Learning Standard ML

COMP 105

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This guide is available both in HTML and PDF.

For someone with a background in COMP 11 and COMP 15, the fastest and easiest way to learn Standard ML is to buy Ullman’s book and work through chapters 2, 3, 5, and 6. But many students choose not to buy Ullman—a move that saves money but costs time. You can recover some of the time by reading this guide; it enumerates the most important concepts, and it tells you where to find key information, not just in Ullman, but also in three other sources:

• Jeff Ullman’s Elements of ML Programming (ML’97 edition)
• Norman Ramsey’s Programming Languages: Build, Prove, and Compare
• Mads Tofte’s “Tips for Computer Scientists on Standard ML (Revised)
• Bob Harper’s draft Programming in Standard ML

Know your sources! Mads Tofte and Bob Harper both worked with Robin Milner on the design of Standard ML, and they helped write the Definition of Standard ML. They know what they’re talking about, and they have good taste—though Tofte’s use of the ML modules is considered idiosyncratic. Norman Ramsey at least knows some functional programming. Jeff Ullman, by contrast, got his start in the theory of formal languages and parsing, then switched to databases. He may like ML, but he doesn’t understand it the way the others do.

Key concepts: Algebraic data types, case expressions, and pattern matching

Here is an excerpt from a chapter of Ramsey that is not included in the abridged edition:

S-expressions are great, but if you think carefully, you might notice that S-expressions work as a kind of high-
level assembly language on top of which you craft your own data structures. ML, by contrast, offers a powerful tool for expressing data structures directly: the algebraic data type. Don’t let the mathy name worry you; algebraic data types solve real programming problems:

- Algebraic data types enable you to define types that are recursive, like trees that contain subtrees of the same type as themselves.
- Algebraic data types enable you to define types by specifying choices, like a list that is made with either `()` or `cons`.
- Algebraic data types give you easy access to the parts of data structures: instead of applying functions like `car` and `cdr`, you use pattern matching to name the parts.

Recursive types and definition by choices enable you to express representations that are very similar to what you might like to define in , and that also give you the benefits of polymorphic type inference that you get with ML. Types help you write good code, and they provide documentation that is checked by the compiler. Pattern matching eliminates the name-space clutter and cognitive overhead associated with choice-identifying and part-extracting functions like `null?`, `car`, `cdr`, `fst`, and `snd`. Using pattern matching, you make choices and extract parts by naming the choices and parts directly. The resulting code is shorter and more perspicuous than code without pattern matching. Algebraic data types and pattern matching are ubiquitous in the ML family and in languages derived from it, including Standard ML, OCaml, HAskell, Agda, Coq/Gallina, and Idris.

When you add algebraic data types to a language, you get a new species of value and type, a new expression form for looking at the values, and a new definition form for introducing the types and values.

The new species of value is called a constructed value. A constructed value is made by applying some value constructor to zero or more other values. In the syntax, however, we don’t apply zero-argument value constructors; a zero-argument value constructor constitutes a value all by itself. As examples, in ML, `[]` is a value constructor for lists, and it expects no arguments, so it constitutes a constructed value all by itself. And cons (spelled `::`) is also a value constructor for lists, but it expects arguments, so to make a constructed value, cons must be applied to two other values: an element and a list.

A constructed value is observed or interrogated by a new syntactic form: the case expression. The case expression does pattern matching: a pattern can match a particular value constructor, and when it does, it can name each of the values to which the constructor was applied. For example, the pattern `(y :: ys)` matches any cons cell, and when it matches, it binds the name `y` to the car and `ys` to the cdr. A case expression includes a sequence of choices, each of which comprises a pattern and an associated right-hand side. One reason that programmers really like case expressions is that if your choices don’t cover all possible cases, a compiler can alert you ().

Here’s an example case expression, a definition of `null`:

```ml
fun null xs = (case xs of [] => true
               | y :: ys => false)
```

And algebraic data type and its value constructors are created by a new form of definition, which uses the keyword `datatype`. In a datatype definition, you can name a type whatever you want. For example, you can define a new algebraic data type that is called `int`, which then hides the built-in `int`.

Key concept: Types and type inference

- Ullman, section 2.2
- Harper, section 2.2, especially 2.2.1, sections 2.3 and 2.4
- Tofte, section 13

The elements of ML

Expressions I: Basic expressions and their types

Ullman is the only resource that goes into simple syntax at any length. If you want more than you find below, search the Web for the “Gentle Introduction to ML.”

- Ullman, sections 2.1 and 2.3
- Tofte, sections 1 to 5
- Examples from Ramsey, section 5.1: `find`, `bind`
- Examples from Ramsey, section 5.2: `equalatoms`, `equalpairs`
- Example from Ramsey, section 5.3: `duplicatename`

Expressions II: Minus signs

For reasons best known to Robin Milner, Standard ML does not use the unary minus sign used in every other known language (except APL). Instead, Standard ML uses the tilde as a minus sign, as in “~1 or “(n+1). The tilde is in fact an ordinary function and may be treated as such.
Expressions III: Conditionals and short circuits

ML uses if e_1 then e_2 else e_3, as well as short-circuit infix `andalso`, `orelse` (never and).

- The abstract syntax is exactly like μScheme’s (if e_1 e_2 e_3) (`&& e_1 e_2`), and (|| e_1 e_2)
- Ullman, sections 2.1.5 and 2.1.6
- Harper, section 2.3 (and desugaring in section 6.3)
- (This material is not covered by Tofte)

Data II: Lists

- Ullman, sections 2.4.3 to 2.4.5, plus 2.4.6 (list types)
- Tofte, section 4
- Harper, chapter 9 (which is short)

The most common mistake I see in list-related code is to write xs = nil (wrong). Never write this. Either use null xs (that’s why null is in the initial basis) or use pattern matching.

You’ll find most of your favorite list functions in the initial basis, either defined at top level or in the List module.

- Ullman, section 5.6
- Neither Tofte nor Harper says much about the initial basis
- Try `help "list"`; at the Moscow ML prompt, then select structure List. (“Structure” is ML’s name for “module”)

Data III: Constructed values and patterns that match them

Aside from the type system, the big new thing in ML is the system of “constructed values,” which belong to algebraic data types.

- Ramsey, sections 8.1, 8.2.1, and 8.2.2 (page 559 includes examples of patterns that do and don’t match)
- Ullman, sections 3.3 and 5.1
- Tofte, sections 8, 9, and 10
- Harper, sections 10.2, 10.3, and possibly 10.4

Tuples and records should also be considered constructed values. In μML, tuples and records are simulated with ordinary algebraic data types. In Standard ML, tuples and records have their own syntax and their own rules, but the ideas of construction and deconstruction (pattern matching) are the same.

Lists are constructed values that are supported with extra syntactic sugar for constructing and matching lists. Some useful list patterns include these patterns, to match lists of exactly 0, 1, 2, or 3 elements:

```ml
[]  x :: xs  x1 :: x2 :: xs
```

You can also use the :: (cons) constructor in patterns, where it appears infix. These patterns match lists of at least 0, 1, 2, or 3 elements:

```ml
xs  x :: xs  x1 :: x2 :: xs
```

Data I: Tuples

In μML, tuples are ordinary value constructors of ordinary abstract data types (see below). But in Standard ML, they have special syntax:

- Ullman, section 2.4.1 (not section 2.4.2, which is an utter disaster, as noted below), plus 2.4.6 (tuple types)
- Tofte, sections 8, “Pairing and Tupling” (but don’t use function #i)
- Harper, section 5.1.1 (tuples)

Ullman pitfall: Jeff Ullman doesn’t understand how to program with tuples. His section 2.4.2 should be torn out of your book and shredded (just kidding). The use of #1 and #3 violates all established customs for writing ML code—in part because #1 and #3 are not really functions, and they don’t have types! The right way to extract an element from a tuple is by pattern matching, like this:

```ml
fun fst (x, _) = x  
fun snd (_, y) = y
```

Never write this:

```ml
fun bogus_first p = #1 p  (* WRONG *)
fun bogus_second p = #2 p  (* WRONG *)
```

(For reasons I don’t want to discuss, but will answer in class if asked, these versions don’t even typecheck.) If your pair or tuple is not an argument to a function, use `val` to do the pattern matching:

```ml
val (x, y) = lookup_pair mumble
```

But usually you can include matching in ordinary `fun` matching.

You probably won’t need to extract elements from a bigger tuple, but if you do, try

```ml
fun third (_, _, z) = z
```

Any uses of #1, #2, and their friends will result in point deductions on homework.

---

The `fun` is function-definition syntax, like μScheme’s `define`. It is described below.
Inexhaustive or redundant pattern matches

In any case expression or function definition, the patterns you provide must match all cases. If they don’t, the pattern match is considered “inexhaustive” and is rejected by the compiler.

And in any case expression or function definition, every pattern you provide must match some case. If one pattern doesn’t match any case, that pattern is considered “redundant,” and the match is rejected by the compiler.

- Harper, section 6.4 (recommended) and page 105
- Ramsey, glossary page 385
- Ramsey, section 8.8.2
- Ullman, section 3.3.6 (inadvertent redundancy)

Types I: Introduction to types

Base types int, string, char, real, bool. Type constructors like 'a list take a type parameter 'a.

- Ullman, section 2.4.6
- Harper, chapter 2 (of which you already know section 2.2.2)
- Tofte, sections 1 and 13

Definitions I: Val bindings

ML’s val bindings resemble those from µScheme, although µScheme’s val corresponds to ML’s val rec, which is µML’s val-rec.

What we call a “definition” form is, to Standard ML, a “declaration” form.

- Ullman, section 2.3
- Tofte, section 6
- Harper, sections 3.2.2 and 3.3

Definitions II: Semicolons

It’s a sad fact that if you’re working interactively with an ML compiler, the compiler can’t tell where a definition ends. You have to mark the end with a semicolon. But such a semicolon should never appear in your code. Ulman’s book is full of unnecessary semicolons, and you must learn to ignore him. Emulate the style in Ramsey’s book, which has no unnecessary semicolons. Use a semicolon only to sequence effects in imperative code.

- Ullman, sections 3.1 and 3.2
- Tofte, section 6

Definitions III: Function definitions

As in µScheme and µML, functions can be defined using lambda with val or val rec. But it is more idiomatic to use fun, which is the analog of the define found in µScheme and µML.

- Ullman, sections 3.1 and 3.2
- Tofte, section 6
- Harper’s chapter 4 is about functions. Although the chapter is long-winded and is more about the mathematical idea of functions than it is about how to program with functions, it is still useful—even though his examples include many unnecessary type annotations. The most helpful part of the chapter is probably Section 4.2, which contains several examples, especially at the end.
- Harper’s chapter on recursive functions contains some more useful examples in sections 7.1, 7.2, and 7.4. The Fibonacci example in section 7.3 may also be useful. This chapter also includes substantial material on the mathematical justification for recursion and on the nature of inductive reasoning. You can learn ML without reading this material.

Definitions IV: Clausal (function) definitions

Standard ML’s fun also provides clausal definitions, which in µML are written define*. These definitions look a lot like algebraic laws.

- Ramsey, define*, pages 575-576
- Ullman, section 3.3. Do not emulate Ullman’s disgraceful placement of the vertical bar, and do not emulate his gratuitous semicolons.
- Tofte, section 11
- Harper, sections 6.2 and 6.4

Expressions IV: ML’s let

ML’s let most closely resembles Scheme’s let*, but instead of a sequence of name/expression pairs, it uses a sequence of definition forms. The effect of letrec can be approximated by using a fun definition form with keyword and. Standard ML has nothing corresponding to Scheme’s let form.

- Ullman, section 3.4
- Tofte, section 6
- Harper, section 3.4

Expressions V: ML’s lambda

As noted above, ML’s lambda expressions are written fn (x₁, ..., xₙ) => e.

- Ullman, section 5.1.3
- Tofte, section 7
- Harper, section 4.2

Expressions VI: Infix operators and precedence

The initial basis of Standard ML defines the following names as infix identifiers:
Expressions VII: Infix operators as functions

The mechanism that ML uses for infix operators is very different from what you are used to from C and C++.

- The infix symbols are names, and they stand for ordinary functions.
- The names are set up to be used as infix operators by so-called fixity declarations. A fixity declaration for an infix name specifies precedence and associativity.
- When you want to use an infix name in a function application, you just write it as an infix operator.
- When you want to refer to the function as a value, you have to put the syntactic particle op in front of the name.

For details, see

- Ullman, section 5.4.4
- Harper, super-brief mention on page 78

Expressions VIII: Parentheses

It’s easy to be confused about when you need parentheses. Here’s a checklist to tell you when to use parentheses around an expression or a pattern:

1. Is it an argument to a (possibly Curried) function, and if so, is it more than a single token?
2. Is it an infix expression that has to be parenthesized because the precedence of another infix operator would do the wrong thing otherwise?
3. Are you forming a tuple?
4. Are you parenthesizing an expression involving fn, case, or handle?
5. Are you parenthesizing an infix operator marked with op?

If the answer to any of these questions is yes, use parentheses. Otherwise, you almost certainly don’t need them—so get rid of them!

Especially,

- Never parenthesize the condition in an if expression. Such parentheses brand you as an unreconstructed C programmer.
- Never put parentheses around a single token. For example, never write something like (0) or (x), as in double(0) or length(x). Write double 0 or length x instead. (Ullman breaks this rule all the time. We hates it!)

Types II: Polymorphic functions

In ML, as in Scheme, you can write polymorphic functions simply by writing functions that are agnostic about some aspects of their arguments. The difference is that in ML, type system infers at compile time the knowledge that the function is polymorphic. You can probably learn all you need by feeding some of your µScheme code to the nano-ML (nml) or µML (uml) interpreters; you can identify a polymorphic function by the forall in the type. (Most unfortunately, Standard ML omits the forall from the type. You’re supposed to imagine it.)

- For an introduction, Ullman, section 5.3
- For a deep look, including some technical details, Harper, chapter 8
- (Not covered in Tofte)

Curried functions

What we call a “partially applied” function, Ullman calls “partially instantiated.” (He’s thinking of a substitution model. Bad Ullman.) There are no new concepts here, but the concrete syntax is radically different from what you’re used to in µScheme.

- Ullman, section 5.5
- Tofte, section 7
- Harper, section 11.3 (as usual, a very technical approach)

Exceptions

ML exceptions behave a lot like the Hanson Except_T type you may have seen in COMP 40, and somewhat like exceptions in C++ or Java.

- Ullman, section 5.2
- Tofte, section 16
- Harper, opening of section 2.2 (example of an “effect”)
- Harper, chapter 12 (this is a long chapter, but after you read through the first example in section 12.2, you’ll know enough to get started)
Types III: Type abbreviations

Type abbreviations are a leading cause of confusion for beginning ML programmers. A type abbreviation, which begins with the keyword `type`, creates a new name for an old type. But in its error messages, the compiler may not honor the abbreviation—it may insist on referring to the old type instead.

If you’re asked to “define a type,” you have to decide if you want a type abbreviation with `type`, or whether you want a “datatype definition” with `datatype`. Because both have similar effects on the type environment, both count as “define a type.”

- Ullman, section 6.1
- Tofte, section 14
- Harper, section 3.2.1

A type abbreviation can take type parameters. A type parameter is identified by a name that begins with a tick mark, and the names traditionally used are ‘a’, ‘b’, ‘c’, and so on. On the topic of type abbreviations with type parameters, both Harper and Tofte are unaccountably silent. Ullman at least gives a sketch in section 6.1.3. For an example, I recommend the definition of type `env` in Ramsey, chunk 359.

Data IV: Datatype definitions

A datatype definition creates a brand new type, which is distinct from any other type—even one that has the same name. If you create multiple types with the same name, you will become confused.

- Ullman, section 6.2
- Ramsey, section 5.2, example datatype definitions, in Standard ML, for the µScheme interpreter
- Ramsey, sections 8.1 and 8.2.3 (sensible only after you already understand what is going on with the types)
- Tofte, section 15
- Harper, chapter 10 (and for something with a type parameter, section 10.3)
- Ramsey, page 548, the example about `option@{2}`, for understanding about multiple types with the same name

Basis I: The `option` type

Let’s suppose you want to represent a value, except the value might not actually be known. For example, I could represent a grade on a homework by an integer, except if a grade hasn’t been submitted. Or the contents of a square on a chessboard is a piece, except the square might be empty. This problem comes up so often that the initial basis for ML has a special type constructor called option, which lets you handle it. The definition of option is

```plaintext
datatype 'a option = NONE | SOME of 'a
```

and it is already defined when you start the interactive system. You need not and should not define it yourself. As in a type abbreviation, the type parameter ‘a stands for an unknown type—you can substitute any type for the type variable ‘a.

Read

- Ramsey, pages 547 and 548
- Ullman, section 4.1 (pages 111–113) and page 208.
- Tofte
- Harper, section 10.2 (in passing)

Here are some more examples:

```plaintext
- datatype chesspiece = K | Q | R | N | B | P
- type square = chesspiece option
- val empty : square = NONE
- val lower_left : square = SOME R
- fun play piece = SOME piece : square;
  > val play = fn : chesspiece -> chesspiece option

> SOME true;
> val it = SOME true : bool option
- SOME 37;
> val it = SOME 37 : int option

> SOME "fish" = SOME "fowl";
> val it = false : bool
- SOME "fish" = NONE;
> val it = false : bool
- "fish" = NONE;
  ! Toplevel input:
  ! "fish" = NONE;
  ! ^^^^ Type clash: expression of type
  ! ‘a option
  ! cannot be made to have type
  ! string
```

Data V: Record types, values, expressions, and patterns

In addition to tuples, Standard ML has records with named fields. A record is notated by a set of key-value pairs, separated by commas, and enclosed in curly braces. The order of the pairs doesn’t matter. Unfortunately, records come with some special rules and special syntax that can cause pain for beginners.

- By far the most useful introduction to records is Harper’s section 5.2, which has the longest explanation and the best examples. Harper’s section 5.3 mixes some useful examples with some dangerous examples. You’ll be all right as long as you heed Harper’s advice that “Use of the sharp notation is strongly discouraged.” In COMP 105, the sharp notation is forbidden.
- Ullman’s sections 7.1.1 and 7.1.5 are reliable, as are parts of section 7.1.4.
• **Ullman pitfall:** Disregard Ullman’s section 7.1.2. The 
  `#name` syntax, like the `#n` syntax for tuples, is worse than 
  useless—it actively makes it more difficult to write your 
  code. Use pattern matching instead.

• **Avoid** using the ellipsis in record patterns. To use it successful-
  fully, you must have a deep understanding of type inference 
  and of Standard ML’s peculiar approach to record types.

• Tofte mentions records briefly in section 8. That pitfall is 
  back: you must **avoid** what Tofte calls the `#lab` syntax— 
  `#lab` is not a function, and it will trip you up.

What’s wrong with the sharp notation? In brief, `#name` is a piece 
  of syntax—it’s not a function, and it doesn’t have a unique type.

What’s wrong with ellipsis patterns? Same thing: an ellipsis 
  pattern doesn’t have a unique type.

### Basis II: Access to functions defined in modules

Standard ML includes a sophisticated module language—one of 
  the most expressive module languages ever designed. But at least 
  to start, you’ll use modules in a very stylized way: by selecting 
  components from modules in the initial basis. Such selection 
  uses “dot notation,” with the name of the module followed by 
  the name of a component. Examples include `Int.toString` and 
  `List.filter`.

  • You can see some examples in Tofte, section 19
  • There’s another example in Ullman, section 8.2.3
  • **Ullman pitfall:** Avoid the open technique described in Ull-
    man’s section 8.2.4
  • I’m not seeing any place where Harper explains this notation.

In section 8.2.4, Ullman shows that you can get access to the 
  contents of a module by opening the module, as in `open TextIO`. 
**Never do this**—it is bad enough to open structures in the standard 
  basis, but if you open other structures, your code will be hope-
  lessly difficult to maintain. Instead, **abbreviate** structure names as 
  needed. For example, after structure `T = TextIO`, you can 
  use `T.openIn`, etc., without (much) danger of confusion.

### Basis III: Getting to know the Standard Basis

The initial basis of Standard ML is called the “Standard Basis,” 
  or sometimes the “Standard Basis Library.” Get to know it, and 
  use it when you can.

Modules you can learn easily include `List`, `Option`, `ListPair`, 
  `Vector`, and `Array`. You may also have some use for `TextIO`.

Moscow ML ships with an extended version of the standard basis 
  library. Tell Moscow ML `help "lib"`; and you’ll see what’s 
  there.

```
ledit mosml -P full
```

as your interactive top-level loop, it will automatically load almost 
  everything you might want from the standard basis.

### Basis IV: Vectors

Although Ullman describes the mutable `Array` structure in Chap-
  ter 7, he doesn’t cover the immutable `Vector` structure except for 
  a couple of pages deep in Chapter 9. Like an array, a vector offers 
  constant-time access to an array of elements, but a vector is not 
  mutable. Because of its immutability, `Vector` is often preferred. 
  It is especially flexible when initialized with `Vector.tabulate`.

The functions to start with include `Vector.tabulate`, 
  `Vector.fromList`, `Vector.length`, and `Vector.sub`. The 
  `Vector` structure also includes variations on `app`, `map`, `foldl`, 
  `foldr`, `find`, `exists`, and `all`. 
Unit Testing

Standard ML does not come with built-in unit-testing support. For COMP 105, we have created a special module called Unit, which exports functions that can be used for unit testing. These and related functions are shown in the table.

Example unit tests

You write a unit test in the form of a val definition with the empty tuple as the pattern. Here are two examples, only one of which passes:

```ml
val () = Unit.checkExpectWith Int.toString "2 is third" (fn () => List.nth ([1, 2, 3], 2)) 3

val () = (* this test fails *) Unit.checkExpectWith Bool.toString "2 is false" (fn () => List.nth ([true, false, true], 2)) false
```

The difference between this module and the check-expect you are used to is that check-expect takes just an expression, but Unit.checkExpectWith requires that expression be wrapped in a function of no arguments. So if you are expecting expression e to evaluated to value v, you must write

```ml
Unit.checkExpectWith... (fn () => e) v
```

Functions Unit.checkAssert and Unit.checkExnWith work the same way. Here are two more examples, both of which pass:

```ml
val () = Unit.checkAssert "has positive" (fn () => List.exists (fn n => n > 0) [~1, 0, 1])

val () = Unit.checkExnWith (Unit.listString Int.toString) "3rd element of empty list" (fn () => List.nth ([], 3))
```

Bureaucracy of getting our module (Moscow ML)

To use the unit tests, you must have a compiled version of the Unit module. You may use ours, or you may compile it yourself.

- To use ours, tell Moscow where to look by giving it the command-line option -I /comp/105/lib. This option works with both mosml and mosmlc.
- To compile it yourself, copy files Unit.sig and Unit.sml from /comp/105/lib, and compile them at your shell prompt:

```bash
$ mosmlc -c Unit.sig
$ mosmlc -c Unit.sml
```

These commands should produce files Unit.ui and Unit.uo.

The batch compiler mosmlc should now be able to compile your code using Unit:

```bash
$ mosmlc -toplevel -I /comp/105/lib -c warmup.sml
```

At this stage, you can load your code into the interactive system:

```bash
$ mosmlc -I /comp/105/lib
Moscow ML version 2.10-3 (Tufts University, April 2012)
Enter 'quit();' to quit.
- load "warmup";
  > val it = () : unit
  - Unit.report();
Both internal Unit tests passed.
  > val it = () : unit
```

If you prefer to bring your source code directly into Moscow ML, without compiling first, you can call ML's use function, but you will need to load the Unit module first:

```bash
$ mosml -I /comp/105/lib
Moscow ML version 2.10-3 (Tufts University, April 2012)
Enter 'quit();' to quit.
- use "warmup.sml";
[opening file "warmup.sml"]
...
[closing file "warmup.sml"]
  > val it = () : unit
```

If you forget this step, you’ll get an error message:

```bash
nr@homedog /tmp> mosml -P full -I /comp/105/lib
Moscow ML version 2.10-3 (Tufts University, April 2012)
Enter 'quit();' to quit.
- use "warmup.sml";
[opening file "warmup.sml"]
File "warmup.sml", line 2, characters 6-22:
  Unit.checkAssert "has positive"
                   ^^^^^^^^^^^^^^^^
  Cannot access unit Unit before it has been loaded. [closing file "warmup.sml"]
```

Just load "Unit"; and you’ll be on your way.

Bureaucracy of getting our module (MLton)

Compiling multiple modules in MLton is a hassle: you have to have an “MLB” file that lists all the modules you want, in dependency order, plus the version of the basis you want.
This is a hassle. To get the unit module, you include /comp/105/lib/unit.mlb in your own MLB file. Where you need unit tests for the homework, we’ll provide an MLB file you can use.

**Documentation of all the functions**

Every function in the Unit module is declared with a name and a type. These declaration forms, which are shown below, are part of ML’s modules system. Each declaration is followed by some informal English. To refer to the function from outside the Unit module, in your code, you need “Unit dot function-name.”

**Testing functions**

The closest analog to check-expect is the function Unit.checkExpectWith:

```ml
val checkExpectWith : ('a -> string) ->
  string ->
  (unit -> 'a) ->
  'a ->
  unit
```

Calling `checkExpectWith show name test result evaluates test(), applying test to the empty tuple. If the result equals result, the test passes; otherwise it fails. If the test fails, name is used to identify the failing test.

The closest analog to check-assert is Unit.checkAssert:

```ml
val checkAssert : string -> (unit -> bool) -> unit
```

Calling `checkAssert name test evaluates test()`, and if the result is true, the test passes; otherwise it fails. If the test fails, name is used to identify the failing test.

The closest analog to check-error is Unit.checkExnWith:

```ml
val checkExnWith : ('a -> string) ->
  string ->
  (unit -> 'a) ->
  'a ->
  unit
```

Calling `checkExn show name test evaluates test()`, and if the evaluation raises an exception e, the test passes, if test() returns a non-satisfying exception, or if test() returns a value, the test fails, complaining that the exception named name was expected. If the test fails, name is used to identify the failing test.

**Reporting functions**

Use these functions to confirm that all your unit tests pass.

```ml
val report : unit -> unit
```

If any tests were run, report, on standard output, how many tests were run in total and how many passed.

```ml
val reportWhenFailures : unit -> unit
```

If any tests failed, report, on standard output, how many tests were run in total and how many passed.

**String-conversion functions**

Use these functions to create string-conversion functions to pass to checkExpectWith and checkExnWith.

```ml
val listString : ('a -> string) ->
  ('a list -> string)
```

If showA converts a value in A to a string, then `listString showA` returns a function that converts a value in “list of A” to a string.

```ml
val pairString : ('a -> string) ->
  ('b -> string) ->
  ('a * 'b -> string)
```

If showA converts a value in A to a string, and showB converts a value in B to a string, `pairString showA showB` returns a function that converts a pair of type A × B to a string.

```ml
val showNothing : 'a -> string
```

If you need to convert a value of type A to a string, but you don’t have a converter—and you don’t want to write one—you can use showNothing with any type A. Function showNothing converts every value to the string "a value".

**An example with a user-defined type**

Here is an example of using checkExpectWith:

```ml
data = datatype color = LAVENDER | BURGUNDY | VIRIDIAN
fun colorString LAVENDER = "LAVENDER"
| colorString BURGUNDY = "BURGUNDY"
| colorString VIRIDIAN = "VIRIDIAN"
```
val favorites = [BURGUNDY, LAVENDER, VIRIDIAN]
val () = (* this test fails *)
    Unit.checkExpectWith colorString
"least favorite color"
    (fn () => List.last favorites)
    LAVENDER

This test fails with this error message:

    In test 'least favorite color', expected value LAVENDER but got VIRIDIAN

Here is an example of using checkExnWith:

val () = (* this test passes *)
    Unit.checkExnWith colorString
"last of empty string"
    (fn () => List.last [])

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit.checkExpectWith</td>
<td>An adequate substitute for check-expect. Requires a function to convert result to a string. And because an ML function does not know where in the source coded its definition is, checkExpectWith also requires a test name, which should uniquely identify the test.</td>
</tr>
<tr>
<td>Unit.checkAssert</td>
<td>An adequate substitute for check-assert. Requires a test name.</td>
</tr>
<tr>
<td>Unit.checkExnWith</td>
<td>An adequate substitute for check-error. Used when you expect evaluating an expression to raise an exception. Also requires a name and a string-conversion function.</td>
</tr>
<tr>
<td>Unit.checkExnSatisfiesWith</td>
<td>A refined version of Unit.checkExnWith that enables you to control which exceptions are considered to pass the test.</td>
</tr>
<tr>
<td>Unit.report</td>
<td>Prints a report of testing outcomes.</td>
</tr>
<tr>
<td>Unit.reportWhenFailures</td>
<td>Prints a report only if some test fails.</td>
</tr>
<tr>
<td>Int.toString</td>
<td>Convert an integer to a string. Sometimes useful for passing to checkExpectWith, checkExnWith, or checkExnSatisfiesWith.</td>
</tr>
<tr>
<td>Bool.toString</td>
<td>Convert a Boolean to a string.</td>
</tr>
<tr>
<td>Char.toString</td>
<td>Convert a character to a string.</td>
</tr>
<tr>
<td>Unit.listString</td>
<td>A higher-order function. Given a function that converts a value to a string, returns a function that converts a list of values to a string. Useful for passing to checkExpectWith and friends.</td>
</tr>
<tr>
<td>Unit.pairString</td>
<td>Another higher-order function. Given two string-conversion functions, returns a function that converts a pair of values to a string.</td>
</tr>
</tbody>
</table>
ML Modules

General information on modules

If you want to review what you heard in class,

- The Code & Co. blog\footnote{https://jozefg.bitbucket.io/about.html} has a nice post on ML modules\footnote{https://jozefg.bitbucket.io/posts/2015-01-08-modules.html}, which covers all three major components: structures, signatures, functors.

- Ullman, in Section 8.1, gives the same sort of guff you heard in lecture about information hiding. It’s a lightweight, non-technical overview.

- Tofte, Section 21 provides the barest possible introduction.

Signatures, Structures, and Ascription

The foundations are interfaces, implementations, and matching one to the other—or in the gratuitously mathematical lingo of Standard ML: signatures, structures, and ascription.

- Harper, although a bit long-winded, provides the most complete and detailed treatment of these topics. I recommend you start there. Chapter 18 presents signatures and structures—not just the basics, but a fair number of details.

A detailed explanation of what it means for a signature to match a structure is there in Chapter 19. The presentation is very careful and well thought out, with examples.

Chapter 20 explains ascription, again very well, with examples. Focus your attention on section 20.2 (opaque ascription). You can skip section 20.3 (transparent ascription)—while Harper does his honorable best to make a case, the sad truth is that there is not really a compelling case for transparent ascription. And transparent ascription is not acceptable in COMP 105.

If Harper is too detailed or too mathematical for your taste, try one of the other sources.

- Most of these topics are addressed by Ullman in Section 8.2, but there are quite a few pitfalls to avoid:
  - Section 8.2.2 describes ascription, which Ullman calls “restriction.” Unfortunately, Ullman uses the legacy “transparent” ascription style with a bare colon. This style is not acceptable in COMP 105. Use proper “opaque” ascription—the one with the “beak” operator (:>). Ullman says a little more about opaque ascription in section 8.5.5.
  - Section 8.2.4 describes open. I won’t waste space here detailing all the reasons open is terrible; just be aware that in COMP 105, use of open is grounds for No Credit on the modules assignment.

- Tofte covers the basics in sections 22 to 27. Again, the “transparent” constraints in section 25 are the ones to avoid, and the “opaque” constraints in section 26 are the ones to use.

Signature refinement or specialization

Quite often, we need to specify the identity of an abstract type after the fact—usually when writing the result signature of a functor. This is done using the \texttt{where type} syntax.

- Ullman completely omits signature refinement using \texttt{where type}. Without this tool, opaque ascription is crippled. You’ll need to read about it in Tofte or Harper.

- Tofte calls the technique “type realization,” and you’ll find it described, with a careful example, in section 27.

- Harper describes signature specialization in section 18.1.2.

Modules can nest

An excellent aspect of Standard ML’s design is that structures can contain other structures. That’s really all you need to know, but if you want to understand why this feature is valuable, there are plenty of good examples in Harper, chapter 21.

Functors

Paraphrased from Harper: an ML functor is a function that operates on the module level. Its formal parameters, if any, are specified by a sequence of declarations, and its actual parameters are given by a sequence of definitions. Its result is a structure. Functors enable a variety of styles of programming, but in 105, we focus on the functor as a mechanism for code reuse.

- The basics are found in Harper, section 23.1.

There is a dirty secret: there is a second mechanism for specifying parameter(s) to a functor, which is to package everything up in a single structure. I much prefer Harper’s “sequence of declarations/definitions” view, and I don’t know why we are stuck with two mechanisms. But you’ll see the second mechanisms from time to time.

- Ullman, in Section 8.3, spends a lot of ink mucking about with various alternative ways of defining functors’ parameters. Ullman manages to take a simple thing and make it seem complicated. On this subject, I recommend avoiding Ullman entirely.

- Tofte, Section 28, is saner than Ullman, but he doesn’t handle the argument issue as well as Harper does. The form that Harper prefers (and that we prefer also) is treated by Tofte as “an alternative form.” You’ll notice, however, that this form is what Tofte uses in his example.
Sharing constraints

Don’t ask. In COMP 105 we do our best to avoid putting you in situations where you need sharing constraints. But if you trip over them, Harper’s Chapter 22 is the best source. Follow up with sections 23.2 and 23.3, in which Harper explains when sharing constraints are needed and why they are better than the alternatives. They are also mentioned by Tofte in section 28.

Abstract data types

Harper completely understands the importance of data abstraction and the use of ML modules to enforce it.

- Section 20.2 introduces opaque ascription by explaining its role in data abstraction.
- Chapter 32 presents a complete, sophisticated example of data abstraction using the familiar abstraction of a dictionary. The chapter shows implementations using two different forms of binary search tree.