PAUL G. ALLEN SCHOOL OF COMPUTER SCIENCE & ENGINEERING

CSE341: Programming Languages

Lecture 9

Function-Closure Idioms

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More idioms

- We know the rule for lexical scope and function closures
  - Now what is it good for

A partial but wide-ranging list:

- Passing functions with private data to iterators: Done
- Combining functions (e.g., composition)
- Currying (multi-arg functions and partial application)
- Callbacks (e.g., in reactive programming) (optional)
- Implementing an ADT with a record of functions (optional)

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Combining functions

Canonical example is function composition:

```
fun compose (f,g) = fn x => f (g x)
```

- Creates a closure that "remembers" what `f` and `g` are bound to
- Type `('b -> 'c) * ('a -> 'b) -> ('a -> 'c)` but the REPL prints something *equivalent*
- ML standard library provides this as infix operator `o`
- Example (third version best):

```
fun sqrt_of_abs i = Math.sqrt(Real.fromInt(abs i))
fun sqrt_of_abs i = (Math.sqrt o Real.fromInt o abs) i
val sqrt_of_abs = Math.sqrt o Real.fromInt o abs
```


Left-to-right or right-to-left

```
val sqrt_of_abs = Math.sqrt o Real.fromInt o abs
```

As in math, function composition is "right to left"

- "take absolute value, convert to real, and take square root"
- "square root of the conversion to real of absolute value"

"Pipelines" of functions are common in functional programming and many programmers prefer left-to-right

- Can define our own infix operator
- This one is very popular (and predefined) in F#

```
infix |>
fun x |> f = f x

fun sqrt_of_abs i =
   i |> abs |> Real.fromInt |> Math.sqrt
```


Another example

- "Backup function"

```
fun backup1 (f,g) =
    fn x => case f x of
                NONE => g x
              | SOME y => y
```

- As is often the case with higher-order functions, the types hint at what the function does

`('a -> 'b option) * ('a -> 'b) -> 'a -> 'b`

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Currying

- Recall every ML function takes exactly one argument
- Previously encoded *n* arguments via one *n*-tuple
- Another way: Take one argument and return a function that takes another argument and…
  - Called "currying" after famous logician Haskell Curry

Example

```
val sorted3 = fn x => fn y => fn z =>
                 z >= y andalso y >= x
val t1 = ((sorted3 7) 9) 11
```

- Calling `(sorted3 7)` returns a closure with:
  - Code `fn y => fn z => z >= y andalso y >= x`
  - Environment maps `x` to `7`
- Calling *that* closure with `9` returns a closure with:
  - Code `fn z => z >= y andalso y >= x`
  - Environment maps `x` to `7`, `y` to `9`
- Calling *that* closure with `11` returns `true`

Syntactic sugar, part 1

```
val sorted3 = fn x => fn y => fn z =>
                 z >= y andalso y >= x
val t1 = ((sorted3 7) 9) 11
```

- In general, `e1 e2 e3 e4 …`, means `(…((e1 e2) e3) e4)`
- So instead of `((sorted3 7) 9) 11`, can just write `sorted3 7 9 11`
- Callers can just think "multi-argument function with spaces instead of a tuple expression"
  - Different than tupling; caller and callee must use same technique

Syntactic sugar, part 2

```
val sorted3 = fn x => fn y => fn z =>
                 z >= y andalso y >= x
val t1 = ((sorted3 7) 9) 11
```

- In general, `fun f p1 p2 p3 … = e`, means `fun f p1 = fn p2 => fn p3 => … => e`
- So instead of `val sorted3 = fn x => fn y => fn z => …` or `fun sorted3 x = fn y => fn z => …`, can just write `fun sorted3 x y z = x >=y andalso y >= x`
- Callees can just think "multi-argument function with spaces instead of a tuple pattern"
  - Different than tupling; caller and callee must use same technique

Final version

```
fun sorted3 x y z = z >= y andalso y >= x
val t1 = sorted3 7 9 11
```

As elegant syntactic sugar (even fewer characters than tupling) for:

```
val sorted3 = fn x => fn y => fn z =>
                 z >= y andalso y >= x
val t1 = ((sorted3 7) 9) 11
```

Curried fold

A more useful example and a call to it
- Will improve call next

```
fun fold f acc xs =
    case xs of
      []      => acc
    | x::xs'  => fold f (f(acc,x)) xs'

fun sum xs = fold (fn (x,y) => x+y) 0 xs
```

Note: `foldl` in ML standard-library has `f` take arguments in opposite order

"Too Few Arguments"

- Previously used currying to simulate multiple arguments
- But if caller provides "too few" arguments, we get back a closure "waiting for the remaining arguments"
  - Called partial application
  - Convenient and useful
  - Can be done with any curried function
- No new semantics here: a pleasant idiom

Example

```
fun fold f acc xs =
    case xs of
      []      => acc
    | x::xs'  => fold f (f(acc,x)) xs'

fun sum_inferior xs = fold (fn (x,y) => x+y) 0 xs

val sum = fold (fn (x,y) => x+y) 0
```

As we already know, `fold (fn (x,y) => x+y) 0` evaluates to a closure that given `xs`, evaluates the case-expression with `f` bound to `fold (fn (x,y) => x+y)` and `acc` bound to `0`

Unnecessary function wrapping

```
fun sum_inferior xs = fold (fn (x,y) => x+y) 0 xs

val sum = fold (fn (x,y) => x+y) 0
```

- Previously learned not to write `fun f x = g x` when we can write `val f = g`
- This is the same thing, with `fold (fn (x,y) => x+y) 0` in place of `g`

Iterators

- Partial application is particularly nice for iterator-like functions
- Example:

```
fun exists predicate xs =
    case xs of
      []      => false
    | x::xs'  => predicate x
                 orelse exists predicate xs'

val no = exists (fn x => x=7) [4,11,23]
val hasZero = exists (fn x => x=0)
```

- For this reason, ML library functions of this form usually curried
  - Examples: `List.map`, `List.filter`, `List.foldl`

The Value Restriction Appears ☹

If you use partial application to *create a polymorphic function*, it may not work due to the value restriction

- Warning about "type vars not generalized"
  - And won't let you call the function
- This should surprise you; you did nothing wrong ☺ but you still must change your code
- See the code for workarounds
- Can discuss a bit more when discussing type inference

More combining functions

- What if you want to curry a tupled function or vice-versa?
- What if a function's arguments are in the wrong order for the partial application you want?

Naturally, it is easy to write higher-order wrapper functions

– And their types are neat logical formulas

```
fun other_curry1 f = fn x => fn y => f y x
fun other_curry2 f x y = f y x
fun curry f x y = f (x,y)
fun uncurry f (x,y) = f x y
```


Efficiency

So which is faster: tupling or currying multiple-arguments?

- They are both constant-time operations, so it doesn't matter in most of your code – "plenty fast"
  – Don't program against an *implementation* until it matters!
- For the small (zero?) part where efficiency matters:
  – It turns out SML/NJ compiles tuples more efficiently
  – But many other functional-language implementations do better with currying (OCaml, F#, Haskell)
    - So currying is the "normal thing" and programmers read `t1 -> t2 -> t3 -> t4` as a 3-argument function that also allows partial application

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ML has (separate) mutation

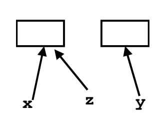
- Mutable data structures are okay in some situations
  – When "update to state of world" is appropriate model
  – But want most language constructs truly immutable
- ML does this with a separate construct: references
- Introducing now because will use them for next closure idiom
- Do not use references on your homework
  – You need practice with mutation-free programming
  – They will lead to less elegant solutions

References

- New types: `t ref` where `t` is a type
- New expressions:
  – `ref e` to create a reference with initial contents `e`
  – `e1 := e2` to update contents
  – `!e` to retrieve contents (not negation)

References example

```
val x = ref 42
val y = ref 42
val z = x
val _ = x := 43
val w = (!y) + (!z) (* 85 *)
(* x + 1 does not type-check *)
```



- A variable bound to a reference (e.g., `x`) is still immutable: it will always refer to the same reference
- But the contents of the reference may change via `:=`
- And there may be aliases to the reference, which matter a lot
- References are first-class values
- Like a one-field mutable object, so `:=` and `!` don't specify the field

Callbacks

A common idiom: Library takes functions to apply later, when an *event* occurs – examples:

- When a key is pressed, mouse moves, data arrives
- When the program enters some state (e.g., turns in a game)

A library may accept multiple callbacks

- Different callbacks may need different private data with different types
- Fortunately, a function's type does not include the types of bindings in its environment
- (In OOP, objects and private fields are used similarly, e.g., Java Swing's event-listeners)

Mutable state

While it's not absolutely necessary, mutable state is reasonably appropriate here

- We really do want the "callbacks registered" to *change* when a function to register a callback is called

Example call-back library

Library maintains mutable state for "what callbacks are there" and provides a function for accepting new ones

- A real library would also support removing them, etc.
- In example, callbacks have type `int->unit`

So the entire public library interface would be the function for registering new callbacks:

```
val onKeyEvent : (int -> unit) -> unit
```

(Because callbacks are executed for side-effect, they may also need mutable state)

Library implementation

```
val cbs : (int -> unit) list ref = ref []

fun onKeyEvent f =  cbs := f :: (!cbs)

fun onEvent i =
    let fun loop fs =
            case fs of
              []      => ()
            | f::fs' => (f i; loop fs')
    in loop (!cbs) end
```


Clients

Can only register an `int -> unit`, so if any other data is needed, must be in closure's environment

- And if need to "remember" something, need mutable state

Examples:

```
val timesPressed = ref 0
val _ = onKeyEvent (fn _ =>
            timesPressed := (!timesPressed) + 1)

fun printIfPressed i =
   onKeyEvent (fn j =>
       if i=j
       then print ("pressed " ^ Int.toString i)
       else ())
```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Optional: Implementing an ADT

As our last idiom, closures can implement abstract data types

- Can put multiple functions in a record
- The functions can share the same private data
- Private data can be mutable or immutable
- Feels a lot like objects, emphasizing that OOP and functional programming have some deep similarities

See code for an implementation of immutable integer sets with operations *insert*, *member*, and *size*

The actual code is advanced/clever/tricky, but has no new features

- Combines lexical scope, datatypes, records, closures, etc.
- Client use is not so tricky