Programming Languages

Records, Datatypes, Case Expressions and more

Jiwon Seo

Late Policy

- 1 sec ~ 23 hour 59 min 59 sec late: 50% of the grade
- 24hr or more : 0%

Five different things

1. Syntax: How do you write language constructs?
2. Semantics: What do programs mean? (Evaluation rules)
3. Idioms: What are typical patterns for using language features to express your computation?
4. Libraries: What facilities does the language (or a well-known project) provide “standard”? (E.g., file access, data structures)
5. Tools: What do language implementations provide to make your job easier? (E.g., REPL, debugger, code formatter, …)
   – Not actually part of the language

These are 5 separate issues

- In practice, all are essential for good programmers
- Many people confuse them, but shouldn’t

Our Focus

This course focuses on semantics and idioms

- Syntax is usually uninteresting
  - A fact to learn, like "The American Civil War ended in 1865"
  - People obsess over subjective preferences

- Libraries and tools crucial, but often learn new ones "on the job"
  - We are learning semantics and how to use that knowledge to understand all software and employ appropriate idioms
  - By avoiding most libraries/tools, our languages may look "silly" but so would *any* language used this way

Related Sections in Elements of ML Programming

Section 7.1 (Records), 6.1, 6.2 (Datatypes),
5.1 (Pattern Matching)

How to build bigger types

- Already know:
  - Have various *base types* like **`int bool unit char`**
  - Ways to build (nested) *compound types*: tuples, lists, options

- Today: more ways to build compound types

- First: 3 most important type building blocks in *any* language
  - "Each of": A **`t`** value contains *values of each of* **`t1 t2 … tn`**
  - "One of": A **`t`** value contains *values of one of* **`t1 t2 … tn`**
  - "Self reference": A **`t`** value can refer to other **`t`** values

  Remarkable: A lot of data can be described with just these building blocks

  Note: These are not the common names for these concepts

  -- Product, sum, recursive type

Examples

- Tuples build each-of types
  - **`int * bool`** contains an **`int`** *and* a **`bool`**

- Options build one-of types
  - **`int option`** contains an **`int`** *or* it contains no data

- Lists use all three building blocks
  - **`int list`** contains an **`int`** *and* another **`int list`** *or* it contains no data

- And of course we can nest compound types
  - **`((int * int) option) * (int list list)) option`**

Rest of this Lecture

- Another way to build each-of types in ML
  - *Records*: have named *fields*
  - Connection to tuples and idea of *syntactic sugar*

- A way to build and use our own one-of types in ML
  - For example, a type that contains an **`int`** or a **`string`**
  - Will lead to *pattern-matching*, one of ML’s coolest and strangest-to-Java-programmers features

- Later in course: How OOP does one-of types
  - Key contrast with procedural and functional programming

Records

Record values have fields (any name) holding values

```
{f1 = v1, …, fn = vn}
```

Record types have fields (and name) holding types

```
{f1 : t1, …, fn : tn}
```

The order of fields in a record value or type never matters

- REPL alphabetizes fields just for consistency

Building records:

```
{f1 = e1, …, fn = en}
```

Accessing components:

```
#myfieldname e
```

(Evaluation rules and type-checking as expected)

Example

```
{name = "Amelia", id = 41123 - 12}
```

Evaluates to

```
{id = 41111, name = "Amelia"}
```

And has type

```
{id : int, name : string}
```

If some expression such as a variable **`x`** has this type, then get fields with:

```
#id x      #name x
```

Note we did not have to declare any record types

- The same program could also make a **`{id=true,ego=false}`** of type **`{id:bool,ego:bool}`**

By name vs. by position

- Little difference between `(4,7,9)` and `{f=4,g=7,h=9}`
  - Tuples a little shorter
  - Records a little easier to remember "what is where"
  - Generally a matter of taste, but for many (6? 8? 12?) fields, a record is usually a better choice

- A common decision for a construct's syntax is whether to refer to things *by position* (as in tuples) or *by some (field) name* (as with records)
  - A common hybrid is like with Java method arguments (and ML functions as used so far):
    - Caller uses *position*
    - Callee uses *variables*
    - Could totally do it differently; some languages have

The truth about tuples

Previous lecture gave tuples syntax, type-checking rules, and evaluation rules

But we could have done this instead:

- Tuple syntax is just a different way to write certain records
- **`(e1,…,en)`** is another way of writing **`{1=e1,…,n=en}`**
- **`t1*…*tn`** is another way of writing **`{1:t1,…,n:tn}`**
- In other words, records with field names 1, 2, …

In fact, this is how ML actually defines tuples

- Other than special syntax in programs and printing, they don't exist
- You really can write **`{1=4,2=7,3=9}`**, but it's bad style

Syntactic sugar

"Tuples are just syntactic sugar for
records with fields named 1, 2, … n"

- *Syntactic*: Can describe the semantics entirely by the corresponding record syntax

- *Sugar*: They make the language sweeter ☺

Will see many more examples of syntactic sugar

- They simplify *understanding* the language
- They simplify *implementing* the language

Why? Because there are fewer semantics to worry about even though we have the syntactic convenience of tuples

Another example we saw: **`andalso`** and **`orelse`** vs. **`if then else`**

Boolean Operations

Operation	Syntax	Type-checking	Evaluation
`andalso`	`e1 andalso e2`	`e1` and `e2` must have type `bool`	Same as Java's `e1` && `e2`
`orelse`	`e1 orelse e2`	`e1` and `e2` must have type `bool`	Same as Java's `e1` || `e2`
`not`	`not e1`	`e1` must have type `bool`	Same as Java's !`e1`

- `not` is just a pre-defined function, but `andalso` and `orelse` must be built-in operations since they cannot be implemented as a function in ML.
  - Why? Because `andalso` and `orelse` "short-circuit" their evaluation and may not evaluate *both* `e1` and `e2`.

- Be careful to always use `andalso` instead of `and`.
- `and` is completely different. We will get back to it later.

Style with Booleans

Language does not *need* `andalso` , `orelse` , or `not`

```
(* e1 andalso e2 *)
if e1
then e2
else false
```

```
(* e1 orelse e2 *)
if e1
then true
else e2
```

```
(* not e1 *)
if e1
then false
else true
```

Using more concise forms generally much better style

And definitely please do not do this:

```
(* just say e (!!!) *)
if e
then true
else false
```

Datatype bindings

A “strange” (?) and totally awesome (!) way to make one-of types:

– A **`datatype`** binding

```
datatype mytype = TwoInts of int * int
                | Str of string
                | Pizza
```

- Adds a new type **`mytype`** to the environment
- Adds *constructors* to the environment: **`TwoInts`**, **`Str`**, and **`Pizza`**
- A constructor is (among other things), a function that makes values of the new type (or is a value of the new type):
  - **`TwoInts : int * int -> mytype`**
  - **`Str : string -> mytype`**
  - **`Pizza : mytype`**

The values we make

```
datatype mytype = TwoInts of int * int
                | Str of string
                | Pizza
```

- Any value of type **`mytype`** is made from *one of* the constructors
- The value contains:
  - A "tag" for "which constructor" (e.g., **`TwoInts`**)
  - The corresponding data (e.g., **`(7,9)`**)
- Examples:
  - **`TwoInts(3+4,5+4)`** evaluates to **`TwoInts(7,9)`**
  - **`Str(if true then "hi" else "bye")`** evaluates to **`Str("hi")`**
  - **`Pizza`** is a value

Using them

So we know how to *build* datatype values; need to *access* them

There are *two* aspects to accessing a datatype value

1. Check what *variant* it is (what constructor made it)
2. Extract the *data* (if that variant has any)

Notice how our other one-of types used functions for this:

- **`null`** and **`isSome`** check variants
- **`hd`**, **`tl`**, and **`valOf`** extract data (raise exception on wrong variant)

ML *could* have done the same for datatype bindings

- For example, functions like “isStr” and “getStrData”
- Instead it did something better

Case

ML combines the two aspects of accessing a one-of value with a *case expression* and *pattern-matching*

– Pattern-matching much more general/powerful

Example:

```
fun f x = (* f has type mytype -> int *)
    case x of
        Pizza => 3
      | TwoInts(i1,i2) => i1+i2
      | Str s => String.size s
```

- A multi-branch conditional to pick branch based on variant
- Extracts data and binds to variables local to that branch
- Type-checking: all branches must have same type
- Evaluation: evaluate between `case` … `of` and the right branch

Patterns

In general the syntax is:

```
case e0 of
      p1 => e1
    | p2 => e2
      …
    | pn => en
```

For today, each *pattern* is a constructor name followed by the right number of variables (i.e., `C` or `C x` or `C(x,y)` or …)

- Syntactically most patterns (all today) look like expressions
- But patterns are not expressions
  - We do not evaluate them
  - We see if the result of `e0` *matches* them

Why this way is better

0. You can use pattern-matching to write your own testing and data-extractions functions if you must
   – But do not do that on your homework

1. You cannot forget a case (inexhaustive pattern-match warning)
2. You cannot duplicate a case (a type-checking error)
3. You will not forget to test the variant correctly and get an exception (like **`hd []`**)
4. Pattern-matching can be generalized and made more powerful, leading to elegant and concise code

Useful examples

Let's fix the fact that our only example datatype so far was silly…

- Enumerations, including carrying other data

```
datatype suit = Club | Diamond | Heart | Spade
datatype card_value = Jack | Queen | King
                    | Ace | Num of int
```

- Alternate ways of identifying real-world things/people

```
datatype id = StudentNum of int
            | Name of string
                    * (string option)
                    * string
```

Don't do this

Unfortunately, bad training and languages that make one-of types inconvenient lead to common *bad style* where each-of types are used where one-of types are the right tool

```
(* use the studen_num and ignore other
   fields unless the student_num is ~1 *)
{ student_num : int,
  first       : string,
  middle      : string option,
  last        : string }
```

- Approach gives up all the benefits of the language enforcing every value is one variant, you don't forget branches, etc.

- And makes it less clear what you are doing

That said…

But if instead the point is that every “person” in your program has a name and maybe a student number, then each-of is the way to go:

```
{ student_num : int option,
  first       : string,
  middle      : string option,
  last        : string }
```

Expression Trees

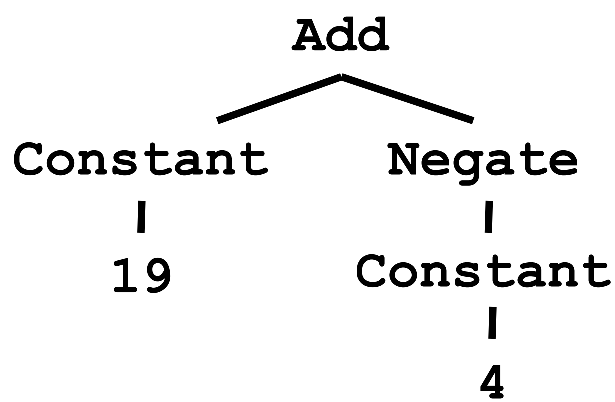
A more exciting example of a datatype, using self-reference

```
datatype exp = Constant of int
             | Negate   of exp
             | Add      of exp * exp
             | Multiply of exp * exp
```

An expression in ML of type **`exp`**:

```
Add (Constant (10+9), Negate (Constant 4))
```

How to picture the resulting value in your head:



Recursion

Not surprising:

Functions over recursive datatypes are usually recursive

```
fun eval e =
   case e of
        Constant i        => i
      | Negate e2         => ~ (eval e2)
      | Add(e1,e2)        => (eval e1) + (eval e2)
      | Multiply(e1,e2)   => (eval e1) * (eval e2)
```

Putting it together

```
datatype exp = Constant of int
             | Negate   of exp
             | Add      of exp * exp
             | Multiply of exp * exp
```

Let's define **`max_constant : exp -> int`**

Good example of combining several topics as we program:

- Case expressions
- Local helper functions
- Avoiding repeated recursion
- Simpler solution by using library functions

See the **`.sml`** file…

Careful definitions

When a language construct is "new and strange," there is *more* reason to define the evaluation rules precisely…

… so let's review datatype bindings and case expressions "so far"

- *Extensions* to come but won't invalidate the "so far"

Datatype bindings

```
datatype t = C1 of t1 | C2 of t2 | … | Cn of tn
```

Adds type `t` and constructors `Ci` of type `ti->t`

- `Ci v` is a value, i.e., the result "includes the tag"

Omit "`of t`" for constructors that are just tags, no underlying data

- Such a `Ci` is a value of type `t`

Given an expression of type `t`, use *case expressions* to:

- See which variant (tag) it has
- Extract underlying data once you know which variant

Datatype bindings

```
case e of p1 => e1 | p2 => e2 | … | pn => en
```

- As usual, can use a case expressions anywhere an expression goes
  - Does not need to be whole function body, but often is

- Evaluate **`e`** to a value, call it **`v`**

- If **`pi`** is the first *pattern* to *match* **`v`**, then result is evaluation of **`ei`** in environment "extended by the match"

- Pattern **`Ci(x1,…,xn)`** matches value **`Ci(v1,…,vn)`** and extends the environment with **`x1`** to **`v1`** … **`xn`** to **`vn`**
  - For "no data" constructors, pattern **`Ci`** matches value **`Ci`**

Datatype bindings

```
case e of p1 => e1 | p2 => e2 | … | pn => en
```

$p ::= \_ \mid c \mid x \mid (p_1, \ldots, p_n) \mid \{x_1 = p_1, \ldots, x_n = p_n\} \mid [\,] \mid p_1 :: p_2 \mid X \mid X(p)$

- Evaluate **`e`** to a value, call it **`v`**
- If **`pi`** is the first *pattern* to *match* **`v`**, then result is evaluation of **`ei`** in environment "extended by the match"
- Pattern **`Ci(x1,…,xn)`** matches value **`Ci(v1,…,vn)`** and extends the environment with **`x1`** to **`v1`** … **`xn`** to **`vn`**
  - For "no data" constructors, pattern **`Ci`** matches value **`Ci`**

Recursive datatypes

Datatype bindings can describe recursive structures

- Have seen arithmetic expressions
- Now, linked lists:

```
datatype my_int_list = Empty
                     | Cons of int * my_int_list

val x = Cons(4,Cons(23,Cons(2008,Empty)))

fun append_my_list (xs,ys) =
   case xs of
      Empty => ys
    | Cons(x,xs') => Cons(x, append_my_list(xs',ys))
```

Options are datatypes

Options are just a predefined datatype binding

- **`NONE`** and **`SOME`** are *constructors*, not just functions
- So use pattern-matching not **`isSome`** and **`valOf`**

```
fun inc_or_zero intoption =
   case intoption of
          NONE => 0
        | SOME i => i+1
```

Lists are datatypes

Do not use **`hd`**, **`tl`**, or **`null`** either

- **`[]`** and **`::`** are constructors too
- (strange syntax, particularly *infix*)

```
fun sum_list xs =
    case xs of
          [] => 0
        | x::xs' => x + sum_list xs'

fun append (xs,ys) =
    case xs of
         [] => ys
       | x::xs' => x :: append(xs',ys)
```

Why pattern-matching

- Pattern-matching is better for options and lists for the same reasons as for all datatypes
  - No missing cases, no exceptions for wrong variant, etc.

- So why are **`null`**, **`tl`**, etc. predefined?
  - For passing as arguments to other functions (next lecture)
  - Because sometimes they are convenient
  - But not a big deal: could define them yourself

Excitement ahead…

Learn some deep truths about “what is really going on”

- Using much more syntactic sugar than we realized

- Every val-binding and function-binding uses pattern-matching

- Every function in ML takes exactly one argument

First need to extend our definition of pattern-matching…

Each-of types

So far have used pattern-matching for one of types because we *needed* a way to access the values

Pattern matching also works for records and tuples:

- The pattern **`(x1,…,xn)`**
  matches the tuple value **`(v1,…,vn)`**
- The pattern **`{f1=x1, …, fn=xn}`**
  matches the record value **`{f1=v1, …, fn=vn}`**
  (and fields can be reordered)

Example

This is poor style, but based on what I told you so far, the only way to use patterns

- Works but poor style to have one-branch cases

```
fun sum_triple triple =
   case triple of
      (x, y, z) => x + y + z

fun full_name r =
   case r of
      {first=x, middle=y, last=z} =>
         x ^ " " ^ y ^ " " ^ z
```

Example

This is poor style, but based on what I told you so far, the only way to use patterns

- Works but poor style to have one-branch cases

```
fun sum_triple triple =
   case triple of
      (x, y, z) => x + y + z

fun full_name r =
   case r of
      {first=x, middle=y, last=z} =>
          x ^ " " ^ y ^ " " ^ z
```

Val-binding patterns

- New feature: A val-binding can use a pattern, not just a variable
  - (Turns out variables are just one kind of pattern, so we just told you a half-truth in Lecture 1)

```
val p = e
```

- Great for getting (all) pieces out of an each-of type
  - Can also get only parts out (not shown here)

- Usually poor style to put a constructor pattern in a val-binding
  - Tests for the one variant and raises an exception if a different one is there (like **`hd`**, **`tl`**, and **`valOf`**)

Better example

This is okay style

- Though we will improve it again next
- Semantically identical to one-branch case expressions

```
fun sum_triple triple =
   let val (x, y, z) = triple
   in
       x + y + z
   end

fun full_name r =
   let val {first=x, middle=y, last=z} = r
   in
       x ^ " " ^ y ^ " " ^ z
   end
```

Function-argument patterns

A function argument can also be a pattern

- Match against the argument in a function call

```
fun f p = e
```

Examples (great style!):

```
fun sum_triple (x, y, z) =
    x + y + z

fun full_name {first=x, middle=y, last=z} =
    x ^ " " ^ y ^ " " ^ z
```

Hmm

A function that takes one triple of type **`int*int*int`** and returns an **`int`** that is their sum:

```
fun sum_triple (x, y, z) =
    x + y + z
```

A function that takes three **`int`** arguments and returns an **`int`** that is their sum

```
fun sum_triple (x, y, z) =
    x + y + z
```

See the difference? (Me neither.) ☺

The truth about functions

- In ML, every function takes exactly one argument (*)
- What we call multi-argument functions are just functions taking one tuple argument, implemented with a tuple pattern in the function binding
  - Elegant and flexible language design
- Enables cute and useful things you cannot do in Java, e.g.,

```
fun rotate_left (x, y, z) = (y, z, x)
fun rotate_right t = rotate_left(rotate_left t)
```

* “Zero arguments” is the unit pattern `()` matching the unit value `()`