Poly-HO!

COS 326
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polymorphic, higher-order programming
Some Design & Coding Rules

• *Laziness* can be a really good force in design.

• Never write the same code twice.
  – factor out the common bits into a reusable procedure.
  – better, use someone else’s (well tested, well documented, and well maintained) procedure.

• Why is this a good idea?
  – why don’t we just cut-and-paste snippets of code using the editor instead of abstracting them into procedures?
• **Laziness** can be a really good force in design.
• Never write the same code twice.
  – factor out the common bits into a re-usable procedure.
  – better, use someone else’s (well-tested, well-documented, and well-maintained) procedure.
• Why is this a good idea?
  – why don’t we just cut-and-paste snippets of code using the editor instead of abstracting them into procedures?
  – find and fix a bug in one copy, have to fix in all of them.
  – decide to change the functionality, have to track down all of the places where it gets used.
Consider these definitions:

```ocaml
let rec inc_all (xs:int list) : int list =
  match xs with
  | [] -> []
  | hd::tl -> (hd+1)::(inc_all tl)

let rec square_all (xs:int list) : int list =
  match xs with
  | [] -> []
  | hd::tl -> (hd*hd)::(square_all tl)
```
Consider these definitions:

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let rec inc_all (xs:int list) : int list =
  match xs with
  | [] -> []
  | hd::tl -> (hd+1)::(inc_all tl)
```

```ocaml
let rec square_all (xs:int list) : int list =
  match xs with
  | [] -> []
  | hd::tl -> (hd*hd)::(square_all tl)
```

The code is almost identical – factor it out!
A *higher-order* function captures the recursion pattern:

```ocaml
let rec map (f:int->int) (xs:int list) : int list =
  match xs with
  | [] -> []
  | hd::tl -> (f hd)::(map f tl);;
```
A \textit{higher-order} function captures the recursion pattern:

\begin{verbatim}
let rec map (f:int->int) (xs:int list) : int list =
  match xs with
  | [] -> []
  | hd::tl -> (f hd)::(map f tl);;
\end{verbatim}

Uses of the function:

\begin{verbatim}
let inc x = x+1;;
let inc_all xs = map inc xs;;
\end{verbatim}
A higher-order function captures the recursion pattern:

```ocaml
let rec map (f:int->int) (xs:int list) : int list =
  match xs with
  | [] -> []
  | hd::tl -> (f hd)::(map f tl);;
```

Uses of the function:

```ocaml
let inc x = x+1;;
let inc_all xs = map inc xs;;

let square y = y*y;;
let square_all xs = map square xs;;
```

Writing little functions like inc just so we call map is a pain.
Factoring Code in OCaml

A higher-order function captures the recursion pattern:

```ocaml
let rec map (f:int->int) (xs:int list) : int list =
    match xs with
    | [] -> []
    | hd::tl -> (f hd)::(map f tl);
```

Uses of the function:

```ocaml
let inc_all xs = map (fun x -> x + 1) xs;;
let square_all xs = map (fun y -> y * y) xs;;
```

We can use an anonymous function instead.

Originally, Church wrote this function using λ instead of fun:

- \(\lambda x. x+1\) or \(\lambda x. x*x\)
Another example

let rec sum (xs:int list) : int =
  match xs with
  | [] -> 0
  | hd::tl -> hd + (sum tl)
;;

let rec prod (xs:int list) : int =
  match xs with
  | [] -> 1
  | hd::tl -> hd * (prod tl)
;;

**Goal**: Create a function called reduce that when supplied with a few arguments can implement both sum and prod. Define sum2 and prod2 using reduce.

(Try it)

**Goal**: If you finish early, use map and reduce together to find the sum of the squares of the elements of a list.

(Try it)
let add x y = x + y;;
let mul x y = x * y;;

let rec reduce (f:int->int->int) (u:int) (xs:int list) : int =
  match xs with
  | [] -> u
  | hd::tl -> f hd (reduce f u tl);;

let sum xs = reduce add 0 xs ;;
let prod xs = reduce mul 1 xs ;;
Using Anonymous Functions

```ocaml
let rec reduce (f:int->int->int) (u:int) (xs:int list) : int =
  match xs with
  | [] -> u
  | hd::tl -> f hd (reduce f u tl);

let sum xs = reduce (fun x y -> x+y) 0 xs ;;
let prod xs = reduce (fun x y -> x*y) 1 xs ;;
```
Using Anonymous Functions

```ocaml
let rec reduce (f:int->int->int) (u:int) (xs:int list) : int =
  match xs with
  | [] -> u
  | hd::tl -> f hd (reduce f u tl);

let sum xs = reduce (fun x y -> x+y) 0 xs ;;
let prod xs = reduce (fun x y -> x*y) 1 xs ;;

let sum_of_squares xs = sum (map (fun x -> x * x) xs)
let pairify xs = map (fun x -> (x,x)) xs
```
(nonrecursive) Function declarations are actually abbreviations:

```ocaml
let square x = x*x ;;
let add x y = x+y ;;
```

are *syntactic sugar* for:

```ocaml
let square = (fun x -> x*x) ;;
let add = (fun x y -> x+y) ;;
```

So, *fun’s* are values we can bind to a variable, just like 3 or “moo” or true.

OCaml obeys the *principle of orthogonal language design.*
Simplifying further:

```ml
let add = (fun x y -> x+y)
```

is shorthand for:

```ml
let add = (fun x -> (fun y -> x+y))
```

That is, `add` is a function which:

- when given a value `x`, *returns a function* \((\text{fun } y \rightarrow x+y)\) which:
  - when given a value `y`, returns `x+y`. 
Curried Functions

fun \( x \to (\text{fun} \ y \to x+y) \) (* curried *)
fun \( x \ y \to x + y \) (* curried *)
fun \( (x,y) \to x+y \) (* uncurried *)

**Currying**: encoding a multi-argument function using nested, higher-order functions.

Named after the logician *Haskell B. Curry* (1950s).

- was trying to find minimal logics that are powerful enough to encode traditional logics.
- much easier to prove something about a logic with 3 connectives than one with 20.
- the ideas translate directly to math (set & category theory) as well as to computer science.
- (actually, *Moses Schönfinkel* did some of this in 1924)
- (thankfully, we don't have to talk about *Schönfinkelled* functions)
What’s so good about Currying?

In addition to simplifying the language (orthogonal design), currying functions so that they only take one argument leads to two major wins:

1. We can *partially apply* a function.
2. We can more easily *compose* functions.
Curried functions allow defs of new, partially applied functions:

```
let add = (fun x -> (fun y -> x+y)) ;;
```

Equivalent to writing:

```
let inc = add 1;;
```

which is equivalent to writing:

```
let inc = (fun y -> 1+y);};;
```

also:

```
let inc2 = add 2;;
let inc3 = add 3;;
```
SIMPLE REASONING ABOUT HIGHER-ORDER FUNCTIONS
We can factor this program

```ocaml
let rec map f xs =
  match xs with
  | [] -> []
  | hd::tl -> (f hd)::(map f tl);

let square_all = map square;;
```

into this program:

```ocaml
let rec map f xs =
  match xs with
  | [] -> []
  | hd::tl -> (f hd)::(map f tl);

let square_all = map square;;
```

a more concise and readable definition of square_all
(assuming we already had defined map)
**Goal**: Rewrite definitions so my program is simpler, easier to understand, more concise, can be refactored, ...

**Question**: What are the reasoning principles for rewriting programs without breaking them? For reasoning about the behavior of programs? About the equivalence of two programs?

I want some *rules* for doing so that never fail.
Simple Equational Reasoning

Rewrite 1 (Function de-sugaring):

\[
\text{let } f \ x = \text{body} \quad \Rightarrow \quad \text{let } f = (\text{fun } x \rightarrow \text{body})
\]

Rewrite 2 (Substitution):

\[
(\text{fun } x \rightarrow \ldots \ x \ldots) \ \text{arg} \quad \Rightarrow \quad \ldots \ \text{arg} \ldots
\]

Rewrite 3 (Eta-expansion):

\[
\text{let } f = \text{def} \quad \Rightarrow \quad \text{let } f \ x = (\text{def}) \ x
\]

- If \( f \) has a function type
- Chose name \( x \) wisely so it does not shadow other names used in \( \text{def} \)
Eta-expansion is an example of Leibniz’s law.

Gottfried Wilhelm von Leibniz
German Philosopher
1646 - 1716

Leibniz’s law:

If every predicate possessed by x is also possessed by y and vice versa, then entities x and y are identical. Frequently invoked in modern logic and philosophy.

Rewrite 3 (Eta-expansion):

```
let f = def
```

==

```
let f = fun x -> (def)x
```

if f has a function type

chose name x wisely so it does not shadow other names used in def
let rec map f xs =
    match xs with
    | [] -> []
    | hd::tl -> (f hd)::(map f tl);
Eliminating the Sugar in Map

```
let rec map f xs =
  match xs with
  | [] -> []
  | hd::tl -> (f hd)::(map f tl);

let rec map =
  (fun f ->
    (fun xs ->
      match xs with
      | [] -> []
      | hd::tl -> (f hd)::(map f tl)));
```
let rec map = (fun f -> (fun xs ->
  match xs with
  | [] -> []
  | hd::tl -> (f hd)::(map f tl)));;

let square_all = map square ;;
let rec map =
  (fun f ->
    (fun xs ->
      match xs with
      | [] -> []
      | hd::tl -> (f hd)::(map f tl));;

let square_all =
  (fun f ->
    (fun xs ->
      match xs with
      | [] -> []
      | hd::tl -> (f hd)::(map f tl)
    ) square ;;
let rec map =
    (fun f ->
      (fun xs ->
        match xs with
        | [] -> []
        | hd::tl -> (f hd)::(map f tl)));

let square_all =
    (fun f ->
      (fun xs ->
        match xs with
        | [] -> []
        | hd::tl -> (f hd)::(map f tl)) square) ;;
let rec map =
  (fun f ->
    (fun xs ->
      match xs with
      | [] -> []
      | hd::tl -> (f hd)::(map f tl)));

let square_all =
  (fun f ->
    (fun xs ->
      match xs with
      | [] -> []
      | hd::tl -> (f hd)::(map f tl)) square ;;
let rec map =
  (fun f ->
   (fun xs ->
    match xs with
    | [] -> []
    | hd::tl -> (f hd)::(map f tl)));

let square_all =
  (fun xs ->
   match xs with
   | [] -> []
   | hd::tl -> (square hd)::(map square tl))

argument square substituted for parameter f
let rec map =
  (fun f ->
    (fun xs ->
      match xs with
      | [] -> []
      | hd::tl -> (f hd)::(map f tl))));;

let square_all ys =
  (fun xs ->
    match xs with
    | [] -> []
    | hd::tl -> (square hd)::(map square tl)
  ) ys
  ;;

add argument via eta-expansion
let rec map =
  (fun f ->
    (fun xs ->
      match xs with
      | [] -> []
      | hd::tl -> (f hd)::(map f tl)));

let square_all ys =
  match ys with
  | [] -> []
  | hd::tl -> (square hd)::(map square tl);;
let rec map f xs =
  match xs with
  | [] -> []
  | hd::tl -> (f hd)::(map f tl);

let square_all xs = map square xs

let square_all ys =
  match ys with
  | [] -> []
  | hd::tl -> (square hd)::(map square tl)
  ;;

let square_all ys =
  match ys with
  | [] -> []
  | hd::tl -> (square hd)>::(map square tl)
  ;;

proof by simple rewriting unrolls definition once
proof by induction eliminates recursive function map
What Happened?

We saw this:

```ocaml
let rec map f xs =  
    match xs with  
    | [] -> []  
    | hd::tl -> (f hd)::(map f tl);;

let square_all ys = map square
```

Is equivalent to this:

```ocaml
let square_all ys =  
    match ys with  
    | [] -> []  
    | hd::tl -> (square hd)::(map square tl) ;;
```

Moral of the story

- (1) OCaml’s **HOT** (higher-order, typed) functions capture recursion patterns
- (2) we can figure out what is going on by **equational reasoning**.
- (3) ... but we typically need to do **proofs by induction** to reason about recursive (inductive) functions
Here’s an annoying thing

```ocaml
let rec map (f:int->int) (xs:int list) : int list =
  match xs with
  | [] -> []
  | hd::tl -> (f hd)::(map f tl);;
```

What if I want to increment a list of floats?
Alas, I can’t just call this map. It works on ints!
Here’s an annoying thing

let rec map (f:int->int) (xs:int list) : int list =
    match xs with
    | [] -> []
    | hd::tl -> (f hd)::(map f tl);;

What if I want to increment a list of floats?
Alas, I can’t just call this map. It works on ints!

let rec mapfloat (f:float->float) (xs:float list) :
    float list =
    match xs with
    | [] -> []
    | hd::tl -> (f hd)::(mapfloat f tl);;
let rec map f xs =
  match xs with
  | [] -> []
  | hd::tl -> (f hd)::(map f tl);;
map (fun x -> x + 1) [1; 2; 3; 4] ;;
map (fun x -> x +. 2.0) [3.1415; 2.718; 42.0] ;;
map String.uppercase ["greg"; "victor"; "joe"] ;;
let rec map f xs =
  match xs with
  | [] -> []
  | hd::tl -> (f hd)::(map f tl)
;;

map : ('a -> 'b) -> 'a list -> 'b list
let rec map f xs =
  match xs with
  | [] -> []
  | hd::tl -> (f hd)::(map f tl)
;;

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

We often use greek letters like \(\alpha\) or \(\beta\) to represent type variables.

Read as: for any types 'a and 'b, if you give map a function from 'a to 'b, it will return a function which when given a list of 'a values, returns a list of 'b values.
We can say this explicitly

```ocaml
let rec map (f:'a -> 'b) (xs:'a list) : 'b list =
  match xs with
  | [] -> []
  | hd::tl -> (f hd)::(map f tl)
;;

map : ('a -> 'b) -> 'a list -> 'b list
```

The OCaml compiler is smart enough to figure out that this is the *most general* type that you can assign to the code.

We say map is *polymorphic* in the types 'a and 'b – just a fancy way to say map can be used on any types 'a and 'b.

Java generics derived from ML-style polymorphism (but added after the fact and more complicated due to subtyping)
More realistic polymorphic functions

```ocaml
let rec merge (lt:'a->'a->bool) (xs:'a list) (ys:'a list) : 'a list =
  match (xs,ys) with
  | (=[],_) -> ys
  | (_,[]) -> xs
  | (x::xst, y::yst) ->
    if lt x y then x::(merge lt xst ys)
    else y::(merge lt xs yst) ;;

let rec split (xs:'a list) (ys:'a list) (zs:'a list) : 'a list * 'a list =
  match xs with
  | [] -> (ys, zs)
  | x::rest -> split rest zs (x::ys) ;;

let rec mergesort (lt:'a->'a->bool) (xs:'a list) : 'a list =
  match xs with
  | ([]) | _::[] -> xs
  | _ -> let (first,second) = split xs [] [] in
    merge lt (mergesort lt first) (mergesort lt second) ;;
```
More realistic polymorphic functions

mergesort : ('a->'a->bool) -> 'a list -> 'a list

mergesort (<) [3;2;7;1] == [1;2;3;7]

mergesort (>) [2.718; 3.1415; 42.0] == [42.0 ; 3.1415; 2.718]

mergesort (fun x y -> String.compare x y < 0) [“Hi”; “Bi”] == [“Bi”; “Hi”]

let int_sort = mergesort (<) ;;
let int_sort_down = mergesort (>) ;;
let str_sort =
  mergesort (fun x y -> String.compare x y < 0) ;;
Another Interesting Function

\[
\text{let}\ \text{comp}\ f\ g\ x = f\ (g\ x)\ ;;
\]
\[
\text{let}\ \text{mystery} = \text{comp}\ (\text{add}\ 1)\ \text{square}\ ;;
\]
\[
\text{let}\ \text{comp} = \text{fun}\ f\ ->\ (\text{fun}\ g\ ->\ (\text{fun}\ x\ ->\ f\ (g\ x)))\ ;;
\]
\[
\text{let}\ \text{mystery} = \text{comp}\ (\text{add}\ 1)\ \text{square}\ ;;
\]
\[
\text{let}\ \text{mystery} = \ (\text{fun}\ f\ ->\ (\text{fun}\ g\ ->\ (\text{fun}\ x\ ->\ f\ (g\ x))))\ (\text{add}\ 1)\ \text{square}\ ;;
\]
\[
\text{let}\ \text{mystery} = \ \text{fun}\ x\ ->\ (\text{add}\ 1)\ (\text{square}\ x)\ ;;
\]
\[
\text{let}\ \text{mystery}\ x = \text{add}\ 1\ (\text{square}\ x)\ ;;
\]
What does this program do?

map f (map g [x1; x2; ...; xn])

For each element of the list x1, x2, x3 ... xn, it executes g, creating:

map f ([g x1; g x2; ...; g xn])

Then for each element of the list [g x1, g x2, g x3 ... g xn], it executes f, creating:

[f (g x1); f (g x2); ...; f (g xn)]

Is there a faster way? Yes! (And query optimizers for SQL do it for you.)

map (comp f g) [x1; x2; ...; xn]
map f (map g [x1; x2; ...; xn])

This kind of optimization has a name:

deforestation

(because it eliminates intermediate lists and, um, trees...)

map (comp f g) [x1; x2; ...; xn]
What is the type of comp?

```ocaml
let comp f g x = f (g x) ;;
```
What is the type of comp?

```ocaml
let comp f g x = f (g x) ;;
```

```ocaml
comp : ('b -> 'c) -> ('a -> 'b) -> ('a -> 'c)
```
let rec reduce f u xs =
    match xs with
    | [] -> u
    | hd::tl -> f hd (reduce f u tl);

What’s the most general type of reduce?
How about reduce?

```
let rec reduce f u xs =
    match xs with
    | [] -> u
    | hd::tl -> f hd (reduce f u tl);
```

What’s the most general type of `reduce`?

Based on the patterns, we know `xs` must be a ('a list) for some type 'a.
How about reduce?

```
let rec reduce f u (xs: 'a list) =
   match xs with
   | []  -> u
   | hd::tl -> f hd (reduce f u tl);
```

What’s the most general type of reduce?
let rec reduce f u (xs: 'a list) =
    match xs with
    | [] -> u
    | hd::tl -> f hd (reduce f u tl);;

What’s the most general type of reduce?

f is called so it must be a function of two arguments.
let rec reduce (f:? -> ? -> ?) u (xs: 'a list) =
    match xs with
    | [] -> u
    | hd::tl -> f hd (reduce f u tl);;

What’s the most general type of reduce?
How about reduce?

```ocaml
let rec reduce (f: ? -> ? -> ?) u (xs: 'a list) =
  match xs with
  | []  -> u
  | hd::tl -> f hd (reduce f u tl);
```

What’s the most general type of reduce?

Furthermore, `hd` came from `xs`, so `f` must take an 'a value as its first argument.
let rec reduce (f:'a -> ? -> ?) u (xs: 'a list) =
    match xs with
    | [] -> u
    | hd::tl -> f hd (reduce f u tl);

What’s the most general type of reduce?
let rec reduce (f:'a -> ? -> ?) u (xs: 'a list) =
  match xs with
  | []      -> u
  | hd::tl  -> f hd (reduce f u tl);;

What’s the most general type of `reduce`?

The second argument to `f` must have the same type as the result of `reduce`. Let’s call it 'b.
let rec reduce (f:'a -> 'b -> 'b) u (xs: 'a list) : 'b =
  match xs with
  | [] -> u
  | hd::tl -> f hd (reduce f u tl);

What’s the most general type of reduce?
How about reduce?

```ocaml
define rec reduce (f:'a -> 'b -> 'b) u (xs: 'a list) : 'b =
    match xs with
    | [] -> u
    | hd::tl -> f hd (reduce f u tl);
```

What’s the most general type of reduce?

If `xs` is empty, then `reduce` returns `u`. So `u`’s type must be `'b.`
let rec reduce (f:'a -> 'b -> 'b) (u:'b) (xs: 'a list) : 'b =
  match xs with
  | [] -> u
  | hd::tl -> f hd (reduce f u tl);;

What’s the most general type of reduce?
How about reduce?

```ocaml
let rec reduce (f:'a -> 'b -> 'b) (u:'b) (xs: 'a list) : 'b =
  match xs with
  | [] -> u
  | hd::tl -> f hd (reduce f u tl);;
```

What’s the most general type of reduce?

```
('a -> 'b -> 'b) -> 'b -> 'a list -> 'b
```
NB: map and reduce are already defined in the List library.
   – However, reduce is called “fold_right”.
   – (Good bet there’s a “fold_left” too.)

I’ll use **reduce** instead of **fold_right**, for 3 reasons:
   – Analogy with Google’s Map/Reduce
   – The library’s arguments to fold_right are in the wrong order
   – Makes the example fit on a slide.
Summary

• Map and reduce are two *higher-order functions* that capture very, very common *recursion patterns*

• Reduce is especially powerful:
  – related to the “visitor pattern” of OO languages like Java.
  – can implement most list-processing functions using it, including things like copy, append, filter, reverse, map, etc.

• We can write clear, terse, reusable code by exploiting:
  – higher-order functions
  – anonymous functions
  – first-class functions
  – polymorphism
Using map, write a function that takes a list of pairs of integers, and produces a list of the sums of the pairs.

- e.g., list_add [(1,3); (4,2); (3,0)] = [4; 6; 3]
- Write list_add directly using reduce.

Using map, write a function that takes a list of pairs of integers, and produces their quotient if it exists.

- e.g., list_div [(1,3); (4,2); (3,0)] = [Some 0; Some 2; None]
- Write list_div directly using reduce.

Using reduce, write a function that takes a list of optional integers, and filters out all of the None’s.

- e.g., filter_none [Some 0; Some 2; None; Some 1] = [0;2;1]
- Why can’t we directly use filter? How would you generalize filter so that you can compute filter_none? Alternatively, rig up a solution using filter + map.

Using reduce, write a function to compute the sum of squares of a list of numbers.

- e.g., sum_squares = [3,5,2] = 38