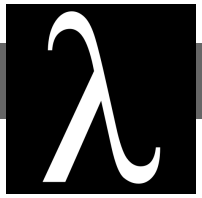

Contents

Welcome to 15-150!

My TAs are:

Their Andrew IDs are:

My lab section letter is:

To annotate this handout, you may either print a physical copy or use a pdf. Some suggestions are Adobe Acrobat DC (paid), XODO or PDFescape (free). Opening the PDF in Word, Preview for MacOS, or various note-taking apps is also an option.

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1 Basics of SML

1.1 Expressions

Expressions are the basic unit of an SML program.

Example(s):

1.2 Types

A program *typechecks* if it has no type errors; type errors come from expressions that are *not well-typed*. If we have:

```
e : t
```

We say that expression `e` has type `t`.

Example(s):

There are also *function types*. A function type can be recognized by an arrow in it, such as:

```
e : t1 -> t2
```

An expression with this type has an *argument type* of `t1` and a *return type* of `t2`.

Example(s):

1.3 `val` Declarations

We can bind values to variable names (also called *identifiers*) using the syntax:

```
val <varname> : <type> = <expr>
```

In order for this to typecheck, the expression `<expr>` must have type `<type>`.

Example(s):

1.4 `fun` Declarations

Functions can be defined using the `fun` keyword, which binds a variable name to a `fn` expression.

Example(s):

1.5 Scope

Declarations have an attribute called *scope*, which is everywhere it can be used. When a new declaration is made, that declaration only has access to variable bindings created *before* it. A declaration can't be made from bindings created *after* it; it's not in the scope of any such bindings.

Environment binding notation can help us to keep track of bindings. *Note*: this is not actual SML syntax.

Task 1.1.

Annotate the following with environment binding notation:

```
val x : int = 10
val y : int = x * x
val z : int = x + y
```

1.6 Shadowing

Binding to variable names in SML is different from assignment in other programming languages. If you bind to the same variable twice, the variable still binds the first value between the first and the second binding; we say that the second binding *shadows* the first binding instead of replacing it everywhere, because prior to the second binding the first binding still exists!

Example(s):

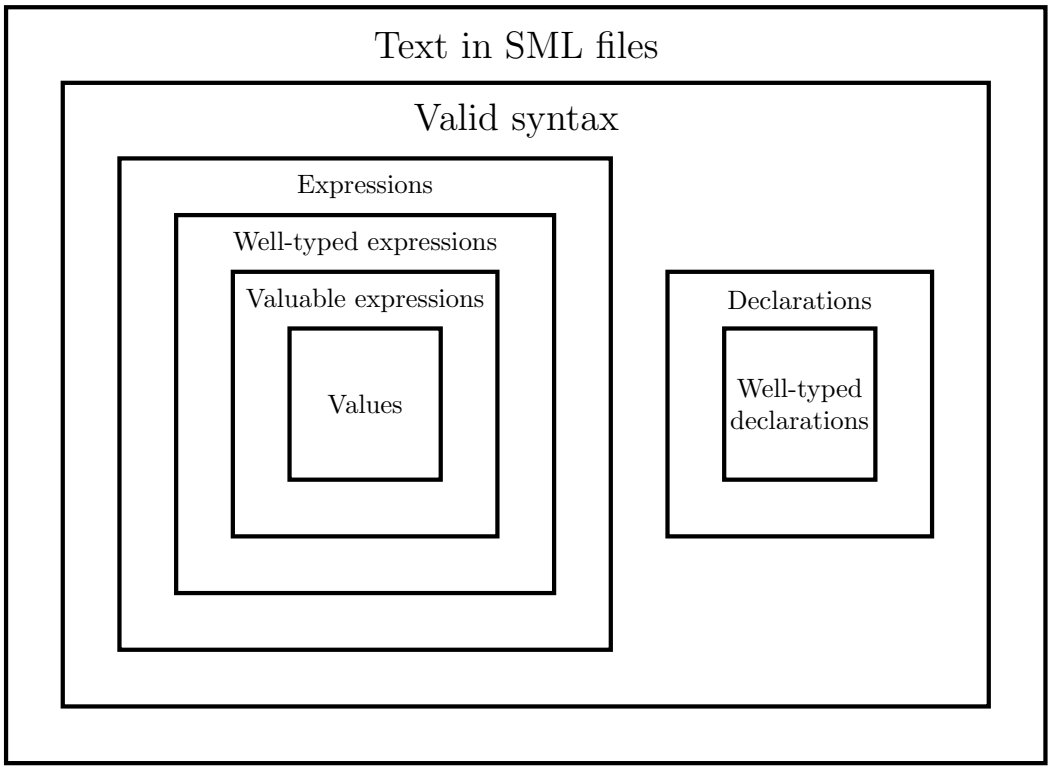

Figure 1: A simple hierarchy of text in SML.

2 Prior to this lab, you should...

Complete the setup reference! You'll need to be able to access AFS for this lab!

It contains important information, including instructions for setting up your AFS environment and downloading lab content.

As a reminder, please untar the handout on AFS (not locally)! Untarring handouts locally may mess with the permissions and lead to issues with checkins, running your code, and more.

3 Expressions

From the REPL, we can type expressions for SML/NJ to evaluate.

Task 3.1. (Recommended)

In order to compute $2 + 2$, type

```
2 + 2;
```

into the REPL and press Enter. What is the output?

The output should have been

```
val it = 4 : int
```

Upon successfully evaluating an expression, the REPL will print

```
val <varname> = <value> : <type>
```

to indicate the type, the value, and the variable name that this value was bound to.

Returning to the example, `4` is the value or result, `int` is the type of the expression - an integer, and `it` is the variable name that `4 : int` has been bound to. If a name is not provided by you, `it` is used as a default name for the value.

SML uses types to ensure at compile time that programs cannot go wrong in certain ways; the phrase `4 : int` can be read as "`4` has type `int`".

Notice that the expression was terminated with a semicolon. If we do not do this, the REPL does not know to evaluate the expression and expects more input.

Note that semicolons are *not* required[1] when writing SML code into `.sml` files. Furthermore, any code you submit for homework should not use semicolons, or you may lose style points.

Task 3.2. (Recommended)

Type

```
2 + 2
```

into the REPL and press Enter. What is the output?

After doing that, enter a semicolon. What happens now?

As you can see, it is possible to put the semicolon on the next line and still get the same result.

[1] With the rare exception of `use` statements.

3.1 Parentheses

In an arithmetic class long ago, you probably learned some standard rules of operator precedence (e.g. multiply before you add but anything grouped in parentheses gets evaluated first). SML follows the exact same rules of precedence[2]. You can insert parentheses into expressions to force a particular order of evaluation.

Task 3.3. (Recommended)

Type

```
1 + 2 * 3 + 4;
```

into the REPL. What would you expect the result to be? What is the actual result?

Now, type

```
(1 + 2) * (3 + 4);
```

into the REPL. Is the result the same? Why or why not?

[2] PEMDAS!

4 Types

There are many types in SML—more than just `int`! For example, there is a type `string` for strings of text.

Task 4.1. (Recommended)

Type

```
"foo";
```

into the REPL. What is the result?

A natural successor to strings is string concatenation, which SML kindly supports with the `^` operator. This operator is **infix**, meaning you insert the function between its two arguments. Thus, `^` is used on strings similar to how `+` is used on integers.

Task 4.2. (Recommended)

Type

```
"foo" ^ " bar";
```

into the REPL. What is the result?

Let's try writing a program that does not typecheck (i.e. has an expression that's not well-typed) to see what SML does in that situation.

Task 4.3. (Recommended)

Concatenation only works given two strings. What happens when you type

```
3 ^ 7;
```

into the REPL?

This is an example of one of SML's error messages. You should start to familiarize yourselves with them, as you will be seeing them quite a lot this semester, at least until you get used to types!

5 Variables

Above, we mentioned that the results of computations are bound to the variable `it` by default. Thus, once we have performed a computation, we can refer to its result in the next computation.

Task 5.1. (Recommended)

Type

```
2 + 2;
```

into the REPL. Then, type

```
it * 5;
```

into the REPL. What is the result?

As you see, before the second evaluation, the value bound to `it` was `4` (the value of `2 + 2`), and now `it` is bound to the result of the most recent expression evaluation, `20` (the value of `it * 5`, with `it` bound to `4`).

5.1 `val` Bindings

The SML runtime system uses `it` as a convenient default and a way to help you debug code. But you shouldn't get into the habit of using `it` like this! SML syntax for value declaration allows you to choose what variable name to *bind* values to.

A value declaration uses the keyword `val` and has the syntax:

```
val <varname> = <expr>
```

This declaration tries to evaluate the expression `<expr>` to a *value* and then *binds* that value to the *variable* named `<varname>`. [3]

If we want to explicitly state the desired type of the variable, we can give it a *type annotation* as follows:

```
val <varname> : <type> = <expr>
```

We prefer type annotations as done above, but we can also write:

```
val <varname> = <expr> : <type>
```

Or even:

```
val <varname> : <type> = <expr> : <type>
```

[3] Sometimes we call this *creating a `val` binding*. Bindings can be combined to form declarations. A binding is an atomic declaration. Each use of `val` is one binding, and a single declaration can consist of many. Two declarations can be combined by simply writing them one after the other, which we could regard as just one declaration.

5.2 Scope

Declarations have an attribute called *scope*. A declaration's scope is wherever it can be used.[4] If we can declare some "thing" using a declaration, then we say that "thing" is *within the scope* of that declaration.

We could make declarations in the SML/NJ REPL, but we can also make them as part of a `let`-expression, using the syntax:

```
let val <varname> = <expr1> in <expr2> end
```

The value of this `let`-expression is obtained by evaluating `<expr1>`, binding its result to the variable named `<varname>`, and using this declaration while evaluating `<expr2>`. The `val` declaration is not available for use outside of the `let`-expression, and we say that the *scope* of the declaration is this expression.

The SML declaration syntax is much more general than we have indicated here, but this introduces the key notions of scope and binding.

Task 5.2. (Recommended)

Type

```
val x : int = 2 + 2;
```

into the REPL. What is the result? How does it differ from just typing the following?

```
2 + 2;
```

As you can see, that declaration binds the value of `2 + 2` to the variable `x`. We can now use `x`.

Task 5.3. (Recommended)

Type

```
x;
```

into the REPL. What is the result?

Task 5.4. (Recommended)

Now type

```
val y : int = x * x;
```

into the REPL. What is the result?

Task 5.5. (Recommended)

How about

```
val y : string = x * x;
```

[4] The concept of scope will be used throughout the semester; if you have any questions, please ask your TAs!

What happens? Why?

Task 5.6. (Recommended)

After that, type

```
z * z;
```

into the REPL. What happens? Why?

5.3 Immutability

Variables in SML refer to values, but are not *re-assignable* like variables in imperative programming languages.

Each time a variable is declared, SML creates a new *binding* and binds that variable to a value. This binding is available, unchanged, throughout the *scope* of the declaration that introduced it.

If the name was used before, the new binding *shadows* the previous one: the old binding is still around, but new uses of the variable refer to the most recent one.

Task 5.7. (Recommended)

Type

```
val x : int = 3;
val x : int = 10;
val x : string = "hello, world";
```

into the REPL. What are the value and type of `x` after each line?

5.4 Tuples

We can introduce multiple identifiers in a single declaration using tuples. When we write a tuple, its elements are comma separated:

```
val (x : int, y : int) = (3,4)
```

This declaration binds `x` to `3` and `y` to `4`.

A tuple of values is itself a value, so we can also do this:

```
val z : int * int = (3,4)
```

This binds `z` to the tuple `(3, 4)`. Note that tuples have what's called a *product type*, indicated by the `*` in it. A tuple will have `*` in its type to separate the types of its elements. For 3-tuples, there would be two `*`'s in its type.

6 Functions

6.1 Using Files

Now that we have written some basic SML expressions, we can take a look at getting input from files. We have provided the file `code/practice/playground.sml` in the `.tar` file you downloaded.

First, move into the `code/practice/` directory:

```
> ls
code
> cd code/practice/
> ls
playground.sml smlnj sources.mlb
```

Then, from the terminal, type `./smlnj sources.mlb`. The output from SML should look like

```
...
[opening playground.sml]
val fst = fn : int * int -> int
...
val detectZeros = fn : 'a -> 'b
-
```

Now that you have done this, you have access to everything that was defined in `code/practice/playground.sml`, as if you had copied and pasted the contents of the file into the REPL.

If this didn't work, you might not be in the right directory. Exit the REPL by pressing Ctrl+D, then type `pwd` and `ls` to verify you're in the right directory and the file `playground.sml` exists in the working directory.

6.2 Applying Functions

In this file, notice that there are functions defined. For example, there is

```
fun fst (x : int, y : int) : int = x
fun snd (x : int, y : int) : int = y
fun diag (x : int) : int * int = (x,x)
```

Notice the return type of `diag` is `int * int` which means it returns a tuple of ints (e.g. `(1,1)`).

The `diag` function can be invoked by writing `diag(37)`. However, the parentheses around the argument are actually unnecessary. It doesn't matter whether we write `diag 37` or `(((diag) (37)))`; both are evaluated exactly the same.

Good SML style uses only as many parentheses as is ***necessary*** to make your intent clear. For instance, even though

```
2 * 6 + 3 * 5
(2 * 6) + (3 * 5)
```

evaluate to the same thing, we prefer the second form, because it is clearer to see the order of operations.

However, since

```
diag 5
```

is parsed the same way as

```
diag(5)
```

while also using fewer characters, we prefer the first form.

Note that the following two expressions are very different, for reasons we will explore later in the course.

```
fst diag(5)
fst (diag 5)
```

This is yet another reason to prefer minimal use of parentheses during function application.

Task 6.1. (Recommended)

What is the type of `fst`, and what does it do?

Task 6.2. (Recommended)

What is the type of `snd`, and what does it do?

Task 6.3. (Recommended)

What is the type of `diag`, and what does it do?

6.3 Defining Functions

6.3.1 Function Specifications

We will generally require you to precede function definitions with a commented ***function spec***, consisting of:

- the function's type
- REQUIRES clause: a logical guarantee about the input (i.e. assumptions you're making about the input)
- ENSURES clause: what you're guaranteeing about the output

Function specs help us to formally reason about the behavior of functions, which is a key part of 15-150.

When the function has no pre-conditions, we use the notation "`REQUIRES: true`" (i.e. all arguments of the correct type satisfy the pre-condition).

You do not ever need to specify in your REQUIRES that the input be of the correct type, nor do you need to specify in the ENSURES what the output type is. This is the point of the type annotation.

For example,

```
(* incr : int -> int
* REQUIRES: true
* ENSURES: incr x ==> the next integer after x
*)
fun incr (x : int) : int = x + 1
```

Notice that our ENSURES clause is just written in English, not any kind of executable code. As mentioned in lecture, we do not execute our REQUIRES and ENSURES clauses alongside the code (like you may have done in 15-122), but rather these are logical guarantees that help us, the people reading this code, reason about it more easily. However, it is ultimately the code itself, ***not the spec***, which is used to formally prove function behavior.

It's a bit superfluous to write specs for functions that are this straightforward, but this is the general form we'll ask you to use when documenting your code, and it will be much more helpful later on when your code becomes very complex!

6.4 Writing Tests

We also ask you to test your code for correctness.

We have provided you with a testing framework, so you can test your code by writing lines like:

```
val () = Test.bool("name_of_test", <expected_result>, <test>)
val () = Test.int("name_of_test", <expected_result>, <test>)
val () = Test.string("name_of_test", <expected_result>, <test>)
```

You can find the complete list of test function in the 150Basis Reference.

For example, if we wanted to test `incr`, which would follow the specs and declaration of `incr` above, we could write:

```
val () = Test.int("incr_1_test", 2, incr 1)
val () = Test.int("incr_4_test", 5, incr 4)
val () = Test.int("incr_neg4_test", ~3, incr ~4)
```

If `incr` did not work as expected, and the result of evaluating `incr 1` was actually `3`, we would recieve the following output:

```
uncaught exception Fail [Fail: incr_1_test!
First argument:
  2
Second argument:
  3
]
```

If there are no exceptions, then all test cases had the expected results.

6.5 Now it's your turn!

For each of the following functions in `code/practice/playground.sml`:

1. write the function's spec (the function's type, the REQUIRES, and the ENSURES)

2. implement the function
3. write some tests for the function (make sure each function passes its tests!)

Do all of this in the `code/practice/playground.sml` file; we've included some starter code for your convenience.

Task 6.4. (Recommended)

A function named `add3` which takes in a triple `(x,y,z)` of three integers and returns their sum $x + y + z$.

Task 6.5. (Recommended)

A function named `flip` which takes a tuple `(x,s)` where x is an integer and s is a string, and it returns the tuple `(s,x)`.

Task 6.6. (Recommended)

A function named `diff` which takes a tuple `(x,y)` of integers where $x < y$ and returns their difference $y - x$.

Task 6.7. (Recommended)

A function named `isZero` which takes an integer `x` and returns `true` if `x` is zero, otherwise `false`.

Note: We use `=` in SML to create bindings, but within an expression it's also an operator.

There are two different ways to do this. See if you can figure out both!

Task 6.8. (Recommended)

A function named `detectZeros` which takes a tuple `(x,y)` and evaluates to `true` if either `x` is zero or `y` is zero.

Hint: You might find the built-in infix operator `orelse` helpful. Here's some examples for how `orelse` is used:

```
true orelse true ≅ true
true orelse false ≅ true
false orelse true ≅ true
false orelse false ≅ false
```

7 Completing Lab Check-in

At the end of each lab, after completing all required sections, your lab TAs will review your work and then use your Andrew ID to generate a unique lab password.

7.0.1 In-Person Lab Check-In Procedure

The check-in procedure for **in-person labs** is as follows:

1. First, make sure you are logged onto AFS.
2. In the `<topic>_lab` directory, type `make checkin`.
3. After running `make checkin`, a QR code should be generated.
4. Wait until a TA reviews your work.
5. Once the TA has reviewed your work, they will scan your QR code, giving you credit for the lab.