol-supported`. When invoked with this switch, Menhir immediately terminates with exit code 0. An earlier version of Menhir, which does not support this protocol, would display a help message and terminate with a nonzero exit code.

15.2 Compilation flags

The following switches allow querying Menhir so as to find out which compilation flags should be passed to the OCaml compiler and linker.

`--suggest-comp-flags`. This switch causes Menhir to print a set of suggested compilation flags, and exit. These flags are intended to be passed to the OCaml compilers (`ocamlc` or `ocamlopt`) when compiling and linking the parser generated by Menhir. What flags are suggested? In the absence of the `--table` switch, no flags are suggested. When `--table` is set, a `-I` flag is suggested, so as to ensure that `MenhirLib` is visible to the OCaml compiler.

`--suggest-link-flags-byte`. This switch causes Menhir to print a set of suggested link flags, and exit. These flags are intended to be passed to `ocamlc` when producing a bytecode executable. What flags are suggested? In the absence of the `--table` switch, no flags are suggested. When `--table` is set, the object file `menhirLib.cma` is suggested, so as to ensure that `MenhirLib` is linked in.

`--suggest-link-flags-opt`. This switch causes Menhir to print a set of suggested link flags, and exit. These flags are intended to be passed to `ocamlopt` when producing a native code executable. What flags are suggested? In the absence of the `--table` switch, no flags are suggested. When `--table` is set, the object file `menhirLib.cmxa` is suggested, so as to ensure that `MenhirLib` is linked in.

`--suggest-menhirLib`. This switch causes Menhir to print (the absolute path of) the directory where `MenhirLib` was installed.

`--suggest-ocamlfind`. This switch is deprecated and may be removed in the future. It always prints `false`.

16. Comparison with `ocamlyacc`

Roughly speaking, Menhir is 90% compatible with `ocamlyacc`. Legacy `ocamlyacc` grammar specifications are accepted and compiled by Menhir. The resulting parsers run and produce correct parse trees. However, parsers that explicitly invoke functions in the module `Parsing` behave slightly incorrectly. For instance, the functions that provide access to positions return a dummy position when invoked by a Menhir parser. Porting

a grammar specification from ocamlyacc to Menhir requires replacing all calls to `Parsing` with new Menhir-specific keywords (§7).

Here is an incomplete list of the differences between `ocamlyacc` and Menhir. The list is roughly sorted by decreasing order of importance.

- Menhir allows the definition of a nonterminal symbol to be parameterized (§5.2). A formal parameter can be instantiated with a terminal symbol, a nonterminal symbol, or an anonymous rule (§4.2.4). A library of standard parameterized definitions (§5.4), including options, sequences, and lists, is bundled with Menhir. EBNF syntax is supported: the modifiers **?**, **+**, and ***** are sugar for options, nonempty lists, and arbitrary lists (Figure 2).
- `ocamlyacc` only accepts LALR(1) grammars. Menhir accepts LR(1) grammars, thus avoiding certain artificial conflicts.
- Menhir's **%inline** keyword (§5.3) helps avoid or resolve some LR(1) conflicts without artificial modification of the grammar.
- Menhir explains conflicts (§6) in terms of the grammar, not just in terms of the automaton. Menhir's explanations are believed to be understandable by mere humans.
- Menhir offers an incremental API (in `--table` mode only) (§9.2). This means that the state of the parser can be saved at any point (at no cost) and that parsing can later be resumed from a saved state.
- Menhir offers a set of tools for building a (complete, irredundant) set of invalid input sentences, mapping each such sentence to a (hand-written) error message, and maintaining this set as the grammar evolves (§11).
- In `--rocq` mode, Menhir produces a parser whose correctness and completeness with respect to the grammar can be checked by Rocq (§12).
- Menhir offers an interpreter (§8) that helps debug grammars interactively.
- Menhir allows grammar specifications to be split over multiple files (§5.1). It also allows several grammars to share a single set of tokens.
- Menhir produces reentrant parsers.
- Menhir is able to produce parsers that are parameterized by OCaml modules.
- `ocamlyacc` requires semantic values to be referred to via keywords: `$1`, `$2`, and so on. Menhir allows semantic values to be explicitly named.
- Menhir warns about end-of-stream conflicts (§6.4), whereas `ocamlyacc` does not. Menhir warns about productions that are never reduced, whereas, at least in some cases, `ocamlyacc` does not.
- Menhir offers an option to typecheck semantic actions *before* a parser is generated: see `--infer`.
- `ocamlyacc` produces tables that are interpreted by a piece of C code, requiring semantic actions to be encapsulated as OCaml closures and invoked by C code. Menhir offers a choice between producing tables and producing code. In either case, no C code is involved. In fact, Menhir's code back-end produces *well-typed* and *highly efficient* code.
- Menhir makes OCaml's standard library module `Parsing` entirely obsolete. Access to locations is now via keywords (§7). Uses of `raise Parse_error` within semantic actions are deprecated. The function `parse_error` is deprecated. They are replaced with keywords (§10).
- Menhir's error-handling mechanism (§10) is inspired by `ocamlyacc`'s, but is not guaranteed to be fully compatible. Error recovery, also known as re-synchronization, is not supported by Menhir.
- The way in which severe conflicts (§6) are resolved is not guaranteed to be fully compatible with `ocamlyacc`.
- Menhir warns about unused **%token**, **%nonassoc**, **%left**, and **%right** declarations. It also warns about **%prec** annotations that do not help resolve a conflict.
- Menhir accepts OCaml-style comments.
- Menhir allows **%start** and **%type** declarations to be condensed.

- Menhir allows two (or more) productions to share a single semantic action.
- Menhir produces better error messages when a semantic action contains ill-balanced parentheses.
- `ocamlyacc` ignores semicolons and commas everywhere. Menhir regards semicolons and commas as significant, and allows them, or requires them, in certain well-defined places.
- `ocamlyacc` allows `%type` declarations to refer to terminal or nonterminal symbols, whereas Menhir requires them to refer to nonterminal symbols. Types can be assigned to terminal symbols with a `%token` declaration.

17. Questions and Answers

◇ **Is Menhir faster than `ocamlyacc`? What is the speed difference between `menhir` and `menhir --table`?** A (not quite scientific) benchmark suggests that the parsers produced by `ocamlyacc` and `menhir --table` have comparable speed, whereas those produced by `menhir` are between 2 and 5 times faster. This benchmark excludes the time spent in the lexer and in the semantic actions.

◇ **How do I write `Makefile` rules for Menhir?** This can be a bit tricky. If you must do this, see §15. It is recommended instead to use a build system with built-in support for Menhir, such as `dune` (preferred) or `ocamlbuild`.

◇ **How do I use Menhir with `ocamlbuild`?** Pass `-use-menhir` to `ocamlbuild`. To pass options to Menhir, pass `-menhir "menhir <options>"` to `ocamlbuild`. If you wish to use Menhir's table back-end, pass `-menhir "menhir --table"` to `ocamlbuild`, and either pass `-package menhirLib` to `ocamlbuild` or add the tag `package(menhirLib)` in the `_tags` file. To combine multiple `.mly` files, say `a.mly` and `b.mly`, into a single parser, say `parser.{ml,mli}`, create a file named `parser.mlypack` that contains the module names `A B`.

◇ **How do I use Menhir with `dune`?** Please use `dune` version 1.4.0 or newer, as it has appropriate built-in rules for Menhir parsers. In the `dune-project` file, write `(using menhir 2.0)` so as to enable support for Menhir.

In the simplest scenario, where the parser resides in a single source file `parser.mly`, the `dune` file should contain a "stanza" along the following lines:

```
(menhir
  (modules parser)
  (flags --explain --dump)
  (infer true)
)
```

Ordinary command line switches, like `--explain` and `--dump`, are passed as part of the `flags` line, as done above. The `--infer` switch has special status and should not be used directly; instead, write `(infer true)` or `(infer false)`, as done above. (The default is `true`.) The `--table` switch can also be listed as part of the `flags` line; if you do so, then you must add `menhirLib` to the list of libraries that your code requires, as in the following example:

```
(executable
   (name myexecutable)
   (libraries menhirLib)
)
```

If the flags `--table` and `--unparsing` switch are listed as part of the `flags` line, then the libraries `menhirLib` and `menhirCST` is required.

The directory `demos` offers several examples. For more details, see `dune`'s documentation. To deal with `.messages` files (§11), please use and adapt the rules found in the file `src/stage2/dune`.

◇ **My `.mly` file begins with a module alias declaration `module F = Foo`. Because of this, the `.mli` file generated by Menhir contains references to `F` instead of `Foo`. This does not make sense!** Beginning with Menhir 20200525, Menhir prefers to use the types inferred by the OCaml compiler over the types provided by the user in **%type** declarations. (This may sound strange, but these types can differ in some situations that involve polymorphic variants. Using the inferred type is required for type soundness.) In the presence of a module alias declaration such as `module F = Foo`, OCaml can infer types that begin with `F.` instead of `Foo.`, and Menhir does not detect that `F` is a local name. The fix is to place the module alias declaration inside `open struct ... end` (§4.1.1).

◇ **Menhir reports *more* shift/reduce conflicts than `ocamlyacc`! How come?** `ocamlyacc` sometimes merges two states of the automaton that Menhir considers distinct. This happens when the grammar is not LALR(1). If these two states happen to contain a shift/reduce conflict, then Menhir reports two conflicts, while `ocamlyacc` only reports one. Of course, the two conflicts are very similar, so fixing one will usually fix the other as well.

◇ **I do not use `ocamllex`. Is there an API that does not involve lexing buffers?** Like `ocamlyacc`, Menhir produces parsers whose monolithic API (§9.1) is intended for use with `ocamllex`. However, it is possible to convert them, after the fact, to a simpler, revised API. In the revised API, there are no lexing buffers, and a lexer is just a function from unit to tokens. Converters are provided by the library module `MenhirLib.Convert`. This can be useful, for instance, for users of `sedlex`, the Unicode-friendly lexer generator. Also, please note that Menhir's incremental API (§9.2) does not mention the type `Lexing.lexbuf`. In this API, the parser expects to be supplied with triples of a token and start/end positions of type `Lexing.position`.

◇ **Is there other useful magic in `MenhirLib`?** There is some. The module `MenhirLib.ErrorReports` offers some facilities for constructing syntax error messages. The module `MenhirLib.LexerUtil` offers facilities for extracting the position of a syntax error out of the lexing buffer and displaying it in a readable way.

◇ **I need both %inline and non-%inline versions of a nonterminal symbol. Is this possible?** Define an **%inline** version first, then use it to define a non-**%inline** version, like this:

```
%inline ioption(X):  (* nothing *) { None } | x = X { Some x }
         option(X): o = ioption(X) { o }
```

This can work even in the presence of recursion, as illustrated by the following definition of (reversed, left-recursive, possibly empty) lists:

```
%inline irevlist(X):    (* nothing *) { [] } | xs = revlist(X) x = X { x :: xs }
         revlist(X): xs = irevlist(X) { xs }
```

The definition of `irevlist` is expanded into the definition of `revlist`, so in the end, `revlist` receives its normal, recursive definition. One can then view `irevlist` as a variant of `revlist` that is inlined one level deep.

◇ **Can I ship a generated parser while avoiding a dependency on `MenhirLib`?** Yes. One option is to use the code back-end (that is, to not use `--table`). In this case, the generated parser is self-contained. Another option is to use the table back-end (that is, use `--table`) and include a copy of the files `menhirLib.{ml,mli}` together with the generated parser. The command `menhir --suggest-menhirLib` will tell you where to find these source files.

◇ **Why is `$startpos` off towards the left? It seems to include some leading whitespace.** Indeed, as of 2015/11/04, the computation of positions has changed so as to match `ocamlyacc`'s behavior. As a result, `$startpos` can now appear to be too far off to the left. This is explained in §7. A solution may be to use `$symbolstartpos` instead.

◇ **Can I pretty-print a grammar in ASCII, HTML, or LaTeX format?** Yes. Have a look at `obelisk` [5].

◇ **Does Menhir support mid-rule actions?** Yes. See *midrule* and its explanation in §5.4.

18. Technical background

After experimenting with Knuth's canonical LR(1) technique [16], we found that it *really* is not practical, even on today's computers. For this reason, Menhir implements a slightly modified version of Pager's algorithm [24], which merges states on the fly if it can be proved that no reduce/reduce conflicts will arise as a consequence of this decision. This is how Menhir avoids the so-called *mysterious* conflicts created by LALR(1) parser generators [8, section 5.7].

Menhir's algorithm for explaining conflicts is inspired by DeRemer and Pennello's [7] and adapted for use with Pager's construction technique.

By default, Menhir produces code, as opposed to tables. This approach has been explored before [3, 10]. Menhir performs some static analysis of the automaton in order to produce more compact code.

When asked to produce tables, Menhir performs compression via first-fit row displacement, as described by Tarjan and Yao [30]. Double displacement is not used. The action table is made sparse by factoring out an error matrix, as suggested by Dencker, Dürre, and Heuft [6].

The type-theoretic tricks that triggered our interest in LR parsers [27] are implemented in Menhir's code back-end. (It took 16 years, from the initial idea in 2005 to the re-implementation of the code back-end in 2021.) A generalized algebraic data type (GADT) is used to describe the shape of the stack and the relationship that exists between the shape of the stack and the current state of the automaton.

The main ideas behind the Rocq back-end are described in a paper by Jourdan, Pottier and Leroy [14]. The C11 parser in the CompCert compiler [19] is constructed by Menhir and verified by Rocq, following this technique. How to construct a correct C11 parser using Menhir is described by Jourdan and Pottier [13].

The approach to error reports presented in §11 was proposed by Jeffery [11] and further explored by Pottier [25] and by Bour and Pottier [4].

The unparsing API and the settlement algorithm were proposed by Pottier [26].

References

[1] Alfred V. Aho, Ravi Sethi, and Jeffrey D. Ullman. *Compilers: Principles, Techniques, and Tools*. Addison-Wesley, 1986.

[2] Andrew Appel. *Modern Compiler Implementation in ML*. Cambridge University Press, 1998.

[3] Achyutram Bhamidipaty and Todd A. Proebsting. Very fast YACC-compatible parsers (for very little effort). *Software: Practice and Experience*, 28(2):181–190, 1998.

[4] Frédéric Bour and François Pottier. Faster reachability analysis for LR(1) parsers. In *Software Language Engineering*, pages 113–125, October 2021.

[5] Lélio Brun. Obelisk. `https://github.com/Lelio-Brun/Obelisk`, 2017.

[6] Peter Dencker, Karl Dürre, and Johannes Heuft. Optimization of parser tables for portable compilers. *ACM Transactions on Programming Languages and Systems*, 6(4):546–572, 1984.

[7] Frank DeRemer and Thomas Pennello. Efficient computation of $LALR(1)$ look-ahead sets. *ACM Transactions on Programming Languages and Systems*, 4(4):615–649, 1982.

[8] Charles Donnelly and Richard Stallman. *Bison*, 2015.

[9] John E. Hopcroft, Rajeev Motwani, and Jeffrey D. Ullman. *Introduction to Automata Theory, Languages, and Computation*. Addison-Wesley, 2000.

[10] R. Nigel Horspool and Michael Whitney. Even faster LR parsing. *Software: Practice and Experience*, 20(6):515–535, 1990.

[11] Clinton L. Jeffery. Generating LR syntax error messages from examples. *ACM Transactions on Programming Languages and Systems*, 25(5):631–640, 2003.

[12] Steven C. Johnson. Yacc: Yet another compiler compiler. In *UNIX Programmer's Manual*, volume 2, pages 353–387. Holt, Rinehart, and Winston, 1979.

[13] Jacques-Henri Jourdan and François Pottier. A simple, possibly correct LR parser for C11. *ACM Transactions on Programming Languages and Systems*, 39(4):14:1–14:36, August 2017.

[14] Jacques-Henri Jourdan, François Pottier, and Xavier Leroy. Validating $LR(1)$ parsers. volume 7211 of *Lecture Notes in Computer Science*, pages 397–416, 2012.

[15] Paul Klint, Ralf Lämmel, and Chris Verhoef. Toward an engineering discipline for grammarware. 14(3):331–380, 2005.

[16] Donald E. Knuth. On the translation of languages from left to right. *Information & Control*, 8(6):607–639, 1965.

[17] Bernard Lang. Deterministic techniques for efficient non-deterministic parsers. In *International Colloquium on Automata, Languages and Programming*, volume 14 of *Lecture Notes in Computer Science*, pages 255–269, August 1974.

[18] Xavier Leroy. The CompCert C verified compiler. `https://github.com/AbsInt/CompCert`, 2014.

[19] Xavier Leroy. The CompCert C compiler. `http://compcert.inria.fr/`, 2015.

[20] Xavier Leroy, Damien Doligez, Alain Frisch, Jacques Garrigue, Didier Rémy, and Jérôme Vouillon. The OCaml system: documentation and user's manual, 2016.

[21] Scott McPeak. Elkhound: A fast, practical GLR parser generator. Technical Report UCB/CSD-2-1214, University of California, Berkeley, December 2002.

[22] Scott McPeak and George C. Necula. Elkhound: A fast, practical GLR parser generator. In *Compiler Construction (CC)*, volume 2985 of *Lecture Notes in Computer Science*, pages 73–88, March 2004.

[23] Rahman Nozohoor-Farshi. *GLR Parsing for ϵ-Grammars*, pages 61–75. Kluwer, 1991.

[24] David Pager. A practical general method for constructing $LR(k)$ parsers. *Acta Informatica*, 7:249–268, 1977.

[25] François Pottier. Reachability and error diagnosis in LR(1) parsers. In *Compiler Construction (CC)*, pages 88–98, 2016.

[26] François Pottier. Correct, fast LR(1) unparsing. In *Journées Francophones des Langages Applicatifs (JFLA)*, January 2024.

[27] François Pottier and Yann Régis-Gianas. Towards efficient, typed LR parsers. *Electronic Notes in Theoretical Computer Science*, 148(2):155–180, 2006.

[28] J. Rekers. Generalized LR parsing for general context-free grammars. Technical Report CS-R9153, CWI, December 1991.

[29] David R. Tarditi and Andrew W. Appel. *ML-Yacc User's Manual*, 2000.

[30] Robert Endre Tarjan and Andrew Chi-Chih Yao. Storing a sparse table. *Communications of the ACM*, 22(11):606–611, 1979.

[31] Masaru Tomita. An efficient context-free parsing algorithm for natural languages. In *International Joint Conferences on Artificial Intelligence*, pages 756–764, August 1985.