ML under Unix

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ABSTRACT

ML is a statically-scoped functional programming language. Functions are first class objects which can be passed as parameters, returned as values and embedded in data structures. Higher-order functions (i.e. functions receiving or producing other functions) are used extensively.

ML is an interactive language. An ML session is a dialogue of questions and answers with the ML system. Interaction is achieved by an incremental compiler, which has some of the advantages of interpreted languages (fast turnaround dialogues) and of compiled languages (high execution speed).

ML is a strongly typed language. Every ML expression has a type, which is determined statically. The type of an expression is usually automatically inferred by the system, without need of type definitions. The ML type system guarantees that any expression that can be typed will not generate type errors at run time. Static type checking traps at compile-time a large proportion of bugs in programs.

ML has a polymorphic type system which confers on the language much of the flexibility of type-free languages, without paying the conceptual cost of run-time type errors or the computational cost of run-time type checking.

ML has a rich collection of data types. Moreover the user can define new abstract data types, which are indistinguishable from the system predefined types. Abstract types are used extensively in large programs for modularity and abstraction.

ML has an exception-trap mechanism, which allows programs to handle uniformly system and user generated exceptions. Exceptions can be selectively trapped, and exception handlers can be specified.

ML programs can be grouped into modules, which can be separately compiled. Dependencies among modules can be easily expressed, and the sharing of common submodules is automatically guaranteed. The system keeps track of module versions to detect compiled modules which are out of date.

This manual describes an implementation of ML running on VAX under the Unix operating system.

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1. Introduction

ML is a functional programming language. Functions are first class objects which can be passed as parameters, returned as values and embedded in data structures. Higher-order functions (i.e. functions receiving or producing other functions) are used extensively. Function application is the most important control construct, and it is extremely uniform: all functions take exactly one argument and return exactly one result. Arguments and results can however be arbitrary structures, thereby achieving the effect of passing many arguments and producing many results. Arguments to functions are evaluated before the function calls.

ML is an interactive language. An ML session is a dialogue of questions and answers with the ML system. Interaction is achieved by an incremental compiler, which has some of the advantages of interpreted languages (fast turnaround dialogues) and of compiled languages (high execution speed).

ML is statically scoped. All the variables are associated with values according to where they occur in the program text, and not depending on run-time execution paths. This avoids name conflicts in large programs, because variable names can be hidden in local scopes, and prevents accidental damage to preexisting programs. Static scoping greatly improves the security and, incidentally, the efficiency of an interactive language, and it is necessary for implementing higher-order functions with their conventional mathematical meaning.

ML is a strongly typed language. Every ML expression has a type, which is determined statically. The type of an expression is usually automatically inferred by the system, without need for type definitions. This type inference property is very useful in interactive use, when it would be distracting having to provide all the type information. However, it is always possible to specify the type of any expression or function, e.g. as good documentation practice in large programs. The ML type system guarantees that any expression that can be typed will not generate type errors at run time (for some adequate definition of what a type error is). Static typechecking traps at compile-time a large proportion of bugs in programs that make extensive use of the ML data structuring capabilities (typechecking does not help in numerical programs!). Usually, only truly "logical" bugs are left after compilation.

ML has a polymorphic type system. Type expressions may contain type variables, indicating, for example, that a function can work uniformly on a class of arguments of different (but structurally related) types. For example the length function which computes the length of a list has type \( \alpha \text{ list} \rightarrow \text{int} \) (which is automatically inferred from the obvious untyped recursive definition). Length can work on lists of any type (lists of integers, lists of functions, lists of lists, etc.), essentially because it disregards the elements of the list. The polymorphic type system confers on ML much of the flexibility of type-free languages, without paying the conceptual cost of run-time type errors or the computational cost of run-time typechecking.

ML has a rich collection of data types. Moreover the user can define new abstract data types, which are indistinguishable from the system predefined types. Abstract types are used extensively in large programs for modularity and abstraction. They put a barrier between the implementor of a package and its users, so that changes in the implementation of an abstract type will not influence the users, as long as the external interface is preserved. Abstract types also provide a clean extension mechanism for the language. If a new data type is needed which cannot be effectively implemented with the existing ML primitives (e.g. bitmaps for graphics), this can be still specified and prototyped in ML as a new abstract type, and then efficiently implemented and added to the basic system. This path has already been followed for arrays, which are not part of the language definition and can be considered as a predefined abstract type which just happens to be more efficient than its ML specification would lead one to believe.

ML has an exception-trap mechanism, which allows programs to uniformly handle system and user generated exceptions. Exceptions can be selectively trapped, and handlers can be specified.

ML programs can be grouped into modules, which can be separately compiled. Dependencies among modules can be easily expressed, and the sharing of common submodules is automatically guaranteed. The system keeps track of module versions to detect compiled modules which are out
else true;

result: false : bool

The if part must be a boolean expression; two predefined constants true and false denote the basic boolean values; and the boolean operators are not, & (and) and or.

1.2. Declarations

Variables can be bound to values by declarations. Declarations can appear at the 'top-level', in which case their scope is global, or in scope blocks, in which case they are have a limited local scope spanning a single expression. Global declarations are introduced in this section, and local declarations in the next one.

Declarations are not expressions; they establish bindings instead of returning values. Value bindings are introduced by the keyword val, additional value bindings are prefixed by and:

```
declaration: val a = 3
and b = 5
and c = 2;

bindings: val a = 3 : int
val b = 5 : int
val c = 2 : int

expression: (a + b) div c;

result: 4 : int
```

In this case we have defined the variables a, b and c at the top level; they will always be accessible from now on, unless redefined. Value bindings printed by the system are always prefixed by val, to distinguish them from type bindings and module bindings which we shall encounter later.

You may notice that all the variables must be initialized when introduced. Their initial values determine their types, which do not need to be given explicitly. The type of an expression is generally inferred automatically by the system and printed after the result.

Value declarations are also used to define functions, with the following intuitive syntax:

```
declaration: val f x = x + 1;

binding: val f : int -> int

declaration: val g(a,b) = (a + b) div 2;

binding: val g : (int * int) -> int

expression: f 3, g(8,4);

result: 4,6 : int * int
```

(the arrow -> denotes the function-space type operator.)

The function f has one argument x. The result of a function is just the value of its body, in this case x+1. Arguments to functions do not need to be parenthesized in general (both in definitions and applications): the simple juxtaposition of two expressions is interpreted as a function application. Function application is treated as an invisible infix operator, and it is the strongest-binding
\[
\text{in } (a + b) \div 2 \text{ end;}
\]

\[
\text{result: } 4 : \text{int}
\]

here the identifiers \(a\) and \(b\) are bound to the values 3 and 5 respectively for the extent of the expression \((a + b) \div 2\). No top-level binding is introduced; the whole \textit{let} construct is an expression whose value is the value of its body.

Variables can be locally redefined, hiding the previous definitions for the extent of the local scope. Outside the local scope, the old definitions are not changed:

\[
\begin{align*}
\text{declaration:} & \quad \text{val } a = 3 \\
& \quad \text{and } b = 5;
\end{align*}
\]

\[
\begin{align*}
\text{bindings:} & \quad \text{val } a = 3 : \text{int} \\
& \quad \text{val } b = 5 : \text{int}
\end{align*}
\]

\[
\begin{align*}
\text{expression:} & \quad (\text{let } \text{val } a = 8 \text{ in } a + b \text{ end}, a; \\
& \quad 13,3 : \text{int} * \text{int}
\end{align*}
\]

The body of a scope-block can access all the variables declared in the surrounding environment (like \(b\)), unless they are redefined (like \(a\)).

The \textit{and} keyword is used to define sets of independent bindings: none of them can use the variables defined by the other bindings. However, a declaration often needs variables introduced by previous declarations. At the top-level this is done by introducing those declarations sequentially (here two declarations are typed on the same line):

\[
\begin{align*}
\text{declarations:} & \quad \text{val } a = 3; \text{ val } b = 2 \times a;
\end{align*}
\]

\[
\begin{align*}
\text{bindings:} & \quad \text{val } a = 3 : \text{int} \\
& \quad \text{val } b = 6 : \text{int}
\end{align*}
\]

Similarly, declarations can be composed sequentially in local scopes by separating them by ‘,’:

\[
\begin{align*}
\text{expression:} & \quad \text{let } \text{val } a = 3; \\
& \quad \text{val } b = 2 \times a \\
& \quad \text{in } a,b \text{ end;}
\end{align*}
\]

\[
\text{result: } 3,6 : \text{int} * \text{int}
\]

In simple cases, the effect of ‘,’ can be achieved by nested scope blocks; here is an equivalent formulation of the previous example:

\[
\begin{align*}
\text{expression:} & \quad \text{let } \text{val } a = 3 \\
& \quad \text{in } \text{let } \text{val } b = 2 \times a \\
& \quad \text{in } a,b \text{ end end;}
\end{align*}
\]

\[
\text{result: } 3,6 : \text{int} * \text{int}
\]
is actually a pair of values.

As every function actually has a single argument, the standard function definition looks like `val f x = ...`. We can put the definition of `plus` in this form as follows:

```plaintext
declaration: val plus x = let val a,b = x in a + b end;
```

What we did in the previous definitions of `plus` was to use a pattern `(a,b)` for `x`, which implicitly associated `a` and `b` respectively with the first and second components of `x`. These patterns come in many forms. For example a pattern `[a;b;c]` matches a list of exactly three elements, which are bound to `a`, `b` and `c`; a pattern `first::rest` matches a non-empty list whose first element is associated with `first`, and the rest to `rest`; similarly `first::second::rest` matches a list of at least two elements; etc. The most common patterns are of course tuples, like `(a,b,c)`, but more complicated patterns can be constructed by nesting, like `((a;b),c,(d,e);...)`. The special pattern `_` matches any value without establishing any binding. Patterns can conveniently replace the use of selector functions for unpacking data.

Patterns do not only appear in function parameters: they can also be used in simple variable declarations:

```plaintext
declaration: val [a;b;c] = a,b,c;
declaration: val a,b,c = [1;2;3];
bindings: val a = 1 : int
          val b = 2 : int
          val c = 3 : int
```

In the above example we have a function `f` returning three values, and the pattern `a,b,c` is used to unpack the result of `[1,2,3]` into its components.

Recursive functions are defined by placing the keyword `rec` in a declaration, just before the function definition:

```plaintext
declaration: val rec factorial n = if n = 0 then 1 else n * factorial(n-1);
binding:    val factorial : int -> int
```

The keyword `rec` is needed to identify the recursive occurrence of the identifier `factorial` with its defining occurrence. If `rec` is omitted, the identifier `factorial` is searched for in the environment outside the definition; in this case there is no previous definition of `factorial`, and an error would be reported.

The effect of `rec` propagates to whole groups of definitions; this is how mutually recursive functions are defined:

```plaintext
val rec f a = .. g ..
and g b = .. f .. ;
```

Functions can also be defined by `case analysis`, as a sequence of pattern-action pairs separated by vertical bars:
operations, whose types are:

\[
\begin{align*}
nil &: \text{'a list} \\
:: &: (\text{'a * 'a list}) \rightarrow \text{'a list} \\
null &: \text{'a list} \rightarrow \text{bool} \\
hd &: \text{'a list} \rightarrow \text{'a} \\
tl &: \text{'a list} \rightarrow \text{'a list} \\
@ &: (\text{'a list * 'a list}) \rightarrow \text{'a list}
\end{align*}
\]

Note that if these operators were not polymorphic, we would need different primitive operators for all possible types of list elements! The 'a shared by the two arguments of :: (cons) prevents any attempt to build lists containing objects of different types.

One can always determine the type of any ML function or object just by typing its name at the top level; the object is evaluated and, as usual, its type is printed after its value.

expression: \[
[;]
\]
result: \[
[;] : \text{'a list}
\]
expression: \[
hd;
\]
result: \[
\text{fun} : (\text{'a list}) \rightarrow \text{'a}
\]

1.7. Higher-order functions

ML supports higher-order functions, i.e. functions which take other functions as arguments or deliver functions as results. A good example of use of higher-order functions is in partial application:

declaration: \[
\text{val times a b = a \times b;}
\]

binding: \[
\text{val times : int} \rightarrow (\text{int} \rightarrow \text{int})
\]
expression: \[
times 3 4;
\]
result: \[
12 : \text{int}
\]

declaration: \[
\text{val twice = times 2;}
\]

binding: \[
\text{val twice : int} \rightarrow \text{int}
\]
expression: \[
twice 4;
\]
result: \[
8 : \text{int}
\]

Note the type of times, and how it is applied to arguments: \text{times 3 4} is read as \text{(times 3) 4}. Times first takes an argument 3 and returns a function from integers to integers; this function is then applied to 4 to give the result 12. We may choose to give a single argument to times (this is what is meant by partial application) to define the function twice, and supply the second argument later.

The function composition function, defined below, is a good example of partial application (it also has an interesting polymorphic type). Note how patterns are used in its definition.

declaration: \[
\text{val comp (f,g) x = f (g x);}
\]
Every exception is associated with an *exception string*, which describes the reason of failure: in this case "hd" and in the previous example "div".

Exceptions can be *trapped* before they propagate all the way to the top level, and an alternative value can be returned:

```
expression:     hd [] ? 3;
result:         3 : int
```

The question mark operator traps all the exceptions which happen during the execution of the expression on its left, and returns the value of the expression on its right. If the left hand side does not raise exceptions, then its value is returned and the right hand side is ignored.

Exceptions can be trapped selectively by a double question mark, followed by a list of strings: only exceptions with strings appearing in that list are trapped, while the other exceptions are propagated outward.

```
expression:     hd [] ?? ["hd"; "ll"] 3;
result:         3 : int
expression:     1 div 0 ?? ["hd"; "ll"] 3;
exception:      Exception: div
```

The user can generate exceptions by the *escape* keyword followed by a string, which is the exception reason.

```
expression:     escape "fail";
exception:      Exception: fail
expression:     hd [] ? escape "emptylist";
exception:      Exception: emptylist
```

There is no real distinction between system and user generated exceptions: both can be trapped and are reported at the top level in the same way.

### 1.9. Types

Types describe the *structure* of objects, i.e. whether they are numbers, tuples, lists, strings etc. In the case of functions, they describe the structure of the function arguments and results, e.g. int to int functions, string list to bool functions, etc.

A type only gives information about attributes which can be computed at compile time, and does not help distinguishing among different classes of objects having the same structure. Hence the set of positive integers is not a type, nor is the set of lists of length 3.

On the other hand, ML types can express structural relations inside objects, for example that the right part of a pair must have the same type (whatever that type is) as the left part of the pair, or that a function must return an object of the same type as its argument (whatever that type may be).

Types like *bool*, *int*, and *string*, which do not show any internal structure, are called *basic*. Compound types are built by *type operators* like * (cartesian product), list (list) and -> (function space). Type operators are usually infix or suffix: int * int, int list and int -> int are the types of
declaration: \( \text{val } (a : \text{int}) = 3; \)

declaration: \( \text{val } f (a : \text{int}, b : \text{int}) : \text{int} = a + b; \)

declaration: \( \text{val } f ((a,b) : \text{int} \times \text{int}) = (a + b) : \text{int}; \)

The last two examples are equivalent. A `:` type just before the `=` of a function definition refers to the result type of the function.

1.10. Concrete types

A concrete type is a type for which constructors are available, together with other operations. A constructor is an operation which creates elements of some concrete type, by assembling simpler objects of other types.

Constructors are invertible functions: whatever a constructor does, can be undone by disassembling the parts which had been put together by the constructor. This allows constructors (or actually, their inverses) to be used in patterns to destruct data. We have already seen examples of this dual usage concerning the tuple constructor `\( \ldots , \ldots \)` and the list constructors `nil` and `::` (cons).

A concrete type and its constructors should be considered as a single conceptual unit. Whenever a new concrete type is defined, its constructors are defined at the same time. Wherever a concrete type is known, its constructors are also known.

New concrete types and their constructors can be defined by type declarations. A type declaration defines at the same time a new type name, the names of the constructors for that type and the structure of the new type. In general a new type can consist of several alternatives, separated by `|`; for each of them we have a separate constructor, followed by the keyword `of` and the type of the argument of that constructor. The keyword `of` and the succeeding type can be omitted: in this case the constructor is also called a constant of the new type.

For example, money can be a coin of some value (in cents), a bill of some value (in dollars), a check of some bank for some amount (in cents), or the absence of money.

declaration: \( \text{type } \text{money} = \text{nomoney} | \text{coin} \text{ of int} | \text{bill of int} | \text{check of string} \times \text{int} \)

bindings: \( \text{type } \text{money} = \text{nomoney} | \text{coin of int} | \text{bill of int} | \text{check of string} \times \text{int} \)
\( \text{con } \text{nomoney} : \text{money} \)
\( \text{con } \text{coin} : \text{int} \rightarrow \text{money} \)
\( \text{con } \text{bill} : \text{int} \rightarrow \text{money} \)
\( \text{con } \text{check} : (\text{string} \times \text{int}) \rightarrow \text{money} \)

Here nomoney, coin, bill and check are money constructors (nomoney is a money constant). Constructors can be used like ordinary functions in expressions:

declaration: \( \text{val } \text{nickel} = \text{coin 5} \)
\( \text{and } \text{dime} = \text{coin 10} \)
\( \text{and } \text{quarter} = \text{coin 25}; \)

But they can also be used in patterns:

declaration: \( \text{val } \text{amount nomoney} = 0 | \text{amount (coin cents)} = \text{cents} | \text{amount (bill dollars)} = 100 \times \text{dollars} | \text{amount (check(bank,cents))} = \text{cents}; \)

binding: \( \text{val } \text{amount : money} \rightarrow \text{int} \)
(parts*red + parts*red') div totalparts,
(parts*blue + parts*blue') div totalparts,
(parts*yellow + parts*yellow') div totalparts)
end;
end;

bindings:
  abtype color
  val white = -- : color
  val red = -- : color
  val blue = -- : color
  val yellow = -- : color
  val mix : (int * color * int * color) --> color

Composite colors can be obtained by mixing the primary colors in different proportions:

declaration:
  val green = mix(2,yellow,1,blue)
  and black = mix(1,red,2,mix(1,blue,1,yellow))
  and pink = mix(1,red,2,white);

The bindings determined by the abstract type declaration are: an abstract type color whose internal structure is hidden; four colors (white, red, blue and yellow, printed as --) which are abstract objects whose structure is hidden; and a function to mix colors. No other operation can be applied to colors (unless defined in terms of the primitives), not even equality: if needed, an equality on colors can be defined as part of the abstract type definition.

An operation like mix, which takes abstract objects and produces abstract objects, typically uses patterns to get the representations of its arguments, manipulates the representations, and then uses constructors to produce the result.

As we said, the structure of abstract types and objects is hidden; for example val redpart,... = pink does not give the intensity of red in that color, but produces a type error:

expression:    val redpart,... = pink;

  type error:    Type Clash in:     ((redpart,...) = pink)
                 Looking for:     'a * 'b * 'c
                 I have found:    color

The correct thing to do is val blend(redpart,...) = pink, but only where blend is available.

This protection mechanism allows one to change the representation of an abstract type without affecting the programs which are already using that type. For example we could have three pigments "red", "blue" and "yellow", and let a color be a list of pigments, where each pigment can appear at most 15 times; white would be blend [], etc. If we define all the operations appropriately, nobody will be able, from the outside, to distinguish between the two implementations of colors.

1.12. Interacting with the ML system

ML is an interactive language. It is entered by typing ml as a Unix command, and it is exited by typing Control-D.

Once the system is loaded, the user types phrases (i.e. expressions, top level declarations or commands), and some result or acknowledgement is printed. This cycle is repeated over and over, until the system is exited.

Every top-level phrase is terminated by a semicolon. A phrase can be distributed on several lines by breaking it at any position where a blank character is accepted. Several phrases can also be written on the same line.
The it variable is very useful in interaction, when used to access values which have 'fallen on the floor' because they have been computed as expressions but have not been bound to any variable. It is not a keyword or a command, but just a plain variable (you can even temporarily redefined it by typing `val it = exp;`). Every time that an expression `exp;` is entered at the top level, this is considered an abbreviation for `val it = exp;`. Hence it is statically scoped, so that old its and new its are totally independent and simply hide each other.

1.13. Errors

Syntax errors report the fragment of code which could not be parsed, and often suggest the reason for the error. The erroneous program fragment is at most one line long; ellipses appear at its left when the source code was longer than a line. It is important to remember that the error was found at the extreme right of the error message.

```plaintext
- if true then 3;
  Syntax Error: if true then 3;
  I was expecting an "else"
```

Identifiers, type identifiers and type variables can be undefined; here are the messages given in those situations (type variables must be present on the left of a type definition whenever they are used on the right):

```plaintext
- noway;
  Unbound Identifier: noway
- 3 : noway;
  Unbound Type Identifier: noway
- type t = 'noway
  Unbound Type Variable: 'noway
```

Type errors show the context of occurrence of the error and the two types which could not be matched. The context might not correspond exactly to the source code because it is reconstructed from internal data structures.

```plaintext
- 3 + true;
  Type Clash in: (3 + true)
  Looking for: int
  I have found: bool
```
declaration:     type unit = ();

bindings:        type unit = ()
                 con () : unit

except that the above is not legal ML syntax: user defined constants must be identifiers, and () is treated specially.

3.2. Booleans

The predefined constants

true, false : bool
(constants)

denote the respective boolean values. Boolean operators are:

not, & or    : bool => bool
(infixes)

Both arguments of & and or are always evaluated. In some languages & and or evaluate only one argument when this is sufficient to determine the result; the same effect can be achieved in ML by using nested conditional expressions.

The boolean type is not primitive; it can be defined in ML as:

declaration:     type bool = false | true;

bindings:        type bool = false | true
                 con false : bool
                 con true : bool

All the boolean operations (including if-then-else) can then be defined or simulated by case analysis.

3.3. Integers

The integer operators are:

.. "2, "1, 0, 1, 2, .. : int
-                   : int => int
+ , - , *, div, mod : (int * int) => int
> , >= , = , <     : (int * int) => bool

(constants)
(infixes)

Negative integers are written '3, where ' is the complement function (while '-' is difference). Integers have unbounded precision; arithmetic exceptions can only be generated by integer division \texttt{div} and module \texttt{mod}, which escapes with string "\texttt{div}" when their second argument is zero.

The integer type could in principle be defined in ML as:

declaration:     type rec nat = one | succ of nat;

declaration:     type int = neg of nat | zero | pos of nat;
null : 'a list -> bool
hd : 'a list -> 'a
tl : 'a list -> 'a list
length : ('a list) -> int
@ : ('a list * 'a list) -> 'a list (infix)
rev : ('a list) -> ('a list)
map : ('a -> 'b) -> ('a list) -> ('b list)
fold, revfold : (('a * 'b) -> 'b) -> ('a list) -> ('b -> 'b))

- null tests whether a list is empty.
- hd (head) extracts the first element of a list; it escapes with string "hd" on empty lists.
- tl (tail) returns a list where the first element has been removed; it escapes with string "tl" on empty lists.
- length returns the length of a list.
- @ (append) appends two lists (e.g. [1;2]@[3;4] is the same as [1;2;3;4]).
- rev returns the reverse of a list.
- map takes a function and then a list, and applies the function to all the elements of the list, returning the list of the results (i.e. map f [e_1; .. ; e_n] is [f (e_1); .. ; f (e_n)]).
- fold maps a binary function to an n-ary function over a list (e.g. it can map + to the function computing the sum of the elements of a list), it takes first a binary function, then the list to accumulate, then the value to return on empty lists (i.e. fold f [e_1; .. ; e_n] e is f (e_1, .. f (e_n,e))).
- revfold is just like fold but accumulates in the opposite direction (i.e. revfold f [e_1; .. ; e_n] e is f (e_n, .. f (e_1,e))).

The type of lists can be defined in ML as:

declarations:
  infix ++

declarations: type rec 'a list = nil | :: of int * (int list);

bindings:
  type 'a list = nil | :: of int * (int list);
  con nil : 'a list
  con :: : ('a * ('a list)) -> ('a list)

All the list operations can then be defined by case analysis. The bracket notation (e.g. [1;2]) is just an abbreviation for the compositions of list constructors (e.g. 1::2::nil).

typing rule: if e_1 : t and .. and e_n : t then [e_1; .. ; e_n] : t list

3.6. Strings

A string constant is a sequence of characters enclosed in quotes, e.g. "this is a string".

Operation on strings are:

<table>
<thead>
<tr>
<th>constant</th>
<th>type</th>
<th>(constants)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot; ... &quot;</td>
<td>string</td>
<td></td>
</tr>
<tr>
<td>size</td>
<td>string -&gt; int</td>
<td></td>
</tr>
<tr>
<td>extract</td>
<td>(string * int * int) -&gt; string</td>
<td></td>
</tr>
<tr>
<td>explode</td>
<td>string -&gt; string list</td>
<td></td>
</tr>
<tr>
<td>implode</td>
<td>string list -&gt; string</td>
<td></td>
</tr>
<tr>
<td>explodeascii</td>
<td>string -&gt; int list</td>
<td></td>
</tr>
<tr>
<td>implodeascii</td>
<td>int list -&gt; string</td>
<td></td>
</tr>
<tr>
<td>intofstring</td>
<td>string -&gt; int</td>
<td></td>
</tr>
<tr>
<td>stringofint</td>
<td>int -&gt; string</td>
<td></td>
</tr>
</tbody>
</table>
binding:  type 'a refpair = refpair of ('a ref) * ('a ref)
          con refpair : ('a ref) * ('a ref) -> ('a refpair)

declaration:  val r = ref 3;
               val p = refpair(r,r);

bindings:  val r = ref 3 : int ref
           val p = refpair(ref 3,ref 3) : int refpair

expression:  r ::= 5;

result:  () : unit

expression:  p;

result:  refpair(ref 5,ref 5) : int refpair

3.8. Arrays

Arrays are ordered collections of values with a constant access time retrieval operation. They have
a lower bound and a size, which are integers, and can be indexed by integer numbers in the range
lowerbound ≤ i ≤ lowerbound+size. Arrays can have any positive or null size, but once they are
built they retain their initial size.

Arrays over values of type t have type t array. Arrays can be built over elements of any type;
arrays of arrays account for multi-dimensional arrays.

The array primitives are:

array  : (int * int * 'a) -> 'a array
arrayoflist  : (int * 'a list) -> 'a array
lowerbound : 'a array -> int
arraysize : 'a array -> int
sub  : ('a array * int) -> 'a
      (infix)
update  : ('a array * (int * 'a)) -> unit
          (infix)
arraytolist : 'a array -> 'a list

- array makes a constant array (all items equal to the third argument) of size n≥0 (second argu-
  ment) from a lowerbound (first argument). It escapes with string "array" if the size is negative.
- arrayoflist makes an array out of a list, given a lower bound for indexing.
- lowerbound returns the lower bound of an array.
- arraysize returns the size of an array.
- sub extracts the i-th item of an array. It escapes with string "sub" if the index is not in range.
- update updates the i-th element of an array with a new value. It escapes with string "update" if
  the index is not in range.
- arraytolist converts an array into the list of its elements.

Arrays are not a primitive concept in ML: they can be defined as an abstract data type over lists of
assignable references. This specification of arrays, which is given below, determines the semantics
of arrays, but does not have a fast indexing operation. Arrays are actually implemented at a lower
level as contiguous blocks of memory with constant time indexing. Here is an ML specification of
arrays, semantically equivalent to their actual implementation (see sections "Lists", "Updatable
references" and "Lexical declarations" to properly understand this program).

infix sub;
infix update;
val op update = ();
val arraytolist = ();

This transforms ML into a purely applicative language, by making all the side-effecting operations and types inaccessible.

3.9. Patterns and matches

The left hand side of an = in a value definition can be a simple variable, or a more complex pattern involving several distinct variables. Patterns are also used in formal parameters of functions and in case expressions. In all these situations a value has to be decomposed according to its structure; the matching process produces a set of bindings by associating the variables in the pattern with the corresponding parts of the value.

A pattern can be a _ sign (matching any value), an identifier (preceded by op if infix), a constant, a constructor, an infix constructor, a list pattern, a tuple pattern, a type specification pattern, or a parenthesized pattern.

```
simp_pat ::= 
  _
  (op) lde
  con
  [pat; .. _pat]
  ( pat )

pat ::= 
  simp_pat
  con simp_pat
  simp_pat con simp_pat
  pat, .. pat
  pat: type
```

The pattern matching rules are given recursively on the structure of the pattern. The letter k denotes constructors, a and b denote variables, u and v denote values, and p and q denote patterns.

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Value</th>
<th>Match(Pattern,Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>_</td>
<td>v</td>
<td>{a = v}</td>
</tr>
<tr>
<td>a</td>
<td>v</td>
<td>{a = v}</td>
</tr>
<tr>
<td>()</td>
<td>()</td>
<td>Ø</td>
</tr>
<tr>
<td>k</td>
<td>k</td>
<td>Ø</td>
</tr>
<tr>
<td>k . p</td>
<td>k v</td>
<td>Match(p,v)</td>
</tr>
<tr>
<td>[p₁; .. pₙ]</td>
<td>[v₁; .. vₙ]</td>
<td>Match(p,q) \cup ... \cup Match(pₙ,qₙ) n ≥ 0</td>
</tr>
<tr>
<td>p₁; .. pₙ</td>
<td>v₁; .. vₙ</td>
<td>Match(p,q) \cup ... \cup Match(pₙ,qₙ) n ≥ 0</td>
</tr>
</tbody>
</table>

Example:

declaration: val (a,b) :: [c₁;] = [1,2; 3,4; 5,6];

bindings: val a = 1 : int
val b = 2 : int
val c = 3,4 : int * int

The variables in a single pattern must all be distinct. Patterns are not expressions; they can only
not part of larger patterns). To completely specify the type of a fun-expression we may use either of the two forms:

\[
\text{expression: } \quad \text{fun } (a : \text{bool}), \text{fun } (b : \text{int}, c : \text{int}), \text{if } a \text{ then } b \text{ else } c : \text{int};
\]

\[
\text{expression: } \quad (\text{fun } a. \text{fun } (b, c). \text{if } a \text{ then } b \text{ else } c) : \text{bool} \rightarrow ((\text{int} \times \text{int}) \rightarrow \text{int});
\]

\[
\text{result: } \quad \text{fun } : \text{bool} \rightarrow ((\text{int} \times \text{int}) \rightarrow \text{int})
\]

In declarations, we have the following options (and more):

\[
\text{declaration: } \quad \text{val } f (a : \text{bool}) (b : \text{int}, c : \text{int}) : \text{int} = \text{if } a \text{ then } b \text{ else } c;
\]

\[
\text{declaration: } \quad \text{val } f (a : \text{bool}) ((b, c) : \text{int} \times \text{int}) = (\text{if } a \text{ then } b \text{ else } c) : \text{int};
\]

\[
\text{binding: } \quad \text{val } f : \text{bool} \rightarrow ((\text{int} \times \text{int}) \rightarrow \text{int})
\]

The first form should be preferred; note how the result type of the function precedes the = sign of the definition.

This explicit type information is often redundant. However, the system checks the explicit types against the types it infers from the expressions. Introducing explicit type information is a good form of program documentation, and helps the system in discovering type errors exactly where they arise. Sometimes, when explicit type information is omitted, the system is able to infer a type (not the intended one) from an incorrect program; this 'misunderstanding' is only discovered in some later use of the program and can be difficult to trace back.

The type of a function expression is determined by the type of its binder (or binders) and the type of its body (or bodies):

\[
\text{typing rule: } \quad \text{if } \varphi_1 : t \text{ and } \ldots \text{ and } \varphi_n : t \text{ and } \theta_1 : t' \text{ and } \ldots \text{ and } \theta_n : t'
\]

\[
\text{then } (\text{fun } \varphi_1, \theta_1 | \ldots | \varphi_n, \theta_n) : t \rightarrow t'
\]

The type automatically inferred by the system is the 'most polymorphic' of the typings which obey the typing rules. For example, from the previous typing rule we can infer that (fun x. x) : int \rightarrow int, and also that (fun x. x) : 'a \rightarrow 'a; the latter type is more polymorphic (in the sense that the int \rightarrow int can be obtained by instantiating the type variables of 'a \rightarrow 'a); in fact it is the most general typing, and is taken as the default type for (fun x. x).

3.11. Application

There are two lexical categories of identifiers, which determine how functions are syntactically applied to arguments: nonfix and infix. Any identifier can be declared to fall in one of these categories: see section "Lexical declarations" about how to do this.

Nonfix identifiers are the ordinary ones; they are applied by juxtaposing them with their argument (in this section we use f and g for functions and a, b, c for arguments):

\[
\text{syntax: } \quad f \ a
\]

The expression a can also be parenthesized (as any expression can), obtaining the standard application syntax f (a). It is common not to use parentheses when the argument is a simple variable, a string (f "abc") or a list (f [1;2;3]). It is necessary to use parentheses when the argument is an infix expression like a tuple or an arithmetic operation (f (a,b,c), f (a+b)) because the precedence of application is normally greater than the precedence of the infix operators (f a,b and f a+b are interpreted as (f a),b and (f a)+b). Function application binds stronger than any operator: see the
type of a sequencing expression is the type of $e_n$. Example:

expression: \((a := 4; a := \lfloor a \div 2 \rfloor; a)\)

result: \(2 : \text{int}\)

Note that (e) is equivalent to e, and that () is the unity.

typing rule: if $e : t$ then \((e_1; \ldots; e_n; e) : t\) n \geq 1

3.14. While

The while construct can be used for iterative computations. It is included in ML more as a matter or style and convenience than necessity, as all tail recursive functions (e.g. functions which end with a recursive call to themselves or to other functions) are automatically optimized to iterations by the compiler.

The while construct has two parts: a test, preceded by the keyword while and a body, preceded by the keyword do. If the test evaluates to true then the body is executed, otherwise () is returned. This process is repeated until the test yields false (if ever) or an exception occurs.

syntax: \(\text{while } e_1 \text{ do } e_2\)

The result of a terminating while construct is always (), hence whiles are only useful for their side effects. The body of the while is also expected to yield () at every iteration.

typing rule: if $e_1 : \text{bool}$ and $e_2 : \text{unit}$ then \((\text{while } e_1 \text{ do } e_2) : \text{unit}\)

As an illustration, here is an iterative definition of factorial which uses two local assignable variables count and result:

declaration: \(\text{val fact } n =\)
\(\quad \text{let } \text{val count } = \text{ref } n\)
\(\quad \text{and } \text{result } = \text{ref } 1\)
\(\quad \text{in } (\text{while } \!\text{count} <> 0 \text{ do}\)
\(\quad \quad (\text{result } := \!\text{count} * \!\text{result};\)
\(\quad \quad \text{count } := \!\text{count} - 1;\)
\(\quad \quad \!\text{result})\)
\(\quad \text{end; }\)

3.15. Case

A case expression is just a different syntax for pattern matching: see section "Patterns and matches" for a description of matches.

syntax: \(\text{case } \text{exp of } \text{match}\)

The expression \(\text{exp}\) is matched against the \(\text{match}\), which is a set of pattern-action pairs; the first pattern to match is activated, and the corresponding action is evaluated and returned as the result of the case expression.

declaration: \(\text{type color } = \text{red | purple | yellow}\)
level, a failure message is printed. In this version of the ML system, exception packets are limited to string values, which are then called exception strings, and failure messages print the contents of the exception strings.

\[ \text{exception: } \text{Exception: reason} \]

where reason is the content of the exception string mentioned above. Note that the exception string is not the value of a failing expression: failing expressions have no value, and exception strings are manipulated by mechanisms which are independent of the usual value manipulation construct. The exception string is often the name of the system primitive or user function which raised the exception.

User exceptions can be raised by the escape construct:

\[ \text{syntax: } \text{escape} \text{ exp} \]

The expression exp above must evaluate to a string, which is the exception string.

The propagation of exceptions can only be stopped by the trap construct.

The result of the evaluation of \( \sigma_1 \ ? \ ? \sigma_2 \) is normally the result of \( \sigma_1 \), unless \( \sigma_1 \) raises an exception, in which case it is the result of \( \sigma_2 \).

The result of the evaluation of \( \sigma_1 \ ? \ ? \ ? \sigma_2 \sigma_3 \) (where \( \sigma_2 \) evaluates to a string list \( sl \)) is normally \( \sigma_1 \), unless \( \sigma_1 \) raises an exception, in which case it is the result of \( \sigma_2 \) whenever the exception string is one of the strings in \( sl \); otherwise the exception is propagated.

The result of the evaluation of \( \sigma_1 \ ? \ ? \ ? \ ? \ ? \ ? \sigma_2 \) is normally the result of \( \sigma_1 \), unless \( \sigma_1 \) raises an exception, in which case it is the result of \( \sigma_2 \), where the variable \( v \) is associated with the exception string and can be used in \( \sigma_2 \).

\[ \text{syntax: } \sigma_1 \ ? \ ? \sigma_2 \]

\[ \text{syntax: } \sigma_1 \ ? \ ? \ ? \sigma_2 \sigma_3 \]

\[ \text{syntax: } \sigma_1 \ ? \ ? \ ? \ ? \ ? \ ? \ ? \sigma_2 \]

Some system exceptions may be raised at any time, independently of the expression which is being evaluated. They are "interrupt", which is generated by pressing the DEL key during execution, and "collect", which is generated when there is no space left. Even these exceptions can be trapped.

The typing rule for escape says that an exception is compatible with every type, i.e. that it can be generated without regard to the expected value of the expression which contains it. The rules for the trap operators state that the exception handler must have the same type as the possibly failing expression, so that the resulting type is the same whether the exception is raised or not.

\[ \text{typing rules: } (\text{escape } e) : 'a \]

\[ \text{if } e : t \text{ and } e' : t \text{ then } (e ? e') : t \]

\[ \text{if } e : t \text{ and } sl : \text{string list and } e' : t \text{ then } (e ?? sl/e') : t \]

\[ \text{if } e : t \text{ and } v : \text{string and } e' : t \text{ then } (e \?\! v \ e') : t \]
expression: (fun x. x) : int -> int;
result: fun : int -> int
expression: (fun x. x + 1) : 'a -> 'a;
result: fun : int -> int

are accepted, even if, according to the previous discussion, 3 does not have type 'a; (fun x. x) has a better type than int -> int; and (fun x. x + 1) may or may not have type 'a -> 'a, according to how it behaves outside the integer domain.

3.19. Equality
The standard equality predicate is structural equality: two objects are equal when they are the same atomic object, or all their components are equal.

The mathematical definition of equality over domains is in general undecidable, hence some restrictions are imposed on the objects which can be compared, in order to obtain a decidable predicate. Equality is considered to be a predefined overloaded operator, i.e. an infinite collection of decidable equality operators, whose types are instances of (\(\alpha \rightarrow \alpha\)) -> bool.

Equality is disallowed on polymorphic objects, on functions, on streams and on elements of abstract data types. When needed, these objects can be marked by data having a decidable equality, but then the user must write a special purpose equality routine.

Equality on reference object is not structural equality, but 'sameness', or pointer equality (e.g. ref 3 = ref 3 is false).

Equality over abstract types might be implemented as equality over the corresponding concrete representations. However in this case abstract types would not be transparent to a change of representation (e.g. from an int list to an int->int), as equality would behave differently on the different representations. Also, if we implement abstract sets by concrete multisets, equality could distinguish between sets which should be equal, giving dangerous insights on the chosen representation, as well as not corresponding to set equality.

Here are examples of 'right' and 'wrong' comparisons (at the top level). The 'wrong' comparisons produce compile time type errors:

```
Right

() = ();
true = false;
3 = 3;
"a" = "a";
(2,:"a") = (2,:"a");
[] = ([]: int list);
[1;2] = [3];
(fun a.b. a=b) : string*string -> bool;
```

```
Wrong

[] = [];
fun a.b. a=b;
fun a. a = fun a. a;
set[3] = set[3];
```

where set is an abstract type.
\{op\} ide simp\_pat \ldots simp\_pat \{\text{: type}\} = \text{exp}
\{op\} ide simp\_pat \{\text{: type}\} = \text{exp} \mid \ldots \mid ide\ pat \{\text{: type}\} = \text{exp}

Each declaration imports the variables used in the expressions \text{exp} and exports the variables defined on the left of \text{=}.

Examples:

\begin{itemize}
\item declaration: \text{val } x = 2 \ast 3;
\item declaration: \text{val } a, b = 4, [;]
\item declaration: \text{val } K x y = x;
\item declaration: \text{val } K : 'a -> ('b -> 'a)
\item declaration: \text{val } \text{null nil} = \text{true} \mid \text{null } (a :: b) = \text{false};
\end{itemize}

Note that function definitions require simple (i.e. possibly parenthesized) patterns as formal parameters. In particular, parameters which have the form of constructors applied to patterns must be parenthesized (e.g. \text{val } f (\text{ref } a) = a; is legal, but \text{val } f \text{ref } a = a; is not).

5.1.2. Parallel bindings

To bind the variables \(x_1 \ldots x_n\) simultaneously to the values of \(e_1 \ldots e_n\) one can write either of the following declarations:

\begin{itemize}
\item \text{val } x_1, \ldots, x_n = e_1, \ldots, e_n;
\item \text{val } x_1 = e_1 \text{ and } \ldots \text{ and } x_n = e_n);
\end{itemize}

In the first case we use a composite pattern, while in the second case we use the infix operator \text{and}:

\text{syntax: } parallel\_value\_binding ::= \text{value\_binding and value\_binding}

The meaning of \text{and} is that the bindings of the two sides are established ‘in parallel’, in the sense that the variables exported from the left side are not imported to the right side, and vice versa. The whole construct exports the union of the variables of the two declarations; it is illegal to declare the same variable on both sides of an \text{and}.

For example, note how it is possible to swap two values without using a temporary variable:

\begin{itemize}
\item declaration: \text{val } a = 10 \text{ and } b = 5;
\item declaration: \text{val } a = b \text{ and } b = a;
\end{itemize}
bindings: type 'a pair = pair of 'a * 'a
            con pair : ('a * 'a) -> ('a pair)

declaration: type ('a, 'b) pairwise = pairwise of ('a * 'b) * ('a * 'b);
            bindings: type ('a, 'b) pairwise = pairwise of ('a * 'b) * ('a * 'b)
                        con pairwise : (('a * 'b) * ('a * 'b)) -> (('a, 'b) pairwise)

All the type variables appearing on the right of the defining = sign must appear on the left as parameters of the type being defined. The list of parameters on the left of the = sign must be a sequence of distinct type variables.

5.2.2. Parallel bindings
As in value bindings, the and operator can be used to combine type binding in parallel, in the sense that the variables exported from the left side are not imported to the right side, and vice versa.

    syntax:  parallel_type_binding ::= type_binding and type_binding

The whole construct exports the union of the variables defined by the two type bindings; it is illegal to declare the same variable on both sides of an and.

5.2.3. Recursive bindings
The operator rec is used to define recursive and mutually recursive types. The binding rec tb exports the variables exported by the type binding tb, and imports the variables imported by tb and the variables exported by tb.

    syntax:  recursive_type_binding ::= rec type_binding
    declaration: type rec 'a tree = leaf of 'a | node of ('a tree) * ('a tree);
    bindings    type 'a tree = leaf of 'a | node of ('a tree) * ('a tree)
                con leaf : 'a -> ('a tree)
                con node : (('a tree) * ('a tree)) -> ('a tree)

If rec were omitted, the type identifier tree on the right of = would not refer to its defining occurrence on the left of =, but to some previously defined tree type (if any) in the surrounding scope.

5.3. Abstract type declarations
Abstract types can be defined by the abstype-with declaration, which is an abbreviation of a special form of private declaration (see section "Private declarations", below).

    syntax:  abstract_declaration ::= abstype type_binding with declaration end

An abstract type defined by the abstype keyword is like a concrete type defined by the type keyword, but its constructors are only available in the declaration following the with keyword.

    declaration: abstype position = position of int * int
which are not redefined in \( c_2 \).

expression: \[
\text{let } \text{val } a = 10; \text{ val } b = a + 5 \\
\text{in } b \text{ end;}
\]

result: \[15 : \text{int}\]

5.5. Private declarations

The \texttt{export} declaration allows one to hide some of the bindings of a declaration, while \texttt{making} other bindings available to the outside.

\texttt{syntax: \[
\text{private\_declaration ::=}
\text{\quad \text{export \ export\_list .. \ export\_list from \ declaration \ end}}
\]

\texttt{syntax: \[
\text{export\_list ::=}
\text{\quad \text{abstype type\_ide .. type\_ide}}
\text{\quad \text{type type\_ide .. type\_ide}}
\text{\quad \text{val ide .. ide}}
\}\]

The type identifiers and the value identifiers (which should be declared in \texttt{declaration}), are exported to the outside, while the other type identifiers and value identifiers defined in \texttt{declaration} are hidden. In the case of a type export, the constructors of that type are automatically exported. In the case of an abstype export the constructors are not exported. Constructors cannot be listed in a \texttt{val} section.

\texttt{declaration: \[
\text{export \ val \ a \ c}
\text{\quad \text{from } (\text{val } a, b = 1.2;}
\text{\quad \quad \text{val } c = a + b)}
\text{\quad \text{end;}}
\]

\texttt{bindings: \[
\text{val } a = 1 : \text{int}
\text{val } c = 3 : \text{int}
\}\]

\texttt{declaration: \[
\text{export \ val \ \text{increment} \ \text{fetch}
\text{\quad \text{from } (\text{val } \text{count} = \text{ref } 0;}
\text{\quad \quad \text{val } \text{increment}() = \text{count} := !\text{count} + 1}
\text{\quad \quad \quad \text{and } \text{fetch}() = !\text{count})}
\text{\quad \text{end;}}
\]

\texttt{bindings: \[
\text{val } \text{increment} : \text{unit} \to \text{unit}
\text{val } \text{fetch} : \text{unit} \to \text{int}
\}\]

\texttt{declaration: \[
\text{export \ abstype \ increasing\_pair}
\text{\quad \text{val } \text{increasing\_pair} \ \text{high} \ \text{low}}
\text{\quad \text{from } \text{type } \text{increasing\_pair} = \text{pair of int} \times \text{int};}
\text{\quad \quad \text{val } \text{increasing\_pair}(x,y) =}
\text{\quad \quad \quad \text{if } x>y \text{ then escape"increasing\_pair"}
\text{\quad \quad \quad \quad \text{else } \text{pair}(x,y)}
\text{\quad \quad \quad \text{and } \text{low}(\text{pair}(x,y)) = x}
\text{\quad \quad \quad \text{and } \text{high}(\text{pair}(x,y)) = y}
\text{\quad \text{end;}}
\]
syntax:  
  lexical_declaration ::=  
    infix ide .. ide  
    nonfix ide .. ide  

declarations:  
  infix <--> ;  
  nonfix + ;  

This example declares an infix operator <--> and puts the operator + back to a status of normal non-infix identifier. These operators can now be uses in expressions and declarations according to their new lexical status.

A lexical declaration can be used in scopes-blocks. In this case the newly defined fixity status is only active in the local scope.

6. I/O streams

Input-output is done on streams. A stream is like a queue; characters can be read from one end and written on the other end. Reads are destructive, and they wait indefinitely on an empty stream for some character to be written. In what follows, a "file" is a file on disk which has a "filename", a "stream" is an ML object (it is a pair of Unix file descriptors, open for input and the other one open for output).

| file        : string -> stream  |
| save       : (string * stream) -> unit  |
| stream      : unit -> stream  |
| channel     : string -> stream  |
| input       : (stream * int) -> string  |
| output      : (stream * string) -> unit  |
| lookahead   : (stream * int * int) -> string  |
| caninput    : stream -> bool  |
| terminal     : stream  |

- Streams are associated with file names in the operating system. The operation file takes a string (a file name) and returns a new stream whose initial content is the content of the corresponding file. It escapes with string "file" if the stream is not available (e.g. the file name syntax is wrong, or the file is locked). If no file exists with that file name, a new empty stream is returned (hence, empty files and streams are indistinguishable from non-existent ones). The same file name can be requested several times; every time a new independent stream is generated.

- A copy of an existing stream can be associated with a file name (i.e. written to a file) by the save operation which takes a string (the file name) and a stream and returns unit. The stream is unaffected by this operation. An exception with string "save" is raised if the association cannot be carried out. Reads and writes on streams do not affect the files they come from. Conversely, a save operation on a file does not affect the streams which have been extracted from that file; it only affects the result of a subsequent file.

- The operation stream returns a new empty stream. It accounts for temporary (unnamed) files. Moreover, a stream-filename association can be removed by reassociating an empty stream with that file name.

- Input operations are destructive; the characters read are removed from the stream. input takes a stream s and a number n and returns a string of n characters reading them from the stream s. If there are less than n characters in the stream, it waits indefinitely until more characters are written on the stream. The wait can be interrupted by the DEL key producing an "interrupt" exception. caninput returns true if a stream is not empty; the input operations do not fail on empty streams, they wait indefinitely for something to be written on the stream.
val right : 'd pair -> 'd

A declaration import `M` can also appear in local scopes and inside functions, wherever a declaration is accepted (the binding module `/usr/lib/ml/lib` above is explained later).

Importing can result in loading a module, when that module is imported for the first time in an interactive session, or in sharing an already loaded module, all the subsequent times. The loading/sharing mechanism is explained below in "Module sharing".

No evaluation takes place when a module is compiled. Instead, the module body is evaluated every time the module is loaded. If the module body contains side effecting operations (such as input/output), they have effect at loading time, i.e. they do not have effect if the module is being shared.

More precisely, we can say that a module is an environment generator; loading a module corresponds to generating a new environment, and sharing a module corresponds to using an already generated environment.

### 7.1. Module hierarchies

A module `A` can import other modules `B, C, etc`. The import relations between modules determine a module hierarchy. The hierarchy is dynamic, because of the possibility of conditional imports and of hidden imports caused by functions imported from other modules.

A module can import other modules for several reasons.

```ml
module: module A1
  body
  val f a =
  let import B1
     in .. end
  end;

module: module A2
  body
  export
  val f g
  from
     import B2;
     val f a = ..
     and g b = ..
  end
  end;

module: module A3
  body
     import B3;
     val f a = ..
     and g b = ..
  end;
```

The first example above shows a module `B1` locally imported for the private use of a function in `A1`. The second example shows a module `B2` imported for private use in a module `A2`; the export construct guarantees that `B2` is not exported from `A2`. The third example shows a module `B3` which is imported by `A3`, and also reexported.

Sometimes an imported module `B` must be reexported from an importing module `A`. This happens when a type identifier `t` defined in `B` is contained in the (types of the) bindings exported by `A`. 
In what follows, when we want to make those hidden bindings explicit, we write them indented under the respective `module` bindings:

**declaration:**
```
import B;
```

**bindings:**
```
module /usr/lib/ml/lib
module A
val a = 3 : int
val b = 5 : int
```

### 7.2. Module sharing

In an interactive session, a compiled module can be imported several times, but it is only loaded once, the first time it is imported. All the following imports of that module simply fetch the already loaded module. For example, two consecutive top level `import A;` declarations are semantically equivalent to only one of them, and no extra work is actually done in the second import.

At any moment there is at most one copy of a module in the system, and that copy is shared among all the modules which import it. Sharing means that types are shared, and that values are shared; for example:

```
module: module A
body
  abstype T = T of int
  with val absT n = T n
      and repT (T n) = n
  end;
  val a = ref 3
end;

module: module B
includes A
body
  val BabsT,BrepT = absT,repT
      and b = a
end;

module: module C
includes A
body
  val CabsT,CrepT = absT,repT
      and c = a
end;

module: module D
includes B C
body
end;

declaration: import D;
```
interface (i.e. the types of the exported bindings) changes.

8. The ML system

8.1. Entering the system
The ML system is entered under Unix by typing ml as a shell command. A library of standard functions is then loaded. This library is installation dependent and is meant to contain the functions which are most used locally. After the system prompt, you can start typing expressions or definitions, or loading source files.

8.2. Loading source files
An ML source file looks exactly like a set of top-level phrases, terminated by semicolons. A file prog.ml containing ML source code can be loaded by the use top-level command:

    use "prog.ml";

where the string surrounded by quotes can be any Unix file name or path. The file extension .ml is normally used for ML source files, but this is not compulsory.

Source files may again contain use commands to load other source files in a cascade. There is a Unix-dependent limit on the depth of recursive loading; the message Cannot open file: filename is printed when such limit is exceeded. The file filename will not be loaded, but the loading of the previously opened files will continue.

Typing DEL while loading a file will interrupt loading and bring you back to the top level. This might not happen immediately, because some parts of the compilation process are not interruptible, but it will have effect as soon as the current phrase has finished compiling.

8.3. Exiting the system
Type Control-D to exit the system. No program or data created during an ML session is preserved, except for compiled modules.

8.4. Error messages
The most common syntax and type errors are described in section "Errors". Here are some unfrequent messages which are generated in particular situations.

An 'unimplemented' error is given when a value or type identifier is specified in an export export list but is not defined in the corresponding from part. This is different from the normal 'undefined' error for undefined identifiers.

 e = export val a from val b = 3 end;
  Unimplemented Identifier: a

 e = export type t from type u = int end;
  Unimplemented Type Identifier: t

A type error occurs when two isomorphism types having the same name are defined, and are allowed to interact:

    let abtype A = A of int
      with val absA n = A n end;
    abtype A = A of int
      with val repA (A n) = n end
    in repA(absA 3) end;
  Type Clash in: (repA (absA 3))
The menu stops at every line, waiting for a y followed by a CarriageReturn for yes, or a CarriageReturn for no. The menu can be exited at any point by DEL: the options chosen up to that point will have effect; the other ones are unchanged. To reset the options to the initial default state, reenter the menu and answer no to all questions. All options have effect until changed again.

- **ParseTree** prints the parse tree of every subsequent top level phrase. This can be useful to see how the precedence of operators works.
- **Types** prints the type of every subsequent top level phrase, before executing it. It is useful only in debugging the system, as the type is the same as the type of the result which is printed after evaluation.
- **TypeVariables** prints all the hidden attributes of type variables. The following is for typechecking wizards only. 'a[i]' means that 'a' has an occurrence level i (i.e. it is used in a fun-nesting of depth i). Generic type variables are written 'a[]' (i for infinity). Weak type variables are written '_a[]', and non-generic type variables are written '!a[]'.
- **Match** prints the intermediate structures generated during the compilation of patterns. Not for human consumption.
- **StackCode** for every subsequent top-level phrase, prints the intermediate Functional Abstract Machine code produced by the compiler [Cardelli 83], after peephole optimization.
- **OptimizerOff** switches off the peephole optimizer for the abstract machine code. The optimizer works mainly on multiple jumps, function return, partial application, and tail recursion.
- **AssemblerCode** for every subsequent top-level phrase, prints the VAX assembler instructions produced from the abstract machine code.
- **ObjectCode** for every subsequent top-level phrase, prints the final hexadecimal result of the compilation.
- **Environment** for every subsequent top-level phrase, prints all the the types currently defined with their definition, and all the variables currently defined with their value and type.
- **StopBeforeExec** for every subsequent top-level phrase, stops immediately before executing the result of compilation, asking for a confirmation to proceed.
- **CheckHeap** for every subsequent top-level phrase, makes a complete consistency check of the data in the heap, and reports problems.
- **MemoryAllocation** reports every Unix memory allocation or deallocation, except the ones caused by Pascal.
- **Watch** is used for internal system debugging.
- **Timing** at the end of every evaluation, gives the parsing time (Pars), typechecking time (Anal), translation to abstract machine code and optimization time (Comp), translation to VAX code time (Assm), total compilation time (Total) and run time (Run). All in milliseconds.

8.6. Garbage collection and storage allocation

Garbage collection is done by a two-spaces copying compacting garbage collector. The size of the spaces grows as needed; garbage collection may escape with string "collect" if Unix refuses to grant more space when needed. For technical reasons, the allocation of very large data structures may escape with string "alloc", even if there is still memory available.
Appendix A. Lexical classes

Ascii characters are classified into the following categories:

- **Illegal**
  Unacceptable in a source program. These characters are ignored, and a
  warning message is printed.

- **Eof**
  End-of-file character. It terminates an interactive session, or stops the pro-
  cess of reading a source ml file. A top level control-D is interpreted as Eof,
  thereby exiting the system.

- **Blank**
  Characters which are interpreted as a space character " ".

- **Digit**
  Digits.

- **Letter**
  Letters and other characters which can be used to form identifiers.

- **Symbol**
  A class of character which can be used to form operators (see appendix
  "Syntax of lexical entities").

- **Escape**
  Escape character in strings. It behaves as a Symbol outside strings.

- **Quote**
  String quotation character.

- **Delim**
  One-character punctuation marks and parentheses.

Moreover, any sequence of legal character enclosed between { and } or end of file is a comment
(except when { and } appear in a string). Comments can be nested. Each comment is considered
equivalent to a single space character. An isolated } is treated as a Delim and may produce various
kinds of syntax errors.

<table>
<thead>
<tr>
<th>Character</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Digit</td>
</tr>
<tr>
<td>3</td>
<td>Digit</td>
</tr>
<tr>
<td>0</td>
<td>Digit</td>
</tr>
<tr>
<td>#</td>
<td>Symbol</td>
</tr>
<tr>
<td>'</td>
<td>Symbol</td>
</tr>
<tr>
<td>'</td>
<td>Symbol</td>
</tr>
<tr>
<td>@</td>
<td>Symbol</td>
</tr>
<tr>
<td>.</td>
<td>Symbol</td>
</tr>
<tr>
<td>A</td>
<td>Letter</td>
</tr>
<tr>
<td>C</td>
<td>Letter</td>
</tr>
<tr>
<td>F</td>
<td>Letter</td>
</tr>
<tr>
<td>H</td>
<td>Letter</td>
</tr>
<tr>
<td>L</td>
<td>Letter</td>
</tr>
<tr>
<td>O</td>
<td>Letter</td>
</tr>
<tr>
<td>R</td>
<td>Letter</td>
</tr>
<tr>
<td>U</td>
<td>Letter</td>
</tr>
<tr>
<td>X</td>
<td>Letter</td>
</tr>
<tr>
<td>T</td>
<td>Delim</td>
</tr>
<tr>
<td>V</td>
<td>Delim</td>
</tr>
<tr>
<td>Escape</td>
<td>Intelligible</td>
</tr>
</tbody>
</table>
Appendix B. Keywords

abstype
and
body
case
do
else
end
export
escape
from
fun
if
import
in
includes
infix
let
local
module
nonfix
of
op
rec
then
type
use
val
where
while
with
:
?
??
?:
=
<table>
<thead>
<tr>
<th>input</th>
<th>output</th>
<th>lookahead</th>
<th>caninput</th>
<th>terminal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read from stream</td>
<td>Write to stream</td>
<td>Peek from stream</td>
<td>Stream status</td>
<td>Terminal stream</td>
</tr>
<tr>
<td>Nonfix</td>
<td>Nonfix</td>
<td>Nonfix</td>
<td>Nonfix</td>
<td>Nonfix</td>
</tr>
</tbody>
</table>
Appendix E. Precedence of operators

Infix operators in order of decreasing precedence (see section "Lexical declarations").

<table>
<thead>
<tr>
<th>Operator</th>
<th>Associativity</th>
</tr>
</thead>
<tbody>
<tr>
<td>(application)</td>
<td>left associative</td>
</tr>
<tr>
<td>sub</td>
<td>left associative</td>
</tr>
<tr>
<td>* div mod</td>
<td>left associative</td>
</tr>
<tr>
<td>+ -</td>
<td>left associative</td>
</tr>
<tr>
<td>:: @</td>
<td>right associative</td>
</tr>
<tr>
<td>= &lt;&gt; &gt; &lt; &gt;= &lt;=</td>
<td>right associative</td>
</tr>
<tr>
<td>&amp;</td>
<td>right associative</td>
</tr>
<tr>
<td>or o</td>
<td>right associative</td>
</tr>
<tr>
<td>{user-infix}</td>
<td>left associative</td>
</tr>
<tr>
<td>update :=</td>
<td>right associative</td>
</tr>
<tr>
<td>.. .. ..</td>
<td>n-ary infix</td>
</tr>
</tbody>
</table>
Appendix G. Syntax of lexical entities

Letter ::= 
    "a" | .. | "z" | "A" | .. | "Z" | "_".

Digit ::= 
    "0" | .. | "9".

Symbol ::= 
    "!" | "#" | "%" | "&" | "*" | "+" | "-" | "/" | ":" | "," | "<" | "=" | ">" | 
    "?" | "@" | "\" | "^" | "~" | "|" | "\".

Character ::= .. (see appendix "Lexical classes" for a list of legal characters)

Ide ::= 
    Letter {Letter | Digit | "}"} | 
    {Symbol}1.

Integer ::= 
    {Digit}1.

String ::= 
    """" "{Character} """".

Con ::= 
    "(" | "")" | 
    Integer | 
    String | 
    Ide.

TypeIde ::= 
    Ide.

TypeVar ::= 
    """" Ide.
Pat := " Exp |
["op"] Ide {Pat}1 [":" Type] "=" Exp |
["op"] Ide Pat [":" Type] "=" Exp / "]2 |
ValBind "and" ValBind |
"rec" ValBind.

TypeBind ::= |
[TypeParams] TypeId "=" {Ide ["of" Type] / "]1 |
TypeBind "and" TypeBind |
"rec" TypeBind.

TypeParams ::= |
TypeVar | "(" (TypeVar / "],")1 ")".

SimplePat ::= |
"_" |
["op"] Ide |
Con |
"[" {Pat / "]", }]1 |
"(" Pat ")".

Pat ::= |
SimplePat |
Con SimplePat |
Pat "=" Type. |
SimplePat Con SimplePat |
{Pat / "]",}]2 |

Match ::= |
{Pat "=" Exp / "]",}]1

Type ::= |
TypeVar |
[TypeArgs] TypeId |
{Type / "]",}]2 |
Type "-->" Type |
"(" Type ")".

TypeArgs ::= |
Type |
"(" (Type / "],")1 ")".

ModuleName ::= Ide | String.

Notes:
• The top-level command monitor provides a menu of check-prints for monitoring the inner workings of the compiler.
• The top-level command use filename loads a file of ML definitions and expressions.
• Recursive definitions can only contain bindings which are syntactically function bindings.
Appendix J. System installation

The ML system usually comes on a tape containing a single directory mlkit (and sometimes a
backup copy of it mlkit.BACKUP). The tape can be read by a tar -x mlkit command, which creates
an mlkit subdirectory in the current directory; mlkit can be kept in any user or system directory.

The mlkit directory contains several files and subdirectories. README repeats the information con-
tained in this section. VERSION contains the system version. doc contains this manual in troff for-
mat, a paper on the ML abstract machine, and a list of known ML sites. src contains the source
programs. progs contains some example ml programs. pub contains the ML object code, libraries
and shell scripts.

To install the system enter the pub subdirectory, and read the install script to make sure that its
execution is not going to cause any damage on your system. To run install you probably need write
permission on /usr/lib and /usr/bin. When you are sure that everything is ok, type install.

Apart from install, pub contains an usr-bin-ml script and an usr-lib-ml subdirectory. The install
procedure simply moves usr-bin-ml to /usr/bin/ml, and usr-lib-ml to /usr/lib/ml. usr-lib-ml contains
the real ML executable code, called mlsys, a file which is loaded every time the system is entered,
called boot, a precompiled library module, called lib.sp and lib.pm, and the library module source,
called lib.ml. The library lib.ml should be considered as part of the ML system, and it is loaded (by
boot) every time the system is entered; it can be extended by the users, but not reduced. usr-lib-
ml also contains other user-defined ML library modules, which have to be explicitly imported
when needed in user programs, and a file genlib.ml which recompiles all the libraries.

After install, the ML system can be run from any directory by typing ml. If you instead wish to
call the system FORTRAN, say, just rename /usr/bin/ml to /usr/bin/FORTRAN.

If for some reason you need to recompile the system, you should proceed as follows. Most of the
work is done by the Makefile file supplied with the source programs (say: make in mlkit/src). This
generates an mlsys executable file which should be stripped (say: strip mlsys) and moved to
/usr/lib/ml/mlsys.

The new ML system is now available, but the ML library has to be recompiled. When loading the
new system for the first time, an error message ‘Module /usr/lib/ml/lib must be compiled’ will
appear. Immediately after, type ‘use "/usr/lib/ml/genlib.ml"’; this will generate the new libraries
for all the future uses of the new system. Now exit the system (don’t try to work: the library has
not been loaded yet). From now on, the library will be loaded automatically when entering the sys-
tem.

The library module lib.ml can be changed at will, as long as the basic ML primitives (like @)
declared there are preserved. It contains some basic ML functions, and can be extended with the
locally most used utilities. After editing the file /usr/lib/ml/lib.ml, enter ML and type ‘use
"usr/lib/ml/lib.ml"’ to compile and install the new library. Exit the system and reenter it, to actu-
ally load the new library.
- Create this file, containing the C function "Address DoFoo(argn, .. ,argl)", implementing the desired behavior. The order of arguments must be the inverse of the order in which "foo(argl, .. ,argn)" is called from ML. WARNING: do not attempt to allocate or change ML data structures in this function without deeply understanding how the garbage collector works. It is safe to inspect (read only) the ML data structures passed as parameters (see appendix "Vax data formats"), and to return them unchanged. The result of this function must match the ML type declared in mlanal.p. If DoFoo needs to produce an ML exception, it can do so by calling "DoFailwith(\"StrFoo\")"

- File Makefile
  - Add a line "FOOOP = amglob.h amfooop.c".
  - Add "amfooop.o" to the definition of "MLSYS".
  - Add a line "amfooop.o: $(FOOOP); CC amfooop.c".
Appendix M. VAX data formats

Each segment "+--" in the pictures is one byte. The symbol "-" below a data structure represents the location pointed to by pointers to that structure; fields preceding "-" are only used during garbage collection and are inaccessible to the ML operations (and hence to the user). Unboxed data is kept on the stack, or in the place of pointers in other data structures; unboxed data does not require storage allocation. Pointers can be distinguished from unboxed data as the former are \( \geq 64K \). There are automatic conversions between SmallIntegers and BigIntegers, so that the ML operations only see the type int.

\[
\begin{array}{c|c|c}
\text{Unit} & & \\
0 & \text{(unity)} & \text{(unboxed)} \\
\end{array}
\]

\[
\begin{array}{c|c|c}
\text{Boolean} & & \\
0 & \text{(false)} & \text{(unboxed)} \\
1 & \text{(true)} & \text{(unboxed)} \\
\end{array}
\]

\[
\begin{array}{c}
\text{SmallInteger} \\
-32768 \ldots +32767 & \text{(unboxed)} \\
\end{array}
\]

\[
\begin{array}{c|c|c|c|c}
\text{BigInteger} & & & & \\
\hline
\text{n} & \text{Chunk 1} & \ldots & \text{Chunk n} & (n \geq 1)
\end{array}
\]

\[
\begin{array}{c|c|c}
\text{Small Record} & & \\
\hline
\text{Fst} & \text{Snd}
\end{array}
\]
Array

| LowerBound | n  | Item 1 | ... | Item n | (n ≥ 0) |

Text

| n | Literals | Cl | Cn | (') when pointed from a Closure. Literals may be Nil or point to Literals |

Literals

| n | Literal 1 | ... | Literal n | (n ≥ 1) | Literal may be a Text, a String or a BigInteger |

Closure

| n | Text | Global 1 | ... | Global n | (n ≥ 0) | Text points to a Text |
Appendix O. Transient

This appendix contains a list of restrictions and limitations due to the accidents of this particular implementation. They are not consequences of rational thought or planning but rather incomplete implementations of features, known bugs to be fixed or problems which are harder to fix than they are worth.

- Several minor problems still afflict modules. These will be fixed gradually in the short and medium term. Meanwhile the following things should be noted.

With the exception of the library functions in /usr/lib/ml/lib.ml, modules must not use predefined functions as argumentless functional objects, e.g. + in fold (op +) [1;2;3;4] 0. At the moment this will produce and 'Unbound identifier' error. However, it is possible to replace (op +) by (fun(x,y). x+y).

Under some complicated circumstances the sharing of types will fail. The scenario is: module A privately imports module B, and then exports a type T defined in B by an export export list; then module C imports A and B and makes T-from-A interact with T-from-B. This will very likely never happen to you. However, if you get an unexplained type conflict (probably two different abstract types having the same name), this might be it. You should be able to fix this by making sure that that type is exported by includes declarations, as opposed to export export lists.

If a module A is recompiled, all the modules depending on it must be recompiled, even if the interface of A has not changed.

Sometimes, when a module B which imports A has to be recompiled, instead of the message Module B must be compiled, the less precise message Module importing A must be compiled is produced.

There is no check on the restriction that modules exporting a type identifier (maybe as part of the type of an exported binder), must also export the type definition. However, nothing bad can come of this.

On some occasions, precompiled modules can give undefined type errors when importing them, or when compiling modules which import them. This can happen if an export declaration rearranges the order of types and values in the body of a module. To fix this, put the export lists back in an appropriate dependency order. You can look at the .so file for that module to see what is happening. Nothing bad can come of this.

Consider the following scenario: module A is defined; module B, which imports A, is defined; module B is imported; module A is redefined. At this point module B is obsolete, and one would expect a version error in importing B again. This would happen if module B had not already been imported; however an import B at this point will share the already imported module B, without any complaint. At this point we have a B including the old A, while we might expect the new A to be in action. To get the new A into play, you must recompile B and reimport it. Nothing bad can come of this, except confusion.

- Input/Output. The current plans are to implement an efficient buffering with in-core cache for internal streams, and to use unbuffered 'raw' I/O on external streams. Internal streams would still look unbuffered to the user, but all the disk I/O would be done in chunks. The current situation is fluid.

At the moment a limited number of streams can be open in an ML session and they cannot be closed. When this limit is exceeded, the operations Stream and File fail. This problem will be solved in a future version by an automatic cache of open streams.

The operations implemented so far are file, save, stream, caninput, input, output and terminal (not yet working: lookahread and channel).

On end of stream, inchar waits forever; type DEL to exit input waits and infinite loops (a trappable exception "interrupt" is produced) (ignore the longjmp botch and System Crash! messages which are sometimes generated).

- Bignums are not yet implemented. Integers currently range between ~32768 and 32767.
Appendix P. Differences from Standard ML

This appendix contains a list of the differences between this implementation and the official definition of the ML language. All the differences are either temporary (due to the conversion process from earlier implementations), or compatible extensions of the standard (some of which are intended to be transferred to the standard in the future), or bugs. This manual is supposed to reflect exactly the current state of the implementation. It will be upgraded to the standard together with the evolution of the implementation.

- The failure mechanism is not the standard one, and should be converted to the standard in the near future.
- The I/O system is not part of the standard (Standard ML does not define any I/O system). It is however a partial implementation of a proposal for I/O in Standard ML. Also, see Appendix "Transient".
- The module system is not part of the standard (Standard ML does not define any separate compilation mechanism). A module system is being studied to be included in Standard ML; it includes parametric modules and persistent data. The current implementation bears resemblance to a special case of that proposal. The "export" declaration construct is part the module system, and not part of Standard ML. Also, see Appendix "Transient".
- The "local" declaration construct is not yet implemented.
- The typechecking of references is more permissive than the one defined for Standard ML. Programs using polymorphic references in this systems might not pass typechecking in Standard ML. This strict extension of the standard will probably be preserved.
- The tests for the correct typechecking of equality are not yet implemented. As it stands, the system is more permissive than it should be, but not wrong.
- The tests for correct scoping of type identifiers are not yet fully implemented. As it stands, the system is more permissive than it should be, but not wrong.
- The scoping of constructors is not yet the one required by the standard. As it stands, the system is more permissive than it should be, but not wrong.
- The evaluation order of function applications is wrong.
- The check against multiple occurrences of the same identifier in a pattern has not yet been implemented. The result of doing so is undefined.
- The typechecking of the "case" statement is more restrictive than it should be, but not wrong.
- Integers and strings are not yet allowed in patterns.
- Integers are only 16-bit integers.
- Curried clausal definitions are not yet supported.
- Pattern matching should issue a series of warning messages in some situations: this is not yet implemented.
- The "<=>" form of abstract types is not yet implemented.
- Arrays are not part of Standard ML. The arrays provided by this implementation are intended as a predefined abstract data type, whose definition is contained in section "Arrays".

Escape sequences for strings are extended by the sequence \#, described in Appendix "Escape sequences for strings". This is not part of the standard, but is necessary for writing terminal drivers.
ML Syntax

Phrase ::=  
[Exp | SimpleDecl | Module | 
  "use" String | "monitor"] 

Module ::=  
"module" ModuleName 
["includes" [ModuleName]1] 
"body" Decl "end".

SimpleExp ::=  
["op"] (Id | Con) | 
("[Exp | ";"]") | 
("[Exp | ";"]")1).

Exp ::=  
SimpleExp | 
Exp SimpleExp | 
Exp ";" Type | 
Exp IdExp | 
(Exp | ";")2 | 
"escape" Exp | 
"if" Exp "then" Exp "else" Exp | 
"while" Exp "do" Exp | 
"let" Decl "in" Exp "end" | 
Exp "where" Decl "end" | 
"case" Exp "of" Match | 
Exp ";" Exp | 
Exp "??" Exp Exp | 
Exp ";" IdExp ";" Exp | 
"fun" Match.

SimpleDecl ::=  
"val" ValBind | 
"type" TypeBind | 
"abstract" TypeBind "with" Decl "end" | 
"export" ExportList "from" Decl "end" | 
"import" [ModuleName]1 | 
"infix" (Id1)1 | "nonfix" [Id1]1.

Decl ::=  
SimpleDecl | 
Decl ";" Decl | 
"(" Decl ")."

ExportList ::=  
("abstract" | "type" | "val") (Id1 | ";")1.

ValBind ::=  
Pat "=" Exp | 
["op"] (SimplePat1, ";" Type) "=" Exp | 
["op"] IdExp SimplePat1, "=" Exp ";"2 | 
ValBind ";and" ValBind |
  "rec" ValBind.

TypeBind ::=  
[Params] TysElts1 | "(" [(TypeVar | ";")1 ")"

Type ::=  
TypeVar | 
[TypeArg] TysElts2 | 
[Type ";"]2 | 
"abstract" Type | 
"(" Type ")".

TypeArg ::=  
[TypeArg] TysElts2 | 
[Type ";"]2 | 
"abstract" Type | 
"(" Type ")".

SimplePat ::=  
"_" | 
["op"] IdExp | 
Con | 
["{ Pat | ";")"] | 
{" Pat" "}.

Pat ::=  
SimplePat | 
Con SimplePat | 
Pat ";" Type | 
SimplePat ";and" SimplePat | 
(Pat | ";")2 |

Match ::=  
(Pat ";" Exp | ";")1

TypeElts ::=  
Type | 
[TypeArg] TysElts2 | 
[Type ";"]2 |

Letter ::=  
"a" | "z" | "A" | "Z" | "_".

Digit ::=  
"0" | "9".

Symbol ::=  
[\#\%\+\-\/<\=\?\@\:\"\ ].

Character ::=  
A to Z or a to z.

Id ::=  

Integer ::=  
[Digit]1.

String ::=  
"" (Character ";") "".

Con ::=  
"(" | Integer | String | Id.

TysElts ::=  
Id.

TypeVar ::=  
"" Id.

ModuleName ::=  
Id | String.

Keywords

abstract and body case do else end export escape from fun import if in includes infix let local module nonfix of op rec then type use val where while with ? ? #: =

Operations

application | (subL \{ div mod \}L \{- = \}L \{<:: ::\}R \{< <= >= -> <=\}R \&\& | or | \{user-inf\}L \{update :=\}R) true false not 
size extract explode implode explodeascii implodeascii intofstring ofint nil hd tl null length map rev fold revfold ref refarray arrayarray lowerbound upperbound arrayarray list sub update arrayarray list file save stream channel input output lookahead caninput terminal user-nonfix

Constructors

integers strings tuples () true false nil :: ref user-defined

Metasyntax

Strings between quotes ";" are terminals.

Identifiers are non-terminals.

Juxtaposition is syntactic concatenation.

"[ ... ]" is syntactic alternative.

"[..]" is zero or one times (i.e. optionally) "..".

"[..]n" is n (default 0) or more times "..".

"[..]n.." is n or more times ".." separated by "..".

Parentheses "[..]" are used for precedence.
References

This paper describes the abstract machine on which the ML implementation is based. It contains a formal definition of the machine, which should guide implementations on different kinds of hardware.

This manual contains the original definition of the ML language. The present ML language is quite different in syntactic details and type declarations, but the basic semantic principles are still the same.

This paper establishes the semantic foundations of the ML type system, and contains a correctness proof for a simplified ML typechecker.
• The exception "corruption" is produced when something goes very wrong (e.g. after a very deep recursion which overruns the stack); the system is currently unsafe after a corruption. You should rarely be thrown out of the system, but on extreme corruptions you may get a Run out of memory message and a core dump.

• Deep recursions producing stack overflow will badly corrupt the system; (this is the most likely cause of crash). The ml exception "corruption", or the message System Crash! may be generated. If you come across this problem, try to rewrite your programs in a linear recursive style, so that the compiler can optimize them to iterations, or directly in iterative style using while-do. This problem cannot be solved easily, given the current Unix memory management primitives.

• The copying garbage collection algorithm is recursive. Because of this, the system can crash during garbage collection when (1) very deep (thousands of levels) lists or other structures are present in memory and (2) not enough virtual memory can be obtained for the system stack, e.g. because of Unix limits on the size of page tables, or for lack of swap space on disk.

• A failure "alloc" may be generated when compiling big programs or big modules. The absolute size of the program is not directly relevant: the important factors are the size of every individual fun-expression and the number of definitions in a module. The preferred programming style should consist in writing a large number of small modules (1-5 pages) containing small (10-100 line) functions. The size of type definitions has no relevance to these problems.
<table>
<thead>
<tr>
<th>0 nul</th>
<th>1 soh</th>
<th>2 stx</th>
<th>3 etx</th>
<th>4 eot</th>
<th>5 enq</th>
<th>6 ack</th>
<th>7 bel</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 bs</td>
<td>9 ht</td>
<td>10 nl</td>
<td>11 vt</td>
<td>12 np</td>
<td>13 cr</td>
<td>14 so</td>
<td>15 si</td>
</tr>
<tr>
<td>16 de</td>
<td>17 dc1</td>
<td>18 dc2</td>
<td>19 dc3</td>
<td>20 dc4</td>
<td>21 nak</td>
<td>22 syn</td>
<td>23 etb</td>
</tr>
<tr>
<td>24 can</td>
<td>25 em</td>
<td>26 sub</td>
<td>27 esc</td>
<td>28 fs</td>
<td>29 gs</td>
<td>30 rs</td>
<td>31 us</td>
</tr>
<tr>
<td>32 sp</td>
<td>33 !</td>
<td>34 &quot;</td>
<td>35 #</td>
<td>36 $</td>
<td>37 %</td>
<td>38 &amp;</td>
<td>39 '</td>
</tr>
<tr>
<td>40 (</td>
<td>41 )</td>
<td>42 *</td>
<td>43 +</td>
<td>44 ,</td>
<td>45 -</td>
<td>46 .</td>
<td>47 /</td>
</tr>
<tr>
<td>48 0</td>
<td>49 1</td>
<td>50 2</td>
<td>51 3</td>
<td>52 4</td>
<td>53 5</td>
<td>54 6</td>
<td>55 7</td>
</tr>
<tr>
<td>56 8</td>
<td>57 9</td>
<td>58 :</td>
<td>59 ;</td>
<td>60 &lt;</td>
<td>61 =</td>
<td>62 &gt;</td>
<td>63 ?</td>
</tr>
<tr>
<td>64 @</td>
<td>65 A</td>
<td>66 B</td>
<td>67 C</td>
<td>68 D</td>
<td>69 E</td>
<td>70 F</td>
<td>71 G</td>
</tr>
<tr>
<td>72 H</td>
<td>73 I</td>
<td>74 J</td>
<td>75 K</td>
<td>76 L</td>
<td>77 M</td>
<td>78 N</td>
<td>79 O</td>
</tr>
<tr>
<td>80 P</td>
<td>81 Q</td>
<td>82 R</td>
<td>83 S</td>
<td>84 T</td>
<td>85 U</td>
<td>86 V</td>
<td>87 W</td>
</tr>
<tr>
<td>88 X</td>
<td>89 Y</td>
<td>90 Z</td>
<td>91 [</td>
<td>92 \</td>
<td>93 ]</td>
<td>94 ^</td>
<td>95 _</td>
</tr>
<tr>
<td>96 `</td>
<td>97 a</td>
<td>98 b</td>
<td>99 c</td>
<td>100 d</td>
<td>101 e</td>
<td>102 f</td>
<td>103 g</td>
</tr>
<tr>
<td>104 h</td>
<td>105 i</td>
<td>106 j</td>
<td>107 k</td>
<td>108 l</td>
<td>109 m</td>
<td>110 n</td>
<td>111 o</td>
</tr>
<tr>
<td>112 p</td>
<td>113 q</td>
<td>114 r</td>
<td>115 s</td>
<td>116 t</td>
<td>117 u</td>
<td>118 v</td>
<td>119 w</td>
</tr>
<tr>
<td>120 x</td>
<td>121 y</td>
<td>122 z</td>
<td>123 {</td>
<td>124</td>
<td>125 }</td>
<td>126 ~</td>
<td>127 del</td>
</tr>
</tbody>
</table>
Medium Record

| Fst | Snd | Trd |

Record

0  (nullrecord)  (unboxed)

| n  | Field 1 | ... | Field n | (n > 0)

Variant

| Case | Tag |

Reference

| At |

String

| n  | C1 | ... | Cn | (n ≥ 0)

...
Appendix L. System limitations

There is a limit on the size of any single ML object, due to storage allocation problems. This limit is determined by the constant "PageSize" in the file "amglob.h". All the limitations mentioned on this section are further constrained by this restriction.

The semantic limit on the length of strings is 64K chars.

The syntactic limit on the length of string quotations in a source program is also 64K chars.

Several memory areas inside the system have fixed size. When one of these is exceeded, compilation fails and a message is printed. The only way to fix this is to search for the point in the source program where the error message is generated, increase the corresponding area (usually by redefining a constant) and recompile the system.
Appendix K. Introducing new primitive operators

This appendix describes how to add to the ML system a new function "foo: t" that cannot be otherwise defined in ML. It has to be defined as a new primitive operation in the Functional Abstract Machine [Cardelli 83] and implemented in C, Pascal, Assembler, or any other language which respects VAX procedure call standards.

This procedure is complex, dangerous and not advisable. Before attempting it, one should consider implementing "foo" as an external program activated through the channel primitive as a subprocess.

- File mfglob.h
  - Add "OpFoo" to enumeration type "SMOperationT" in ASCII ALPHABETIC ORDER!
  - Add "OpFoo: ();" to the case list of type "SMCodeT".
  - Add "AtomFoo: AtomRefT" in section "{Parser Vars}".
  - If foo is prefix (infix, etc.) add "SynOpFoo" to the enumeration type "SynPrefixOpClassT" ("SynInfixOpClassT", etc.).

- File mfscan.p
  - Add "AtomFoo := TableInsertAtom( 3, 'foo');" in procedure "SetupTable" (where "3" is the length of "foo").
  - Add "PushSynRoleId(AtomFoo);" in the same procedure (assuming that foo is nonfix, else use PushSynRoleInfix, etc. as appropriate, with second argument "SynOpFoo").

- File mlanal.p
  - Add "Predefined(AtomFoo, OpFoo, n,t);" to the procedure "SetupEnvironment", where foo: t (you can understand how to express t from the code of SetupEnvironment), and n is the arity of foo (i.e. the number of arguments it expects on the stack).

- File mldeb.p
  - Add "SetupMon(EmitSimpleOp(OpFoo));" to the procedure "SetupEnvValues" (if foo is not monadic, use SetupBin etc. Monadic, diadic, etc means that foo takes 1, 2, etc. arguments on the top of the stack and returns a result there, after popping the arguments). It is essential that the order of setups in this procedure matches the order of definitions in SetupEnvironment (in mlanal.p).

- File mlconv.p
  - Add "OpFoo: Operand:=0(nil);" to the case list in function "ConvertOperand".

- File mfglob.h
  - Add 

- Add "OpFoo: CallOp((Address)DoFoo,n); break;" to the case list in procedure "Assem", where n is the arity of Foo (i.e. how many arguments it expects on the stack).

- File ammall.c
  - If foo may escape with string "foo", declare "Address *StrFoo;" and add "StrFoo = PushGCBBox(StringFromC("foo"));" to the procedure "AllocFailStrings".

- File amdebug.c
  - Add "case OpFoo: printf("Foo"); break;" to the case list of procedure "AMStatPrint".

- File amfoocp.c
Appendix I. Escape sequences for strings

The escape character for strings is \; it introduces characters according to the following code:

<table>
<thead>
<tr>
<th>Escape</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>\1 .. \9</td>
<td>One to nine spaces</td>
</tr>
<tr>
<td>\0</td>
<td>Ten spaces</td>
</tr>
<tr>
<td>\r</td>
<td>Carriage return</td>
</tr>
<tr>
<td>\l</td>
<td>Line feed</td>
</tr>
<tr>
<td>\t</td>
<td>Horizontal tabulation</td>
</tr>
<tr>
<td>\b</td>
<td>Backspace</td>
</tr>
<tr>
<td>\e</td>
<td>Escape</td>
</tr>
<tr>
<td>\n</td>
<td>Null (Ascii 0)</td>
</tr>
<tr>
<td>\d</td>
<td>Del (Ascii 127)</td>
</tr>
<tr>
<td>\c</td>
<td>Ascii control char 'c (c any appropriate char)</td>
</tr>
<tr>
<td>\c</td>
<td>c (for any other char c different from #)</td>
</tr>
<tr>
<td>#s</td>
<td>128 + s (for any of the previous sequences s)</td>
</tr>
</tbody>
</table>

Strings are printed at the top level in the same form in which they are read; that is surrounded by quotes, with all the \ and with no non-printable characters. Output operations instead print strings in their crude form.
Appendix H. Syntax

Syntactic alternatives are in order of decreasing precedence.

Phrase ::=  
  [Exp | SimpleDecl | Module | Use | Monitor] ";".

Module ::=  
  "module" ModuleName ["includes" {ModuleName}]+ "body" Decl "end".

Use ::=  
  "use" String.

Monitor ::=  
  "monitor".

SimpleExp ::=  
  [:op:] (Ide [Con] | 
  [: Exp / ";" ] | 
  [: Exp / ";"] [ ]).

Exp ::=  
  SimpleExp | 
  Exp SimpleExp | 
  Exp ";" Type | 
  Exp Ide Exp | 
  {Exp / ","} [ ] | 
  escape Exp | 
  if Exp "then" Exp "else" Exp | 
  while Exp "do" Exp | 
  let Decl "in" Exp "end" | 
  Exp "where" Decl "end" | 
  case Exp "of" Match | 
  Exp ";" Exp | 
  Exp ";" Exp | 
  Exp "??" Exp Exp | 
  Exp ";" Ide "." Exp. 
  "fun" Match.

SimpleDecl ::=  
  "val" ValBind | 
  "type" TypeBind | 
  "abstype" TypeBind "with" Decl "end" | 
  "export" ExportList "from" Decl "end" | 
  "import" {ModuleName} | 
  "infix" {Id} | "noinfix" {Id}.

Decl ::=  
  SimpleDecl | 
  Decl ";" Decl | 
  (" Decl ") .

ExportList ::=  
  [:type:] {Id / ","} [ ] | "val" {Id / ","} [ ].

ValBind ::=  
  ...
Appendix F. Metasyntax

Strings between quotes \"\" are terminals.

Identifiers are non-terminals.

Juxtaposition is syntactic concatenation.

'|' is syntactic alternative.

'[]' is the empty string.

'[.. ]' is zero or one times (i.e. optionally) ' .. '.

'{ .. }n' is n or more times ' .. ' (default n=0).

'{ .. / -- }n' means n (default 0) or more times ' .. ' separated by '--'.

Parentheses '( .. )' are used for precedence.
Appendix D. Predefined type identifiers

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Type</th>
<th>Precedence</th>
</tr>
</thead>
<tbody>
<tr>
<td>unit</td>
<td>Unit Type</td>
<td>Nonfix</td>
</tr>
<tr>
<td>bool</td>
<td>Boolean Type</td>
<td>Nonfix</td>
</tr>
<tr>
<td>int</td>
<td>Integer Type</td>
<td>Nonfix</td>
</tr>
<tr>
<td>string</td>
<td>String Type</td>
<td>Nonfix</td>
</tr>
<tr>
<td>*</td>
<td>Cartesian Product</td>
<td>N-ary infix</td>
</tr>
<tr>
<td>-&gt;</td>
<td>Function Space</td>
<td>Infix</td>
</tr>
<tr>
<td>list</td>
<td>List Type</td>
<td>Suffix</td>
</tr>
<tr>
<td>ref</td>
<td>Reference Type</td>
<td>Suffix</td>
</tr>
<tr>
<td>array</td>
<td>Array Type</td>
<td>Suffix</td>
</tr>
</tbody>
</table>
## Appendix C. Predefined identifiers

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Description</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>true</td>
<td>Logic true</td>
<td>Nonfix constant</td>
</tr>
<tr>
<td>false</td>
<td>Logic false</td>
<td>Nonfix constant</td>
</tr>
<tr>
<td>not</td>
<td>Logic not</td>
<td>Nonfix</td>
</tr>
<tr>
<td>&amp;</td>
<td>Logic and</td>
<td>Infix</td>
</tr>
<tr>
<td>or</td>
<td>Logic or</td>
<td>Infix</td>
</tr>
<tr>
<td>-</td>
<td>Complement</td>
<td>Nonfix</td>
</tr>
<tr>
<td>+</td>
<td>Plus</td>
<td>Infix</td>
</tr>
<tr>
<td>-</td>
<td>Difference</td>
<td>Infix</td>
</tr>
<tr>
<td>*</td>
<td>Times</td>
<td>Infix</td>
</tr>
<tr>
<td>div</td>
<td>Divide</td>
<td>Infix</td>
</tr>
<tr>
<td>mod</td>
<td>Modulo</td>
<td>Infix</td>
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<td>=</td>
<td>Equal</td>
<td>Infix</td>
</tr>
<tr>
<td>&lt;&gt;</td>
<td>Different</td>
<td>Infix</td>
</tr>
<tr>
<td>&gt;</td>
<td>Greater than</td>
<td>Infix</td>
</tr>
<tr>
<td>&lt;</td>
<td>Less than</td>
<td>Infix</td>
</tr>
<tr>
<td>&gt;=</td>
<td>Greater-eq</td>
<td>Infix</td>
</tr>
<tr>
<td>&lt;=</td>
<td>Less-eq</td>
<td>Infix</td>
</tr>
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<td>size</td>
<td>String length</td>
<td>Nonfix</td>
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<tr>
<td>extract</td>
<td>Substring extraction</td>
<td>Nonfix</td>
</tr>
<tr>
<td>explode</td>
<td>String explosion</td>
<td>Nonfix</td>
</tr>
<tr>
<td>implode</td>
<td>String implosion</td>
<td>Nonfix</td>
</tr>
<tr>
<td>explodeascii</td>
<td>String to Ascii conv.</td>
<td>Nonfix</td>
</tr>
<tr>
<td>implodeascii</td>
<td>Ascii to string conv.</td>
<td>Nonfix</td>
</tr>
<tr>
<td>`</td>
<td>String concat.</td>
<td>Infix</td>
</tr>
<tr>
<td>intofstring</td>
<td>String to int conv.</td>
<td>Nonfix</td>
</tr>
<tr>
<td>stringofint</td>
<td>Int to string conv.</td>
<td>Nonfix</td>
</tr>
<tr>
<td>nil</td>
<td>Empty list</td>
<td>Nonfix constant</td>
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<tr>
<td>::</td>
<td>List cons</td>
<td>Infix constructor</td>
</tr>
<tr>
<td>hd</td>
<td>List head</td>
<td>Nonfix</td>
</tr>
<tr>
<td>tl</td>
<td>List tail</td>
<td>Nonfix</td>
</tr>
<tr>
<td>null</td>
<td>List null</td>
<td>Nonfix</td>
</tr>
<tr>
<td>length</td>
<td>List length</td>
<td>Nonfix</td>
</tr>
<tr>
<td>@</td>
<td>List append</td>
<td>Infix</td>
</tr>
<tr>
<td>map</td>
<td>List map</td>
<td>Nonfix</td>
</tr>
<tr>
<td>rev</td>
<td>List reverse</td>
<td>Nonfix</td>
</tr>
<tr>
<td>fold</td>
<td>List folding</td>
<td>Nonfix</td>
</tr>
<tr>
<td>revfold</td>
<td>List rev folding</td>
<td>Nonfix</td>
</tr>
<tr>
<td>ref</td>
<td>New reference</td>
<td>Nonfix constructor</td>
</tr>
<tr>
<td>!</td>
<td>Dereferencing</td>
<td>Nonfix</td>
</tr>
<tr>
<td>:=</td>
<td>Assignment</td>
<td>Infix</td>
</tr>
<tr>
<td>array</td>
<td>New array</td>
<td>Nonfix</td>
</tr>
<tr>
<td>arrayoflist</td>
<td>List to array</td>
<td>Nonfix</td>
</tr>
<tr>
<td>lowerbound</td>
<td>Array lower bound</td>
<td>Nonfix</td>
</tr>
<tr>
<td>arraysize</td>
<td>Array size</td>
<td>Nonfix</td>
</tr>
<tr>
<td>sub</td>
<td>Array indexing</td>
<td>Infix</td>
</tr>
<tr>
<td>update</td>
<td>Array update</td>
<td>Infix</td>
</tr>
<tr>
<td>arraytolist</td>
<td>Array to list</td>
<td>Nonfix</td>
</tr>
<tr>
<td>o</td>
<td>Function comp</td>
<td>Infix</td>
</tr>
<tr>
<td>file</td>
<td>Stream from file</td>
<td>Nonfix</td>
</tr>
<tr>
<td>save</td>
<td>Stream to file</td>
<td>Nonfix</td>
</tr>
<tr>
<td>stream</td>
<td>Empty stream</td>
<td>Nonfix</td>
</tr>
<tr>
<td>channel</td>
<td>External channel</td>
<td>Nonfix</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td><code>1</code></td>
<td>Delim;</td>
<td></td>
</tr>
<tr>
<td><code>&quot;</code></td>
<td>Symbol;</td>
<td></td>
</tr>
<tr>
<td>`'a'</td>
<td>Letter;</td>
<td></td>
</tr>
<tr>
<td>`'b'</td>
<td>Letter;</td>
<td></td>
</tr>
<tr>
<td>`'c'</td>
<td>Letter;</td>
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<tr>
<td>`'d'</td>
<td>Letter;</td>
<td></td>
</tr>
<tr>
<td>`'e'</td>
<td>Letter;</td>
<td></td>
</tr>
<tr>
<td>`'f'</td>
<td>Letter;</td>
<td></td>
</tr>
<tr>
<td>`'g'</td>
<td>Letter;</td>
<td></td>
</tr>
<tr>
<td>`'h'</td>
<td>Letter;</td>
<td></td>
</tr>
<tr>
<td>`'i'</td>
<td>Letter;</td>
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<td>`'j'</td>
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<td>`'m'</td>
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<td>`'t'</td>
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<td>`'y'</td>
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<td>`'z'</td>
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</tr>
<tr>
<td><code>\</code></td>
<td>Symbol;</td>
<td></td>
</tr>
<tr>
<td><code>DEL</code></td>
<td>Illegal;</td>
<td></td>
</tr>
</tbody>
</table>
The frequency of garbage collection depends on the amount of active data and follows a simple adaptive algorithm; when there is little active data garbage collection is frequent, when there is much active data garbage collection is less frequent.

Garbage collection is not interruptible: pressing the DEL key during collection has no effect until the end of collection.

Data structures are kept in different pages according to their format. Pages are linked into three lists: the 'other space' list, the 'active' list and the 'free' list. There are always as many pages in the 'other space' list as in the union of the 'active' and 'free' lists.
Equality has its own type errors:

- let val f a = a
  in f = f end;
Invalid type of args to "=" or "<>": 'a -> 'a
I cannot compare functions

- let f a = (a = a);
Invalid type of args to "=" or "<>": 'a
I cannot compare polymorphic objects

- let abs A = int
  with val absA n = A n
  and repA (A n) = n
  in absA 3 = absA 3 end;
Invalid type of args to "=" or "<>": A
I cannot compare abstract types

In modules, all variables must be either locally declared or imported from other modules: global variables cannot be used:

- val a = 3;
> val a = 3 : int

- module A
  body val b = a end;
Modules cannot have global variables.
Unbound Identifier: a

Modules which have never been compiled, or which are obsolete, produce a link exception:

- import A;

Module A must be compiled
Exception: link

8.5. Monitoring the compiler

The top level command monitor; gives access to a menu of commands for monitoring the internal functions of the ML compiler. In most cases these commands produce some check prints of internal data structures. Some options, like printing the parse trees, can be useful in becoming familiar with the system.

- monitor;
"y" for Yes; <CR> for No.
ParseTree?
Types?
TypeVariables?
Match?
bindings:

module /usr/lib/ml/lib
module B
module /usr/lib/ml/lib
module A
module /usr/lib/ml/lib
type T
val absT : T -> int
val repT : int -> T
val a = (ref 3) : int ref

module C
module /usr/lib/ml/lib
module A
module /usr/lib/ml/lib
type T
val absT : T -> int
val repT : int -> T
val a = (ref 3) : int ref

type T
val absT : T -> int
val repT : int -> T
val c = (ref 3) : int ref

Note that A is imported by D through two different import paths.

Sharing of types means that the module A is not typechecked twice: if it were, then we would have two different abstract types called T and CrepT(BabsT 3), for example, would produce a type error.

Sharing of values means that the module A is not evaluated twice: hence b and c are the same reference variable, so that any side effect on b will be reflected on c, and vice versa.

Sharing of values also has the desirable effect that multiply imported functions (e.g. the library functions) are not replicated.

7.3. Module versions

The system automatically keeps track of module versions, to make sure, for example, that when a module is significantly modified, all the modules which depend on it are recompiled. The system however does not automatically recompile obsolete modules; it simply produces an error message and an exception. For example, when an obsolete module A is trying to import a new version of module B, we have:

    declaration: import A;

    exception: Module A must be compiled
                Exception: link

This error message is generated in a variety of circumstances, but the effect is always the same: module A must be recompiled.

A new version of a module is generated whenever that module is recompiled and its external
Exporting those binders without exporting B may potentially generate objects of an unknown (in the current scope) type t, on which no operations are available. Hence the following restriction applies: whenever a type identifier is involved in the exports of a module, its type definition must also be exported.

There is an alternative notation for modules which are imported and reexported:

    module:    module A
              includes B C
              body
              end;

    module:    module A
              body
              import B C;
              end;

The two forms above are equivalent; the first one is just an abbreviation for the second one. The includes keyword should be understood as the set-theoretical inclusion of the bindings of B and C; not as the inclusion of the source lines constituting the definition of B and C.

Every module automatically imports a standard library module called /usr/lib/ml/lib, which contains all the predefined ML types, functions and values (remember that a module cannot access any outside binding, except the ones explicitly imported; this also applies to the predefined ML identifiers). The library module is shown as a module /usr/lib/ml/lib binding, on import:

    module:    module A
              body
                val a = 3
              end;

    declaration:    import A;

    bindings:    module /usr/lib/ml/lib
                   val a = 3 : int

The module /usr/lib/ml/lib binding is only an abbreviation for all the bindings defined in /usr/lib/ml/lib.ml: they are really imported and (re-)defined at this point.

Similarly, when importing a module B which exports a module A, the bindings of A are not explicitly listed. Instead a module A binding is presented as an abbreviation.

    module:    module A
              body
                val a = 3
              end;

    module:    module B
              includes A
              body
                val b = 5
              end;

    declaration:    import B;
Output operations are constructive; the characters written are appended to the end of the stream. Output writes a string of characters at the end of a stream.

The operation `lookahead` reads characters from a stream without affecting it. The arguments are like in the string operation `extract`; the first argument is the source stream, the second argument is the starting position of the string to be extracted from the stream (the first character in a stream is at position 1), and the third argument is the length of the string to be extracted; it escapes with string "lookahead" if the numeric arguments are out of range.

There are two flavors of streams, which can be called `internal` and `external` streams. Streams returned by `file` and `stream` are internal, because ML is the only process which can access them. Other streams, like the predefined `terminal` stream, are external because the ML system holds only one end of them, while the other end belongs to some external process. Some external streams may be read-only or write-only; the I/O operations escape when trying to read from a write-only stream, or write to a read-only stream.

The operation `channel` will be provided to open new external streams, for example to allow direct communication between two ML systems, or between ML and an external process. The way this will work is still to be defined.

All the above operations may escape for various I/O error. Multiplexed read and multiplexed write operations can be obtained by passing the same stream to several readers and writers respectively (i.e. to different parts of a program).

7. Modules

A `module` is a set of bindings (values, functions and types) which can be compiled and stored away, and later `imported` as a declaration wherever those bindings are needed. Modules are identified by `module names`. Module names can syntactically be represented as simple identifiers, or as strings containing Unix file paths (to access modules in directories other than the current one).

Here is a module called `Pair` which defines a type and two functions.

```ml
module Pair

body

abstype 'a pair = pair of 'a * 'a
with
  val newpair (a,b) = pair(a,b)
  and left (pair(a,..)) = a
  and right (pair(..,b)) = b

end

```

Module definitions can only appear at the top level, and they cannot rely on bindings defined in the surrounding scope (e.g. previous top level definitions). All the bindings used by a module must either be defined in the module itself, or imported from other modules.

The processing of a module definition is called a module `compilation`, whose only effect is to produce a separately compiled version of the module. Module definitions do not evaluate to values, and they do not introduce new bindings.

Modules can be defined interactively, but usually they are contained in external source files. In the latter case, a command `use "Mod.ml"`; (see section "Loading source files") can be used to compile a module definition contained in the file `Mod.ml`. Once a module is compiled, it can be imported:

```ml
declaration: import Pair;

bindings: module /usr/lib/ml/lib
          abstype 'a pair
          val newpair : ('b * 'b) -> ('b pair)
          val left : 'c pair -> 'c
```

bindings:  
  abstype increasing_pair  
  val increasing_pair : (int * int) => increasing_pair  
  val low : increasing_pair => int  
  val high : increasing_pair => int

In the first example, the variable b is unknown at the top level. The second example shows how a variable can be made private to a function or a group of functions: only the functions increment and fetch have access to count, so that nobody can corrupt count. The third example is an abstract data type increasing_pair; note that the constructor pair has been hidden, so that it is impossible to generate non-increasing pairs.

The 'abstype tb with d' declaration construct (see section "Abstract declarations") is just an abbreviation for 'export xl from type tb; d end', where the types defined in tb are listed in an abstype export list in xl, and the types and values defined in d are listed in appropriate export lists in xl.

The increasing_pair example above can be written more conveniently as:

declaration:  
  abstype increasing_pair = pair of int * int  
  with  
        val increasing_pair(x,y) =  
          if x>y then escape "increasing_pair"  
          else pair(x,y)  
        and low (pair(x,y)) = x  
        and high (pair(x,y)) = y  
      end;

bindings:  
  abstype increasing_pair  
  val increasing_pair : (int * int) => increasing_pair  
  val low : increasing_pair => int  
  val high : increasing_pair => int

5.6. Import declarations

The import environment operator acts on precompiled modules, and it is explained in detail in section "Modules". A declaration import M imports no variables from the surrounding environment, and exports the variables exported by the module M.

syntax:  
  Import_declaration ::=  
    import module_name .. module_name

declaration:  
  import minmax;

bindings:  
  val min : (int * int) => int  
  val max : (int * int) => int

where the module minmax contains definitions for the min and max functions.

5.7. Lexical declarations

Special kinds of declaration, introduced by the keywords nonfix and infix are used to specify lexical attributes of identifiers. These declarations have only a lexical meaning; they do not introduce bindings, nor causes evaluations.

All identifiers have a property called fixity, which can be infix or nonfix (i.e. normal). The fixity of an identifier determines the way arguments are syntactically supplied to it (see section "Application" for the patterns of usage). Fixity can be specified in a lexical declaration, before the identifier is used in declarations or expressions:
with val origin = position (0,0)
    and stepx (position(x,y)) = position(x+1,y)
    and stepy (position(x,y)) = position(x,y+1)
end;

bindings: abstype position
val origin = - : position
val stepx : position -> position
val stepy : position -> position

In this example, a position can only be achieved by small steps from the origin. We cannot ‘jump’ to an arbitrary position because there is no operation to directly build one.
Here is the definition of a parametric recursive type of binary trees with leaves of type 'a:

declaration: abstype rec 'a tree = leaf of 'a | node of 'a tree * 'a tree
    with val mkleaf a = leaf a
        and mknode (t,t') = node(t,t')
        and isleaf (leaf _) = true | isleaf(node _) = false
        and left (node(_,t)) = t
        and right (node(_,t)) = t
        and tip (leaf a) = a
end;

bindings: abstype 'a tree
val mkleaf : 'a -> 'a tree
val mknode : ('a tree * 'a tree) -> 'a tree
val isleaf : 'a tree -> bool
val left : 'a tree -> 'a tree
val right : 'a tree -> 'a tree
val tip : 'a tree -> 'a

The constructors leaf and node are only known during the definition of the basic operations on trees, and are not exported outside the abstract type definition. All users of the tree abstract type will be unable to take advantage of the concrete representation of trees given by 'leaf of 'a | node of 'a tree * 'a tree', thus making this type ‘abstract’.
The with operator can be preceded by several type definitions connected by and and rec; this allows one to define mutually recursive abstract types:

declaration: abstype rec a = .. b ..
    and b = .. a ..
    with .. end;

5.4. Sequential declarations
Cascaded, or ‘sequential’ declarations are provided by the environment operator ‘;’, which makes earlier declarations available inside later declarations.
syntax: sequential_declaration ::= declaration ; declaration

In \( d_1 ; d_2 \), the variables exported by \( d_1 \) are imported into \( d_2 \), but not vice versa. The variables exported by the whole declaration are the ones exported by \( d_2 \), plus the ones exported by \( d_1 \).
5.1.3. Recursive bindings

The operator `rec` builds recursive bindings, and it is used to define recursive and mutually recursive functions. The binding `rec d` exports the variables exported by the binding `d`, and imports the variables imported by `d` and the variables exported by `d`.

**syntax:**

\[
\text{recursive\_value\_binding} ::= \\
\text{rec value\_binding}
\]

**declaration:**

\[
\text{val rec fib n = if } n < 2 \text{ then 1 else fib(n-1) + fib(n-2);}
\]

Note that if `rec` were omitted, the identifier `fib` on the right of `=` would not refer to its defining occurrence on the left of `=`, but to some previously defined `fib` value (if any) in the surrounding scope.

A recursive value declaration can only define functions; simple value bindings are not allowed to be recursive. Moreover, all the bindings contained in a `rec` must be syntactically functions, e.g. simple, curried or clausal function bindings, or simple variable bindings having fun-expressions on the right of `=`. A definition like `val rec g = f;` is not accepted, even if `f` is a function.

5.2. Type bindings

Type bindings define new types and their constructors, and are prefixed by the keyword `type`. After `type` there can be a definition, a parallel binding or a recursive binding.

**syntax:**

\[
\text{type\_binding} ::= \\
\text{simple\_type\_binding} \\
\text{parallel\_type\_binding} \\
\text{recursive\_type\_binding}
\]

5.2.1. Simple bindings

The simplest form of type binding introduces a single, possibly parametric, type and its constructors:

**syntax:**

\[
\text{simple\_type\_binding} ::= \\
\text{type\_id} = \text{type\_cases} \\
\text{type\_var type\_id} = \text{type\_cases} \\
\text{(type\_var, .. ,type\_var type\_id} = \text{type\_cases}
\]

**syntax:**

\[
\text{type\_cases} ::= \\
\text{con [of type\_exp]} | .. | \text{con [of type\_exp]}
\]

Here are examples of types with zero, one and two type parameters:

**declaration:**

\[
\text{type intpair = intpair of int * int;}
\]

**bindings:**

\[
\text{type intpair = intpair of int * int} \\
\text{con intpair : (int * int) \rightarrow intpair}
\]

**declaration:**

\[
\text{type 'a pair = pair of 'a * 'a;}
\]
4. Type expressions
A type expression is either a type variable, a basic type, or the application of a type operator to a sequence of type expressions. Type operators are usually suffix, except for cartesian product * and the infix operator ➝.

4.1. Type variables
A type variable is an identifier starting with "" and possibly containing other "" characters. Type variables are used to represent polymorphic types.

4.2. Type operators
A basic type is a type operator with no parameters, like int. A parametric type operator, like ➝ or List, takes one or more arguments which are arbitrary type expressions, as in 'a ➝ ("a List) list'. If an operator takes many parameters, these are separated by commas and enclosed in parentheses, as in ('a, 'b) tree. See appendix "Predefined type identifiers" for a list of the predefined type operators.

5. Declarations
Declarations are used to establish bindings of variables to values. Every declaration is said to import some variables, and to export other variables. The imported variables are the ones which are used in the declaration, and are usually defined outside the declaration (except in recursive declarations). The exported variables are the ones defined in the declaration, and that are accessible in the scope of the declaration.

A declaration can be a value binding, a type binding, a sequential composition, a private declaration, a module import, a lexical declaration or a parenthized declaration.

\[
\text{syntax: } \quad \text{declaration} ::= \quad \text{val value\_binding} \\
\text{type type\_binding} \\
\text{abstract\_declaration} \\
\text{sequential\_declaration} \\
\text{private\_declaration} \\
\text{Import\_declaration} \\
\text{lexical\_declaration} \\
( \ \text{declaration} )
\]

5.1. Value bindings
Value bindings define values and functions, and are prefixed by the keyword val. After val there can be a simple definition, a parallel binding or a recursive binding.

\[
\text{syntax: } \quad \text{value\_binding} ::= \quad \text{simple\_value\_binding} \\
\text{parallel\_value\_binding} \\
\text{recursive\_value\_binding}
\]

5.1.1. Simple bindings
The simplest form of value binding, called a value definition, introduces a single pattern or function:

\[
\text{syntax: } \quad \text{simple\_value\_binding} ::= \quad \text{pat} = \text{exp}
\]
3.18. Type semantics and type specification

The set of all values is called \( V \); it contains basic values, like integers, and all the composite objects built on elements of \( V \), like pairs, functions, etc. The structure of \( V \) can be given by a recursive type equation, of which there are known solutions (+ is disjoint union, * is cartesian product and \( \rightarrow \) is continuous function space):

\[
V = \text{Bool} + \text{Int} + \ldots + (V + V) + (V \times V) + (V \rightarrow V)
\]  

[1]

All functions are interpreted as functions from \( V \) to \( V \), so when we say that \( f \) has type \( \text{int} \rightarrow \text{bool} \) we do not mean that \( f \) has domain \( \text{int} \) and codomain \( \text{bool} \) in the ordinary mathematical sense. Instead we mean that whenever \( f \) is given an integer argument it produces a boolean result. This leaves \( f \) free to do whatever it likes on arguments which are not integers: it might return a boolean, or it might not. This idea leads to the following definition for function spaces:

\[
A \rightarrow B = \{ f \in V \rightarrow V | a \in A \implies f \, a \in B \}
\]  

[2]

where \( \rightarrow \) is the conventional continuous function space, while \( \rightarrow \) is the different concept that we are defining. \( A \) and \( B \) are domains included in \( V \), and \( A \rightarrow B \) is a domain included in \( V \rightarrow V \), and hence embedded in \( V \) by [1].

In this way we can give meaning to monotypes like \( \text{int} \rightarrow \text{int} \), but what about polytypes? Consider the identity function \( \text{fun} \, x \, x : a \rightarrow a \); whenever it is given an argument of type \( a \) it returns a result of type \( a \). This means that when given an integer it returns an integer, when given a boolean it returns a boolean, etc. Hence by [2], \( \text{fun} \, x \, x \) belongs to the domains \( \text{int} \rightarrow \text{int} \), \( \text{bool} \rightarrow \text{bool} \), and to \( d \rightarrow d \) for any domain \( d \). Therefore \( \text{fun} \, x \, x \) belongs to the intersection of all those domains, i.e. to \( \cap_{d \in T} d \rightarrow d \) (where \( T \) is the set of all domains). We can now take the latter expression as the meaning of \( a \rightarrow a \).

In general a polymorphic object of type \( a[a] \) belongs to all the domains \( a[d/a] \), and hence to their intersection.

Some surprising facts derive from these definitions. First, \( a \) is not the type of all objects, as one might expect; in fact the meaning of \( a \) is the intersection of all domains. The only element contained in all domains is the divergent computation, which is therefore the only object of type \( a \).

Second, \( a \rightarrow a \), as a domain, is smaller than any of its instances, for example \( \text{int} 
\rightarrow \text{int} \). In fact any function returning an \( a \) when given an \( a \), must return an \( a \) when given an \( \text{int} \) (i.e. \( a 
\rightarrow \text{int} \subseteq \text{int} \rightarrow \text{int} \)), but an \( \text{int} \rightarrow \text{int} \) function is not required to return a boolean when given a boolean (i.e. \( \text{int} \rightarrow \text{int} \cap \text{int} \rightarrow \text{a} \)). Hence a function like \( \text{fun} \, x \, x+1 \) : \( \text{int} \rightarrow \text{int} \) is not an \( a 
\rightarrow \text{a} \).

Similarly, \( a \) list as a domain is smaller than \( \text{int} \) list, \( \text{bool} \) list, etc. In fact \( a \) list is the intersection of all list domains and only contains the empty list (and the undefined computation).

When specifying a type in ML, by the notation:

\[
\text{syntax:}
\]

\[
\text{exp : type}
\]

the effect is to take the meet of the type of the expression inferred by the system and of the type following `::` specified by the user (if this meet exists) as the type of the expression. The meet of two domains is their intersection.

This implicit join operation explains why the specifications:

expression: \( 3 : 'a; \)

result: \( 3 : \text{int} \)
and fruit = apple | plum | banana;

bindings: type color = red | purple | yellow
type fruit = apple | plum | banana

declaration: val fruitcolor (fruit: fruit): color =
  case fruit of
    apple. red |
    banana. yellow |
    plum. purple;

binding: val fruitcolor : fruit => color

The case construct is a convenient form of saying if fruit=apple then red else if fruit=banana then yellow else if fruit=plum then purple else escape "match" (else escape "match is never executed in this case because the list of cases is exhaustive).

The typing rule for case is:

typing rule: if x : t' and p₁ : t and .. and pₙ : t'
and e₁ : t and .. and eₙ : t
then (case x of p₁: e₁ | .. | pₙ: eₙ) : t

This says that all the patterns must have the same type as value being inspected, and that the values returned for each case must have the same type.

3.16. Scope blocks

A scope block is a control construct which introduces new variables and delimits their scope. Scope blocks have the same function of begin-end constructs in Algol-like languages, but they have a fairly different flavor due to the fact of being expressions returning values, instead of groups of statements. There are two kinds of scope blocks:

| syntax: | let declaration in exp end |
| syntax: | exp where declaration end |

The let construct introduces new variable bindings in the declaration part which can be used in the exp part (and there only). Newly introduced variables hide externally declared variables having the same name for the scope of exp; the externally declared variables remain accessible outside exp.

The where construct behaves just like let; it simply inverts the order in which the expression and the declaration appear.

The value returned by a scope block is the value of its expression part. Similarly the type of a scope block is the type of its expression part. The different kinds of declarations are described in section "Declarations".

| typing rule: | if e : t then (let d in e end) : t |

3.17. Exceptions and traps

An exception (sometimes also called a failure) can be raised by a system primitive or by a user program. When an exception is raised, the execution of the current expression is abandoned, and an exception packet is propagated outward, tracing back along the history of function calls and expression evaluations which led to the exception. If the exception is allowed to propagate up to the top
appendix "Precedence of operators" for details. In case of partial application, the form \( f \ g \ a \), is interpreted as \((f \ g) \ a\), and not as \( f \ (g \ a)\); note that they are both equally meaningful.

Infix identifiers can be applied in two ways:

```
syntax:       a f b

syntax:       op f (a,b)
```

The first form is the expected one; an infix identifier has always a type matching \((a \ * \ 'b) \to \ 'c\). The second possibility derives from the fact that there must be a way of passing an infix operator \( f \) as an argument to a function \( g \); \( g(f) \) will produce a syntax error, but \( g(op \ f) \) is accepted. In general the \( op \) keyword coerces any infix identifier to a nonfix one.

The typing rule for function application states that the type of the argument must match the type of the domain of the function:

```
typing rule:     if \( f : t \to t' \) and \( a : t \) then \( (f \ a) : t' \)
```

For example, \((\text{fun } x. \ x)\) has the type \('a \to 'a\) and all the instances of it, e.g. \(\text{int} \to \text{int}\). Hence \((\text{fun } x. \ x) \ 3\) has type \(\text{int}\).

### 3.12. Conditional

The syntactic form for conditional expressions is:

```
syntax:        if \( e_1 \) then \( e_2 \) else \( e_3 \)
```

The expression \( e_1 \) is evaluated to obtain a boolean value. If the result is \text{true} then \( e_2 \) is evaluated; if the result is \text{false} then \( e_3 \) is evaluated. Example:

```
expression:     \text{val sign n =}
                \text{if } n < 0 \text{ then } "1"
                \text{else if } n = 0 \text{ then } 0
                \text{else } 1;
```

The \text{else} branch must always be present.

The typing rule for the conditional states that the \text{if} branch must be a boolean, and that the \text{then} and \text{else} branches must have compatible types:

```
typing rule:    if \( e_1 : \text{bool} \) and \( e_2 : t \) and \( e_3 : t \)
                then \( (\text{if } e_1 \text{ then } e_2 \text{ else } e_3) : t \)
```

Note that the types of two branches only have to match, not to be identical. If one branch is more polymorphic than the other, than it also has the type of the other (by instantiation of the type variables), and the above rule can be applied.

### 3.13. Sequencing

When several side-effecting operations have to be executed in sequence, it is useful to use **sequencing**:

```
syntax:        (\( e_1 ; \ldots ; e_n \))    \( n \geq 2 \)
```

(the parentheses are needed), which evaluates \( e_1 \ldots e_n \) in turn and returns the value of \( e_n \). The
appear as part of value declarations, functions and case expressions.

A *match* is a sequence of pattern-action pairs separated by vertical bars.

```
syntax: match ::= pat . exp | .. | pat . exp
```

Matches are used to destructuring values and to execute fragments of code depending on the form of
values: they replace test and selection operations. The patterns in a match are matched in turn,
from left to right, against some value v. The first successful match is used to destructuring v, and the
variables in the pattern are bound to the respective parts of v. Then the corresponding expression
is executed, and its result is returned as the result of the matching. If none of the patterns matches
v, then an exception "match" is raised.

Matches are not expressions; they can only appear in function expressions, case expressions and, in
a sugared form, in clausal function definitions.

### 3.10. Functions

Functions can be introduced by a *curried definition*, for partially applicable functions, or by a
*clausal definition*, for case analysis:

```
syntax: {op} f simp_pat .. simp_pat {: type} = exp  (curried)
syntax: {op} f simp_pat {: type} = exp | .. | f pat {: type} = exp  (clausal)
```

- The `op` keyword should be used when `f` is an infix; alternatively `pat f pat'` can be used instead
  of `op f (pat, pat')`.
- The `simp_pat` patterns are `..`, variables, constants, lists and parenthesized patterns, in particular
  they must be parenthesized when they have the form `(pat' : type)`.
- The optional type expressions refer to the type of the result of the function.
- Curried functions cannot be defined by case analysis: if needed, the arguments can be analyzed
  after the `=.`

Unnamed functions can be introduced as expressions by the use of the *fun-notation*, which is just a
match preceded by the keyword `fun`:

```
syntax: fun match
```

A `fun` expression denotes a function, which can be associated with an identifier by a normal value
definition, for example:

```
declaration: val plus = fun x . fun y . x + y

declaration: val null = fun nil . true | a :: b . false;
```

A curried function definition is a sugaring of the first declaration above, and a clausal function
definition is a sugaring of the second declaration:

```
declaration: val plus x y = x + y

declaration: val plus nil = true | plus (a :: b) = false;
```

The type of every expression and pattern can be specified by suffixing a colon and a type expres-
sion to it (note that parentheses are needed around type specifications in patterns, when they are
export

abstype array
val array arrayoflist lowerbound arraysize sub update arraytolist
from

  type 'a array = arr of {lowerbound:} int * {size:} int * {table:} 'a ref list;

  val rec el (n: int, (head :: tail): 'a list): 'a =
    if n=0 then head else el(n-1,tail);

  val array (lb: int, length: int, item: 'a): 'a array =
    if length<0 then escape "array"
    else arr(lb,length,list length)
      where rec val list n =
        if n=0 then [] else (ref item) :: list(n-1)
    end

  and arrayoflist (lb: int, list: 'a list): 'a array =
    arr(lb,length list,map ref list)

  and lowerbound (arr(lb,_): 'a array): int = lb

  and arraysize (arr(_,size,_): 'a array): int = size

  and (arr(lb,size,table): 'a array) sub (n: int): 'a =
    let val n' = n-lb
    in  if n'<0 or n'>=size then escape "sub"
        else !el(n',table)
    end

  and (arr(lb,size,table): 'a array) update (n: int, value: 'a): unit =
    let val n' = n-lb
    in  if n'<0 or n'>=size then escape "update"
        else el(n',table) := value
    end

  and arraytolist (arr(_,_,table): 'a array): 'a list =
    map (op !) table

end;

Applicative programming fans should type the following declarations, or introduce them in the standard library:

  type 'a ref = ref;
  type 'a array = array;
  val op := = ();
  val ! = ();
  val arrayoflist = ();
  val lowerbound = ();
  val arraysize = ();
  val op sub = ();
• The escape character for strings is \\; the conventions used to introduce quotes and non-printable characters inside strings are described in appendix "Escape sequences for strings".
• size returns the length of a string.
• extract extracts a substring from a string: the first argument is the source string, the second argument is the starting position of the substring in the string (the first character in a string is at position 1), and the third argument is the length of the substring; it escapes with string "extract" if the numeric arguments are out of range.
• explode maps a string into the list of its characters, each one being a 1-character string.
• implode maps a list of strings into a string which is their concatenation.
• explodeascii is like explode, but produces a list of the Ascii representations of the characters contained in the string.
• implodeascii maps a list of numbers interpreted as the Ascii representation of characters into a string containing those characters; it escapes with string "implodeascii" if the integers are not valid Ascii codes.
• intofstring converts a numeric string to the corresponding integer number, negative numbers start with "-"; it may escape with string "intofstring" if the string is not numeric.
• stringofint converts an integer to a string representation of the necessary length; negative numbers start with "-".

For Ascii characters we intend here full 8-bit codes in the range 0..255.

3.7. Updatable references

Assignment operations act on reference objects. A reference object is an updatable pointer to another object. References are, together with arrays, the only data objects which can be side effected; they can be inserted anywhere an update operation is needed in variables or data structures.

References are created by the operator ref, updated by := and dereferenced by !. The assignment operator := always returns unity. Reference objects have type t ref, where t is the type of the object contained in the reference.

\[
\begin{align*}
\text{ref} & : a \rightarrow \text{a ref} \quad \text{(constructor)} \\
\! & : \text{a ref} \rightarrow \text{a} \\
:= & : \text{a ref} \times a \rightarrow \text{unit} \quad \text{(infix)}
\end{align*}
\]

Here is a simple example of the use of references. A reference to the number 3 is created and updated to contain 5, and its contents are then examined.

```
declaration: val a = ref 3;

binding: val a = ref 3 : int ref

expression: a := 5;

result: () : unit

expression: ! a;

result: 5 : int
```

References can be embedded in data structures. Side effects on embedded references are reflected in all the structures which share them:

```
declaration: type 'a refpair = refpair of 'a ref * 'a ref;
```
3.4. Tuples

A tuple is a fixed-length heterogeneous sequence of values. The unity value (i.e., \( () \)) might be considered as a zero-length tuple. There are no tuples of length one; they are identified with their unique component. Tuples of length two or more are written as sequences of values separated by commas:

\[
\text{syntax: } \quad \exp_1, \ldots, \exp_n \\
\text{n=2}
\]

Tupling is an n-ary operation; in order to build non-flat tuples of tuples, parentheses must be used. For example the following is not a 4-tuple: it is a triple, whose second component is a pair:

\[
\begin{align*}
\text{expression: } & \quad 1, (2, 3), 4; \\
\text{result: } & \quad 1, (2, 3), 4 : \text{int } \ast (\text{int } \ast \text{int}) \ast \text{int}
\end{align*}
\]

The type of an n-ary tuple is an n-ary cartesian product, denoted by the symbol \( \ast \). Parentheses can be used to express non-flat cartesian products.

There are no primitive functions on tuples, except the basic use of commas to build them (note that it is not possible to define a function which extracts the first element of a tuple for tuples of any length). Destructuring must be done by pattern matching:

\[
\begin{align*}
\text{declaration: } & \quad \text{val a, b, c = 1, 2, 3;} \\
\text{result: } & \quad a = 1 : \text{int} \\
& \quad b = 2 : \text{int} \\
& \quad c = 3 : \text{int}
\end{align*}
\]

The type of a tuple is the cartesian product of the types of its components:

\[
\begin{align*}
\text{typing rule: } & \quad \text{if } \theta_1 : t_f \text{ and } \ldots \text{ and } \theta_n : t_f \\
& \quad \text{then } (\theta_1, \ldots, \theta_n) : t_f \ast \ldots \ast t_f
\end{align*}
\]

Tuples are one of the few really fundamental types in ML; they cannot be explained in terms of other constructs in the language.

3.5. Lists

A list of elements \( \exp_j \) is written:

\[
\text{syntax: } \quad [\exp_1, \ldots, \exp_n] \\
\text{n=0}
\]

with \([\ ]\) as the empty list. All the elements of a list must have the same type, otherwise a compile-time type error will occur.

The basic constructors for lists are:

\[
\begin{align*}
\text{nil} & \quad : \text{a list} & \text{(constant)} \\
:: & \quad : (\text{a } \ast \text{a list}) \rightarrow \text{a list} & \text{(infix constructor)}
\end{align*}
\]

- \text{nil} is the empty list (the same as \([\ ]\)).
- \text{::} (cons) adds an element to a list (e.g., \(1::[2;3;4]\) is the same as \([1,2,3,4]\)).

Some other frequent operations on lists are predefined in the system:
The example above is a common matching type error. A different kind of matching error can be generated by self-application, and in general by constructs leading to circularities in the type structures:

```ml
  - fun x. x x;
  Type Clash in:  (x x)
  Attempt to build a self-referential type
  by equating var:  'a
  to type expr:    'a -> 'b

  - val rec f_ = f;
  Type Clash in:  f_ = f
  Attempt to build a self-referential type
  by equating var:  'a
  to type expr:    'b -> 'a
```

Less common error messages are described in section "Error messages".

2. Lexical matters

The following lexical entities are recognized: identifiers, keywords, integers, strings, delimiters, type variables and comments. See appendix "Syntax of lexical entities" for a definition of their syntax.

An identifier is either (i) a sequence of letters, numbers, primes '(', and underscores '_', not starting with a digit, or (ii) a sequence of special characters (like *, @, /, etc.).

Keywords are lexically like identifiers, but they are reserved and cannot be used for program variables. The keywords are listed in appendix "Keywords".

Integers are sequences of digits.

Strings are sequences of characters delimited by string quotes "". String quotes and non-printable characters can be introduced in strings by using the escape character '\'. The details of the escape mechanism are described in appendix "Escape sequences for strings".

Type variables are only accepted in type expressions. They are identifiers starting with the character '_'. For example: '_', '__', '1_tyvar', etc.

Delimiters are parentheses ((), [], and {}), and other one-character punctuation marks like '.', and ':'. Delimiters never stick to any other character, so that no space is ever needed around them.

Comments are enclosed in curly brackets '{' and '}', and can be nested.

3. Expressions

Expressions denote values, and have a type which is statically determined. Expressions can be constants, identifiers, data constructors, conditionals, fun-expressions, function applications, infix operator applications, scope blocks, while expressions, case expressions, exception and trap expressions, and type specifications. All these different kinds of expressions are described in this section.

3.1. Unit

The expression () (called unity) denotes the only object of type unit.

```ml
  () : unit  (constant)
```

The unit type is useful when defining functions with no argument or no values: they take a unit argument or produce a unit result. There are no primitive operations on unity.

The unit type is not strictly primitive; it could be introduced by the declaration:
There is no provision in the ML system for editing or storing programs or data which are created during an ML session. Hence ML programs and definitions are usually prepared in text files and loaded interactively. The use of a multi-window editor like Emacs is strongly suggested: one window may contain the ML system, and other windows contain ML definitions which can be modified (without having to exit ML) and reloaded when needed, or they can even be directly pasted from the text windows into the ML window.

An ML source file looks exactly like a set of top-level phrases, terminated by semicolons. A file `prog.ml` containing ML source code can be loaded by the `use` top-level command:

```ml
use "prog.ml";
```

where the string surrounded by quotes can be any Unix file name or path. The files loaded by `use` may contain more `use` commands (up to a certain stacking depth), so that the loading of files can be cascaded. The file extension `.ml` is normally used for ML source files, but this is not compulsory.

When working interactively at the top level, the first two characters of every line are reserved for system prompts.

```
val a = 3
and f x = x + 1;
> val a = 3 : int
  | val f : int -> int

- a + 1;
  4 : int
```

`-` is the normal system prompt, indicating that a top-level phrase is expected, and `>` is the continuation prompt indicating that the phrase on the previous line has not been completed. Again, all the top level expressions and declarations must be terminated by a semicolon.

In the example above, the system responded to the first definition by confirming the binding of the variables `a` and `f`; `>` marks the confirmation of the a new binding, followed `|` on the subsequent lines when many variables are defined simultaneously. In general, the prompts `>` and `|` are followed by a variable name, an `=` sign, the new value of the variable, a `|`, and finally the type of the variable. If the value is a functional object, then the `=` sign and the value are omitted.

When an expression is evaluated, the system responds with a blank prompt `|`, followed by the value of the expression (just `fun` for functions), a `|` and the type of the expression.

Every phrase-answer pair is followed by a blank line.

The variable `it` is always bound to the value of last expression evaluated; it is undefined just after loading the system, and is not affected by declarations or by computations which for some reason fail to terminate.

```
- 1 + 1;
  2 : int

- it;
  2 : int

- it + 1;
  3 : int

- val a = 5;
  > val a = 5 : int
```
Note that quarter is not a constructor, and we cannot have a clause 'amount quarter = 25' in the above definition (quarter would be interpreted as a normal variable, like x).

A type can be entirely made of constants, in which case we have something similar to Pascal enumeration types. A type can also have a single constructor; then the type definition can be considered as an abbreviation for the type following of.

```
declaration:    type color = red | blue | yellow;
```

```
declaration:    type point = point of int * int;
```

If the definition of a type involves type variables, the type is called parametric and all the type variables used on the right hand side of the = must be listed on the left hand side as type parameters; here are type operators with one and two type parameters:

```
declaration:    type 'a predicate = predicate of 'a -> bool
                and ('b,'c) leftposition = leftposition of ('b * 'c) -> 'b;
                
bindings:       type 'a predicate = 'a -> bool
                con predicate : ('a -> bool) -> ('a predicate)
                type ('b,'c) leftposition = leftposition of ('b * 'c) -> 'b
                con leftposition : (('b * 'c) -> 'b) -> ('b,'c) leftposition
```

Recursive types are introduced by the keyword rec. Here is how the predefined list type is defined:

```
declaration:    type rec 'a list = nil | :: of 'a * 'a list;
                
bindings:       type 'a list = nil | :: of 'a * ('a list)
                con nil : 'a list
                con :: : ('a * ('a list)) -> ('a list)
```

1.11. Abstract types

An abstract data type is a type with a set of operations defined on it. The structure of an abstract type is hidden from the user of the type, together with all the constructors of the underlying structure. The associated operations are the only way of creating and manipulating objects of that type. However, the hidden structure and constructors are available while defining the operations.

An abstract data type provides an interface between the use and the implementation of a set of operations. The structure of the type, and the implementation of the operations, can be changed while preserving the external meaning of the operations.

For example we can define an abstract type (additive-) color which is a combination of three primary colors which can each have an intensity in the range 0..15:

```
declaration:    abstype color = blend of int * int * int
                with val white = blend(0,0,0)
                and red = blend(15,0,0)
                and blue = blend(0,15,0)
                and yellow = blend(0,0,15)
                and mix (parts: int, blend(red,blue,yellow): color,
                           parts': int, blend(red',blue',yellow'): color) : color =
                           if parts < 0 or parts' < 0 then escape "mix"
                           else let val total = parts + parts' in blend(}
integer pairs, lists and functions. Strictly speaking, basic types are type operators which take no arguments. Type operators can be arbitrarily nested: e.g. `((int -> int) list) list` is the type of lists of lists of integer functions.

Type variables can be used to express polymorphic types. Polytypes are mostly useful as types of functions, although some non-functional objects, like `[] : a list`, are also polymorphic. A typical example of polymorphic function is `hd : a list -> a`, which extracts the first element (of type `a`) of a list (of type `a list`, in general). The type of `hd` tells us that `hd` can work on any list, and that the type of the result is the same as the type of the elements of the list.

Every type denotes a domain, which is a set of objects, all of the given type; for example `int * int` is (i.e. denotes) the domain of integer pairs, and `int -> int` is the domain of all integer functions. An object can have several types, i.e. it can belong to several domains. For example the identity function `fun x. x` has type `int -> int` as it maps any object (of type integer) to itself (of type integer), but it is also has the type `bool -> bool` for the same reason. The most general type for the identity function is `a -> a` because all the types of the identity are instances of it. `a -> a` gives more information than `int -> int`, for instance, because the former encompasses all the types that the identity function can have and thus expresses all the ways that the identity function can be used. Hence `a -> a` is a ‘better’ type for `fun x. x`, although `int -> int` is not wrong. The ML typechecker always determines the ‘best’ type for an expression, i.e. the one which corresponds to the smallest domain, given the information contained in that expression.

A type constraint can be appended to an expression, in order to specify the type of the expression:

```
expression: 3 : int;
result: 3 : int

expression: [3,4; (5,6) : int * int];
result: [(3,4); (5,6)] : (int * int) list
```

In the above examples, the type specifications following `:` do not really have any effect. The types are independently inferred by the system and checked against the specified types. Any attempt to specify a type incorrectly will result in a type error:

```
expression: 3 : bool;
type error: Type Clash in: 3 : bool
Looking for: bool
I have found: int
```

However, a type specification can restrict the types inferred by the system by constraining polymorphic objects or functions:

```
expression: [] : int list;
result: [] : int list

expression: (fun x. x) : int -> int;
result: fun : int -> int
```

note that the type normally inferred for `[]` is `a list` and for `(fun x. x)` is `a -> a`.

Type specifications can be used in bindings:
binding: \( \text{val comp : (('a -> 'b) * ('c -> 'a)) -> ('c -> 'b)} \)

declaration: \( \text{val fourtimes = comp(twice, twice);} \)

binding: \( \text{val fourtimes : int -> int} \)

expression: \( \text{fourtimes 5;} \)

result: \( \text{20 : int} \)

Function composition \( \text{comp} \) takes two functions \( f \) and \( g \) as arguments, and returns a function which when applied to an argument \( x \) yields \( f(g(x)) \). Composing \( \text{twice} \) with itself, by partially applying \( \text{comp} \) to the pair \( \text{twice, twice} \), produces a function which multiplies numbers by four. Function composition is also a predefined operator in ML; it is called \( o \) (infix), so that the composition of \( f \) and \( g \) can be written \( f \circ g \).

Suppose now that we need to partially apply a function \( f \) which, like \( \text{plus} \), takes a pair of arguments. We could simply redefine \( f \) as \( \text{val f a b = f(a, b)} \); the new \( f \) can be partially applied, and uses the old \( f \) with the expected kind of arguments.

To make this operation more systematic, it is possible to write a function which transforms any function of type \( ('a * 'b) \to 'c \) (which requires a pair of arguments) into a function of type \( 'a \to ('b \to 'c) \) (which can be partially applied); this process is usually called currying a function:

declaration: \( \text{val curry f a b = f(a, b);} \)

binding: \( \text{val curry : (('a * 'b) \to 'c) \to ('a \to ('b \to 'c))} \)

declaration: \( \text{val curryplus = curry plus;} \)

binding: \( \text{val curryplus : int \to (int \to int)} \)

declaration: \( \text{val successor = curryplus 1;} \)

binding: \( \text{val successor : int \to int} \)

The higher-order function \( \text{curry} \) takes any function \( f \) defined on pairs, and two arguments \( a \) and \( b \), and applies \( f \) to the pair \((a, b)\). If we now partially apply \( \text{curry} \) to \( \text{plus} \), we obtain a function \( \text{curryplus} \) which works exactly like \( \text{plus} \), but which can be partially applied.

1.8. Exceptions

Certain primitive functions may raise \textit{exceptions} on some arguments. For example, division by zero interrupts the normal flow of execution and escapes at the top level with an error message informing us that division failed:

expression: \( \text{1 div 0;} \)

exception: \( \text{Exception: div} \)

Another common exception is raised when trying to extract the head of an empty list:

expression: \( \text{hd [];} \)

exception: \( \text{Exception: hd} \)
The patterns are evaluated sequentially from left to right. When a pattern matches the argument, the variables in the pattern are bound to the respective parts of the argument, and the corresponding action is executed. If there are several patterns matching some argument, only the first one is activated. If all patterns fail to match some argument, a run-time exception occurs.

### 1.6. Polymorphism

A function is said to be **polymorphic** when it can work uniformly over a class of arguments of different data types. For example consider the following function, computing the length of a list:

```plaintext
declaration: val rec length nil = 0 |
             length (_, :: tail) = 1 + length tail;

binding:    val length : 'a list -> int

expression: length [1; 2; 3], length ["a"; "b"; "c"; "d"];

result:     3, 4 : int * int
```

The type of `length` contains a *type variable* (`'a`), indicating that any kind of list can be used; e.g. an integer list or a string list. Any identifier or number prefixed by a prime `'`, and possibly containing more primes, is a type variable.

A type is called **polymorphic**, or a **polytype**, if it contains type variables, otherwise it is called **monomorphic**, or a **monotype**. A type variable can be replaced by any ML type to form an *instance* of that type, for example, `int list` is a monomorphic instance of `'a list`. The instance types can contain more type variables, for example `(b * 'c) list` is a polymorphic instance of `'a list`.

Several type variables can be used in a type, and each variable can appear several times, expressing contextual relationships between components of a type; for example, `'a * 'a` is the type of all pairs having components of the same type. Contextual constraints can also be expressed between arguments and results of functions, like in the identity function, which has type `'a -> 'a`, or the following function which swaps pairs:

```plaintext
declaration: val swap(x,y) = y;x;

binding:        val swap : ('a * 'b) -> ('b * 'a)

expression:     swap([1],"abc");

result:         "abc",[1] : string * ('a list)
```

Incidentally, you may notice that the empty list `[]` is a polymorphic object of type `'a list`, in the sense that it can be considered an empty integer list, or an empty string list, etc.

In printing out polymorphic types, the ML system uses the type variables `'a`, `'b`, etc. in succession (they are pronounced 'alpha', 'beta', etc.), starting again from `'a` at every new top-level declaration. After `'z` there are `"a", "z", "a", .. "z`, etc., but these are rarely necessary. Type variables are really anonymous objects, and it is not important how they are expressed as long as the contextual relations are clear.

Several primitive functions are polymorphic. For example, we have already encountered the list
1.4. Lists

List are *homogeneous*, i.e. all their elements must have the same type. It is possible to create lists of any type, e.g. lists of strings, lists of lists of integers, lists of functions (of some given type), etc. Many functions dealing with lists can work on lists of any kind (e.g. computing the length), and they do not have to be rewritten every time a new kind of list is needed. Other list functions are more specialized, like taking the sum of all the elements in a list. Even specialized functions can often be quickly defined from general list utilities; for example, summation can be defined by distributing the integer sum operation by a general fold function which folds lists under binary operations.

The fundamental list operations are `nil`, the empty list, and the infix `::` (cons), which appends an element (its left argument) to the head of a list (its right argument). The square-brackets notation for lists (e.g. `[1;2;3]`), is an abbreviation for a sequence of cons operations terminated by `nil`; hence `[]` is another way of writing `nil`. The system always uses the square-brackets notation when printing lists.

```
nil               []
1 :: [2; 3]       [1; 2; 3]
1 :: 2 :: 3 :: nil [1; 2; 3]
```

Other predefined operations on lists include:
- `null`, which returns true if its argument is `nil`, and false on any other list.
- `hd`, which returns the first element of a non-empty list.
- `tl`, which strips the first element from the head of a non-empty list.
- `@` (append), which concatenates lists.

```
null []               is true
null [1; 2; 3]        is false
hd [1; 2; 3]          is 1
tl [1; 2; 3]          is [2; 3]
[1; 2] @ []           is [1; 2]
[;] @ [3; 4]          is [3; 4]
[1; 2] @ [3; 4]       is [1; 2; 3; 4]
```

1.5. Functions

All functions take exactly one argument and deliver exactly one result. However arguments and results can be arbitrary structures, thereby achieving the effect of passing multiple arguments and returning multiple results. For example:

```
declaration:        val plus(a,b) = a + b;
```

the function `plus` above takes a single argument `(a,b)`, which is a pair of values. This could seem to be a pointless distinction, but consider the two following ways of using `plus`:

```
expression:         plus(3,4);
```

```
expression:         let val x = 3.4 in plus x end;
```

The first use of `plus` is the standard one: two arguments 3 and 4 seem to be supplied to it. However we have seen that `,' is a pair-building operator, and it constructs the pair 3,4 before applying `plus` to it. This is clearer in the second use of `plus`, where `plus` receives a single argument, which

*This is true conceptually; in practice a compiler can optimize away the extra pair constructions in most situations.*
infix operator; expressions like f 3 + 4 are parsed like (f 3) + 4 and not like f (3 + 4).
The function g above has a pair of arguments, a and b; in this case parentheses are needed for, otherwise g 8,4 is interpreted as (g 8), 4.
The identifiers f and g are plain variables which denote functions. Function variables do not need to be applied to arguments:

expression: f, f 3;
result: \text{fun}, 4 \rightarrow \text{int} = \text{int} 
declaration: val h = g;
binding: val h : (\text{int} \times \text{int}) \rightarrow \text{int}

In the first example above, f is returned as a function and is paired with a number. Functional values are always printed fun, without showing their internal structure. In the second example, g is bound to h as a whole function. Instead of val h = g we could also have written val h(a,b) = g(a,b).

Variables are statically scoped, and their types cannot change. When new variables are defined, they may 'hide' previously defined variables having the same name, but they never 'affect' them. For example:

declaration: val f x = a + x;
binding: val f : int \rightarrow int
declaration: val a = [1;2;3];
binding: val a = [1;2;3] : int list
expression: f 1;
result: 4 : int

here the function f uses the top-level variable a, which was bound to 3 in a previous example. Hence f is a function from integers to integers which returns its argument plus 3. Then a is redefined at the top level to be a list of three integers; any subsequent reference to a will yield that list (unless a is redefined again). But f is not effected at all: the old value of a was 'frozen' in f at the moment of its definition, and f keeps adding 3 to its arguments.

This kind of behavior is called \textit{lexical} or \textit{static} scoping of variables. It is quite common in block-structured programming languages, but it is rarely used in languages which, like ML, are interactive. The use of static scoping at the top-level may sometimes be counterintuitive. For example, if a function f calls a previously defined function g, then redefining g (e.g. to correct a bug) will not change f, which will keep calling the old version of g.

1.3. Local scopes

Declarations can be made local by embedding them between the keywords \texttt{let} and \texttt{in} in a scope-block construct. Following the keyword \texttt{in} there is an expression, called the \texttt{body} of the scope-block, terminated by the keyword \texttt{end}. The scope of the declaration is limited to this body.

expression: \texttt{let} val a = 3
\texttt{and} b = 5
of date.

1.1. Expressions
ML is an expression-based language; all the standard programming constructs (conditionals, declarations, procedures, etc.) are packaged into expressions yielding values. Strictly speaking there are no statements: even side-effecting operations return values.

It is always meaningful to supply arbitrary expressions as arguments to functions (when the type constraints are satisfied), or to combine them to form larger expressions in the same way that simple constants can be combined.

Arithmetic expressions have a fairly conventional appearance; the result of evaluating an expression is presented as a value and its type separated by a colon:

expression: \((3 + 5) \times 2\);
result: \(16 : \text{int}\)

Sequences of characters enclosed in quotes "" are called strings:

expression: "this is it";
result: "this is it" : \text{string}

Tuples of values are built by an infix operator "," (comma); the type of a tuple is given by the infix type operator ",", which denotes cartesian products.

expression: \(3,4\);
result: \(3,4 : \text{int} \times \text{int}\)

expression: \(3,4,5\);
result: \(3,4,5 : \text{int} \times \text{int} \times \text{int}\)

Lists are enclosed in square brackets and their elements are separated by semicolons. The list type operator is a suffix: \text{int list} means list of integers.

expression: \([1; 2; 3; 4]\);
result: \([1; 2; 3; 4] : \text{int list}\)

expression: \([3,4; 5,6]\);
result: \([3,4; 5,6] : (\text{int} \times \text{int}) \text{ list}\)

Conditional expressions have the ordinary if-then-else syntax (but else cannot be omitted):

expression: if true then 3 else 4;
result: 3 : \text{int}

expression: if \((3 = 4\) then false else true\) then false
5.1.2. Parallel bindings
5.1.3. Recursive bindings
5.2. Type bindings
   5.2.1. Simple bindings
   5.2.2. Parallel bindings
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5.3. Abstract type declarations
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6. I/O streams
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8. The ML system
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Appendix A: Lexical classes
Appendix B: Keywords
Appendix C: Predefined identifiers
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