Project

The programming assignments you will implement will be over a small subset of Standard ML called Mini-ML; your implementation will be in Standard ML. While Mini-ML shares strong syntactic and semantic similarity with SML, it differs in a number of important respects. When the semantics of an expression are underspecified in the documentation, it should be assumed that the semantics follows ML semantics for that expression.

Mini-ML is a higher-order mostly functional language that supports integer lists, recursive functions, pattern-matching using case expressions, tuples, records, and various unary and binary operations. Its syntax is identical to SML.

Programs

A Mini-ML program is a sequence of declarations and expressions. There are two kinds of declarations. A val declaration, val x = e evaluates expression e and binds the result to the variable x. A fun declaration, fun f(x:argType):resType = e declares a recursive function f whose result type is resType and which takes a single argument x having type argType. The body of the function is defined by expression e.

Each declaration makes its binding name visible to subsequent declarations in the program. For example, the following program defines variables a and b, a factorial function fact, and several function calls to fact:

```ml
val a = 10
val b = 4
fun fact(n:int):int = 
  if n = 0
    then 1
  else n * fact(n-1)
val r1 = fact(a)
val r2 = fact(b)
val r3 = r1 + r2
```

Unlike SML, type declarations specifying the argument type and result type of a function are required. Also, Mini-ML does not support pattern-matching on function arguments. Thus, the following SML expression is ill-formed:

```ml
fun f(a:int, b:int):int = a + b
```
To get the effect of this function in Mini-ML, we would write the slightly more wordy:

fun f(args: (int * int)):int = (case args of 
                   (a,b) => a + b )

**Primitive Types**

Mini-ML supports integers, reals and strings as primitive types. For integers and reals, the following infix operations are provided:

+,-,*,~>,>=,<,<=,=(

Thus, for integers (reals) a and b,

- \~a ⇒ negation of a
- a + b ⇒ sum of a and b
- a - b ⇒ difference of a and b
- a * b ⇒ product of a and b
- a logical op b ⇒ true if a logical op b holds for logical op ∈ \{<,>,<:,>=,=\} and false otherwise.

Mini-ML does not support implicit coercions between integers and reals. Thus, reals and integers cannot be supplied as different arguments to the same binary arithmetic or logical operation.

A string constant is written using quotations (e.g., “this is a string”). Strings can be concatenated using " thus: "foo"^"bar".

**Tuples and Records**

Besides simple types, mini-ML also provides support for tuples and records. These types have a syntax and semantics similar to SML. Thus, the expression (1,2.0,’’foo’’) defines a three-tuple consisting of integer values 1,2.0 and ‘’foo’’. Elements of a tuple are extracted using pattern-matching (see below).

A record defines a collection of label, value pairs. The expression,

{x = 1, y = 2.0, z = "foo"}

defines a record consisting of fields x, y and z whose corresponding type is \{x:int,:real,z:string\}. Like SML, fields are extracted from a record thus:

let val r = { x = 1, y = 2.0, z = "foo" }
in #z r
end
Let-expressions

As in SML, local bindings can be declared using let-syntax. The expression: \texttt{let val x = b in e end} evaluates expression \( b \) to yield value \( v \), and binds \( v \) to \( x \) and returns the result of evaluating expression \( e \) in this augmented context. Thus,

\[
\texttt{let val x = 2 + 3 in x + x end}
\]

yields 10. Note that \( x \) is \textit{not} visible in the evaluation of \( b \).

Local recursive functions can be declared thus:

\[
\texttt{let fun f(x:int):int = if x = 0 then 1 else f(x-1) in f(3) end}
\]

Like SML, any pattern can appear on the left-hand side of a \texttt{let}-binding. Thus, the following expressions are also valid:

\[
\texttt{let val (x,y) = (1,2) in x + y end}
\]

or

\[
\texttt{let val f = fn (x:int) => (x,3)}
\]

\[
\texttt{val (x,y) = f(3) in x + y (* result is 6 *) end}
\]

Unlike SML, Mini-ML does not support mutually-recursive function definitions.

Local functions and application

Like SML, functions are first-class objects in Mini-ML and can be declared within a local context. The expression:

\[
\texttt{fn (z:int) => z + 1}
\]

declares a function that adds one to its integer argument. Type annotations on arguments is required. No type annotations are necessary on the result type.

Because functions are first-class, they can take functional arguments. Thus, the following expression defines a function \texttt{twice}, which given a functional argument \( f \), returns a function which given an integer argument \( z \) applies \( f \) twice to \( z \). In the expression, \texttt{twice} is applied to a function that adds one to its argument. The function returned by \texttt{twice} in this example, when applied to 10, returns 12 as its result.
let val twice = fn (f:int -> int) => fn (z:int) => f(f(z))
in twice (fn (a:int) => a + 1) 10
end

Note that functional argument types are written using arrow notation: the type expression \( t_1 \rightarrow t_2 \) defines a type describing functions that take \( t_1 \) arguments and returns \( t_2 \) results.

Case Expressions and Pattern Matching

Mini-ML supports a simple form of pattern-matching using case expressions. Let-expressions described above can be thought of a simple form of case; thus:

let p = e1 in e2 end

is equivalent to:

case e1 of
  p => e2

A subject defined as the first part of the case expression can match against a number of different target patterns defined as separate cases. The rules for matching are similar to SML. A subject pattern can be any expression. The value of this expression \( v \) is matched against the patterns defined by the targets. Patterns are evaluated top-down. Once a pattern successfully matches the subject, the corresponding match expression is evaluated, and returned as the value of the case expression. A successful match may bind variables in the target pattern to the values of the corresponding components in the subject.

For example, the following pattern defines a subject whose value is a tuple \((1,2)\), and a matching pattern that binds \(x\) to 2 in the corresponding match expression; the value of the entire case expression is 3.

\[
\begin{align*}
\text{case} \; (1,2) \; \text{of} \\
(\text{y,1}) & \Rightarrow \; y \quad \quad \quad \quad \quad \text{(* does not match subject (1,2) *)} \\
| \; (1,x) & \Rightarrow \; x + 1 \quad \quad \text{(* matches subject *)} \\
| \; _ & \Rightarrow \; 0 \quad \quad \quad \quad \quad \text{(* will never be tested *)}
\end{align*}
\]

The _ defines a wildcard that matches any pattern. Unlike SML, pattern matching in mini-ML does not check for exhaustiveness or overlapping patterns.

Note the following use of case encodes simple if-then-else conditionals:

\[
\text{fn (x:bool) => case x of} \\
\quad \text{true => true branch} \\
\quad \text{false => false branch}
\]

Records can also be used in pattern matching expressions. Thus, the following expression yields the value of field \(x\) if field \(z\) is true and the value of field \(y\) otherwise.
fn (z:{x:int,y:int,z:bool}) =>
  case z of
    { x = x, y = y, z = c } => if c then x else y

Like SML, mini-ML does not support duplicate identifiers in record patterns. Unlike SML, string constants are not allowed on the right-hand side of a binding in a record pattern.

**Datatypes and constructors**

Mini-ML provides three built-in datatypes:

```plaintext
datatype bool = true | false
datatype intlist = Nil | Cons of (int * intlist)
datatype intoption = NONE | SOME of int
```

The `bool` datatype is obvious, and defines nullary constructors `true` and `false`. Integer lists are constructed using the `intlist` datatype. The following program defines a function `map` that applies its function argument to all elements of its integer list argument. The function `iota` given an integer `n` returns a list containing all numbers from 0 to `n`.

```plaintext
fun map (f:int->int):intlist->intlist =
  (fn (l:intlist) =>
    case l of
      Nil => Nil
    | Cons (x,xs) => Cons (f(x), (map f) xs))

fun iotaHelper(x: (int * intlist)):intlist =
  (case x of
    (0,l) => l
  | (n,l) => iotaHelper(n-1,Cons(n,l)))

fun iota(n:int):intlist = iotaHelper(n,Nil)

val l = iota(3)
val m = map (fn (x:int) => x + 1) l
```

**Assignment**

Like SML, Mini-ML allows first-class references to be created, referenced, and assigned. The expression `ref x` returns a reference containing the value denoted by `x`. The expression `(!r)` returns the contents of location `r`; and the expression `r:=v` assigns the value `v` to the contents denoted by `r`.

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We will use Standard ML as our implementation language. SML is a strongly-typed higher-order programming language with a rich module system. Each assignment will define a collection of structures (module implementations) and signatures (module specifications). We’ll provide the relevant signatures for these modules; your job will be to provide implementations that conform to these signatures.

Documentation about the SML/NJ implementation can be found at http://www.smlnj.org/doc. SML/NJ is installed on the machines in the Xinu lab. However, you are not obligated to use these machines; if you prefer to work on separate machines, download SML/NJ from http://www.smlnj.org/software.html. Programming assignments will use the compilation manager facility (CM) of SML to organize signatures and implementations. For those of you unfamiliar with CM, details can be found at http://www.smlnj.org/doc/CM/index.html

For those you who use Emacs, there is an sml-mode available that provides formatting, font highlighting, and an interface to the SML/NJ compiler. It is part of the emacs path on the Xinu machines, but for those of you who want to work on different machines, you can get sml-mode from http://www.smlnj.org/software.html