CSE341: Programming Languages
Lecture 9
Function-Closure Idioms

Dan Grossman
Spring 2019
More idioms

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

A partial but wide-ranging list:

• Pass functions with private data to iterators: Done
• Combine functions (e.g., composition)
• Currying (multi-arg functions and partial application)
• Callbacks (e.g., in reactive programming)
• Implementing an ADT with a record of functions (optional)
Combine 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 \((b \to c) \times (a \to b) \to (a \to c)\)
  but the REPL prints something equivalent

- ML standard library provides this as infix operator \( \circ \)
- 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

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#

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

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

- “Backup function”

```plaintext
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
More idioms

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

A partial but wide-ranging list:

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

```haskell
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

In general, \( \text{fun } f \ p1 \ p2 \ p3 \ ... = e \),
means \( \text{fun } f \ p1 = \text{fn } p2 => \text{fn } p3 => ... => e \)

So instead of \( \text{val } \text{sorted3 } = \text{fn } x => \text{fn } y => \text{fn } z => ... \)
or \( \text{fun } \text{sorted3 } x = \text{fn } y => \text{fn } z => ... \),
can just write \( \text{fun } \text{sorted3 } x \ y \ z = x >=y \ \text{andalso } y >= x \)

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

```ml
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:

```ml
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

```ml
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

```haskell
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, \( \text{fold (fn (x,y) => x+y) 0} \) evaluates to a closure that given \( xs \), evaluates the case-expression with \( f \) bound to \( \text{fold (fn (x,y) => x+y)} \) 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:

```ml
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.foldl1`
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

```plaintext
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 \( t_1 \rightarrow t_2 \rightarrow t_3 \rightarrow t_4 \) as a 3-argument function that also allows partial application
More idioms

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

A partial but wide-ranging list:

• Pass functions with private data to iterators: Done
• Combine functions (e.g., composition)
• Currying (multi-arg functions and partial application)
• Callbacks (e.g., in reactive programming)
• Implementing an ADT with a record of functions (optional)
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: \( t \text{ ref} \) where \( t \) is a type

• New expressions:
  - \( \text{ref } e \) to create a reference with initial contents \( e \)
  - \( e_1 := e_2 \) to update contents
  - \( !e \) to retrieve contents (not negation)
References example

```ocaml
code
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., \textit{x}) is still immutable: it will always refer to the same reference
- But the contents of the reference may change via \texttt{:=}
- And there may be aliases to the reference, which matter a lot
- References are first-class values
- Like a one-field mutable object, so \texttt{:=} and \texttt{!} 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 \( \text{int} \rightarrow \text{unit} \)

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

\[
\text{val onKeyEvent} : \ (\text{int} \rightarrow \text{unit}) \rightarrow \text{unit}
\]

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

```plaintext
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 \texttt{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:

\begin{verbatim}
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 ()
\end{verbatim}
More idioms

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

A partial but wide-ranging list:

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