CSE341: Programming Languages

Lecture 7
First-Class Functions

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What is functional programming?

“Functional programming” can mean a few different things:

1. Avoiding mutation in most/all cases (done and ongoing)
2. Using functions as values (this unit)

... 
- Style encouraging recursion and recursive data structures
- Style closer to mathematical definitions
- Programming idioms using laziness (later topic, briefly)
- Anything not OOP or C? (not a good definition)

Not sure a definition of “functional language” exists beyond “makes functional programming easy / the default / required”
    - No clear yes/no for a particular language
First-class functions

- **First-class functions**: Can use them wherever we use values
  - Functions are values too
  - Arguments, results, parts of tuples, bound to variables, carried by datatype constructors or exceptions, ...

```
fun double x = 2*x
fun incr x = x+1
val a_tuple = (double, incr, double(incr 7))
```

- Most common use is as an argument / result of another function
  - Other function is called a **higher-order function**
  - Powerful way to *factor out* common functionality
Function Closures

- **Function closure**: Functions can use bindings from outside the function definition (in scope where function is defined)
  - Makes first-class functions *much* more powerful
  - Will get to this feature in a bit, after simpler examples

- Distinction between terms *first-class functions* and *function closures* is not universally understood
  - Important conceptual distinction even if terms get muddled
Onward

The next week:

– How to use first-class functions and closures
– The precise semantics
– Multiple powerful idioms
Functions as arguments

• We can pass one function as an argument to another function
  – Not a new feature, just never thought to do it before

```plaintext
fun f (g,…) = … g (…) …
fun h1 … = …
fun h2 … = …
... f(h1,…) ... f(h2,…) ...
```

• Elegant strategy for factoring out common code
  – Replace $N$ similar functions with calls to 1 function where
    you pass in $N$ different (short) functions as arguments

[See the code file for this lecture]
Example

Can reuse \texttt{n\_times} rather than defining many similar functions

\begin{itemize}
  \item Computes \( f(f(\ldots f(x) )) \) where number of calls is \texttt{n}
\end{itemize}

\begin{verbatim}
fun n_times (f,n,x) = 
  if n=0 
  then x 
  else f (n_times(f,n-1,x))

fun double x = x + x 
fun increment x = x + 1 
val x1 = n_times(double,4,7) 
val x2 = n_times(increment,4,7) 
val x3 = n_times(tl,2,[4,8,12,16])

fun double_n_times (n,x) = n_times(double,n,x) 
fun nth_tail (n,x) = n_times(tl,n,x)
\end{verbatim}
Relation to types

- Higher-order functions are often so “generic” and “reusable” that they have polymorphic types, i.e., types with type variables.

- But there are higher-order functions that are not polymorphic.

- And there are non-higher-order (first-order) functions that are polymorphic.

- Always a good idea to understand the type of a function, especially a higher-order function.
Types for example

fun n\_times (\(f\), \(n\), \(x\)) = 
  if \(n\)=0
  then \(x\)
  else \(f\) (n\_times(f,\(n\)-1,\(x\)))

• **val** n\_times : ('\(\text{a} \rightarrow \text{a}\) * int * '\(\text{a} \rightarrow \text{a}\)
  – Simpler but less useful: (int \(\rightarrow\) int) * int * int \(\rightarrow\) int

• Two of our examples *instantiated* '\(\text{a}\) with int
• One of our examples *instantiated* '\(\text{a}\) with int list
• This *polymorphism* makes n\_times more useful

• Type is *inferred* based on how arguments are used (later lecture)
  – Describes which types must be exactly something (e.g., int) and which can be anything but the same (e.g., '\(\text{a}\)
Polymorphism and higher-order functions

• Many higher-order functions are polymorphic because they are so reusable that some types, “can be anything”

• But some polymorphic functions are not higher-order
  – Example: \texttt{len : 'a list -> int}

• And some higher-order functions are not polymorphic
  – Example: \texttt{times\_until\_0 : (int -> int) * int -> int}

\begin{verbatim}
fun times_until_0 (f,x) =
  if x=0 then 0 else 1 + times_until_0(f, f x)
\end{verbatim}

Note: Would be better with tail-recursion
**Toward anonymous functions**

- Definitions unnecessarily at top-level are still poor style:

  ```plaintext
  fun triple x = 3*x
  fun triple_n_times (f,x) = n_times(triple,n,x)
  ```

- So this is better (but not the best):

  ```plaintext
  fun triple_n_times (f,x) = 
      let fun trip y = 3*y 
      in
          n_times(trip,n,x)
      end
  ```

- And this is even smaller scope
  - It makes sense but looks weird (poor style; see next slide)

  ```plaintext
  fun triple_n_times (f,x) = 
      n_times(let fun trip y = 3*y in trip end, n, x)
  ```
Anonymous functions

• This does not work: A function binding is not an expression

```plaintext
fun triple_n_times (f, x) =
    n_times((fun trip y = 3*y), n, x)
```

• This is the best way we were building up to: an expression form for anonymous functions

```plaintext
fun triple_n_times (f, x) =
    n_times((fn y => 3*y), n, x)
```

  – Like all expression forms, can appear anywhere
  – Syntax:
    • `fn` not `fun`
    • `=>` not `=`
    • no function name, just an argument pattern
Using anonymous functions

• Most common use: Argument to a higher-order function
  – Don’t need a name just to pass a function

• But: Cannot use an anonymous function for a recursive function
  – Because there is no name for making recursive calls
  – If not for recursion, `fun` bindings would be syntactic sugar for `val` bindings and anonymous functions

```ocaml
fun triple x = 3*x
val triple = fn y => 3*y
```
A style point

Compare:

\[ \text{if } x \text{ then true else false} \]

With:

\[ (\text{fn } x \Rightarrow f \ x) \]

So don’t do this:

\[ \text{n_times}((\text{fn } y \Rightarrow \text{tl } y),3,\text{xs}) \]

When you can do this:

\[ \text{n_times}((\text{tl}),3,\text{xs}) \]
Map

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

val map : ('a -> 'b) * 'a list -> 'b list

Map is, without doubt, in the “higher-order function hall-of-fame”
  – The name is standard (for any data structure)
  – You use it all the time once you know it: saves a little space, but more importantly, communicates what you are doing
  – Similar predefined function: List.map
    • But it uses currying (coming soon)
Filter

fun filter (f, xs) =
  case xs of
    [] => []
  | x::xs' => if f x
    then x::(filter(f, xs'))
    else filter(f, xs')

val filter : ('a -> bool) * 'a list -> 'a list

Filter is also in the hall-of-fame
  – So use it whenever your computation is a filter
  – Similar predefined function: List.filter

  • But it uses currying (coming soon)
Generalizing

Our examples of first-class functions so far have all:
– Taken one function as an argument to another function
– Processed a number or a list

But first-class functions are useful anywhere for any kind of data
– Can pass several functions as arguments
– Can put functions in data structures (tuples, lists, etc.)
– Can return functions as results
– Can write higher-order functions that traverse your own data structures

Useful whenever you want to abstract over “what to compute with”
– No new language features
Returning functions

• Remember: Functions are first-class values
  – For example, can return them from functions

• Silly example:

  ```
  fun double_or_triple f =
  if f 7
  then fn x => 2*x
  else fn x => 3*x
  ```

  Has type \((\texttt{int} \rightarrow \texttt{bool}) \rightarrow (\texttt{int} \rightarrow \texttt{int})\)

  But the REPL prints \((\texttt{int} \rightarrow \texttt{bool}) \rightarrow \texttt{int} \rightarrow \texttt{int}\)
  because it never prints unnecessary parentheses and
  \(\texttt{t1 \rightarrow t2 \rightarrow t3 \rightarrow t4}\) means \(\texttt{t1} \rightarrow (\texttt{t2} \rightarrow (\texttt{t3} \rightarrow \texttt{t4}))\)
Other data structures

• Higher-order functions are not just for numbers and lists

• They work great for common recursive traversals over your own data structures (datatype bindings) too

• Example of a higher-order predicate:
  – Are all constants in an arithmetic expression even numbers?
  – Use a more general function of type
    \[(\text{int} \rightarrow \text{bool}) \ast \text{exp} \rightarrow \text{bool}\]
  – And call it with \((\text{fn } x \Rightarrow x \mod 2 = 0)\)