Review

Previously in 3110:
• modules, structures, signatures, abstract types
• aspects of modularity: namespaces, abstraction

Today:
• higher-order usage of modules: functors
• another aspect: code reuse
Review

Structure: a group of related definitions

```
struct
    type 'a t = 'a list
    let push x s = x::s
end
```

Signature: a group of related declarations aka type specifications

```
sig
    type 'a t
    val push : 'a -> 'a t -> 'a t
end
```

Signatures are the types of structures
module type StackSig = sig
    val empty : 'a t
    val push : 'a -> 'a t -> 'a t
    val peek : 'a t -> 'a
end

module MyStack = struct
    type 'a t = Empty | Entry of 'a * 'a t
    let empty = Empty
    let push x s = Entry (x, s)
    let peek = function
        | Empty -> failwith "Empty"
        | Entry(x,_) -> x
end

module ListStack = struct
    type 'a t = 'a list
    let empty = []
    let push x s = x :: s
    let peek = function
        | [] -> failwith "Empty"
        | x::_ -> x
end
Review

Module and module types: bind structures and signatures to names

```ocaml
module type Stack = sig
  type 'a t
  val push : 'a -> 'a t -> 'a t
end

module ListStack : Stack = struct
  type 'a t = 'a list
  let push x s = x::s
end
```
Encapsulation: hide parts of module from clients

```ocaml
module type Stack = sig
  type 'a t
  val push : 'a -> 'a t -> 'a t
end

module ListStack : Stack = struct
  type 'a t = 'a list
  let push x s = x::s
end
```
**Encapsulation:** hide parts of module from clients

```ocaml
module type Stack = sig
  type 'a t
  val push : 'a -> 'a t -> 'a t
end
```

```ocaml
module ListStack : Stack = struct
  type 'a t = 'a list
  let push x s = x :: s
end
```

Type constructor `t` is *abstract*: clients of this signature know the type exists but not what it is.
Review

Encapsulation: hide parts of module from clients

```ocaml
module type Stack = sig
  type 'a t
  val push : 'a -> 'a t -> 'a t
end

module ListStack : Stack = struct
  type 'a t = 'a list
  let push x s = x::s
end
```

module is sealed: all definitions in it except those given in signature Stack are hidden from clients
Question

Consider this code:

```ocaml
datatype Stack =
  { type 'a t
  val empty : 'a t
  val push : 'a -> 'a t -> 'a t
}

module ListStack : Stack =
  { type 'a t = 'a list
  let empty = []
  let push x s = x::s
  }
```

Which of the following expressions will type check?

A. `Stack.empty`
B. `ListStack.push 1 []`
C. `fun (s:ListStack) -> ListStack.push 1 s`
D. All of the above
E. None of the above
Question

Consider this code:

```ocaml
module type Stack =
sig
  type 'a t
  val empty : 'a t
  val push : 'a -> 'a t -> 'a t
end

module ListStack : Stack =
struct
  type 'a t = 'a list
  let empty = []
  let push x s = x::s
end
```

Which of the following expressions will type check?

A. Stack.empty
B. ListStack.push 1 []
C. fun (s:ListStack) -> ListStack.push 1 s
D. All of the above
E. None of the above
INCLUDES
Include a signature

Interface inheritance: reuse code from other signatures

```ocaml
module type Ring = sig
  type t
  val zero : t
  val one : t
  val add : t -> t -> t
  val mult : t -> t -> t
  val neg : t -> t
end

module type Field = sig
  include Ring
  val div : t -> t -> t
end
```
Include a module

Implementation inheritance: reuse code from other structures

```ocaml
module FloatRing = struct
  type t = float
  let zero = 0.
  let one  = 1.
  let add  = (+.)
  let mult = ( *. )
  let neg  = (~-.)
end

module FloatField = struct
  include FloatRing
  let div = (/.)
end
```
Code reuse from includes

• Implementer of one module can rely on code from another module: no need to copy code

• Solves a similar problem as class inheritance in Java
  – but without creating subtype relationships
  – decouples inheritance from subtyping
FUNCTORS

(funk you up?)

Cornell (CS) funk you up:
https://www.youtube.com/watch?v=Au56Ah92Ulk
Higher order structures

• You can write "functions" that manipulate structures
  – take structures as input, return structure as output
  – syntax is a bit different than functions we've seen so far

• These "functions" are called *functors*
  – One of the most advanced features in OCaml
  – A *higher-order module system*
  – Time for some *funky higher-order fun…*
Simple functor

module type X = sig val x : int end

module IncX (M : X) = struct
  let x = M.x + 1
end

module A = struct let x = 0 end
module B = IncX(A) (* B.x is 1 *)
module C = IncX(B) (* C.x is 2 *)

functor: takes structure of type X as input, uses M as the name of that structure in its own body, returns a structure
Alternative functor syntax

Instead of:

```ocaml
module IncX (M : X) = struct
  let x = M.x + 1
end
```

Could write:

```ocaml
def module IncX = functor (M : X) -> struct
  let x = M.x + 1
end
```

Parallels syntax for anonymous functions
Using functor to eliminate duplication

- To test MyStack:

  ```
  assert (MyStack.(empty |> push 1 |> peek) = 1)
  ```

- To test ListStack:

  ```
  assert (ListStack.(empty |> push 1 |> peek) = 1)
  ```

- To test any other stack...

  ```
  assert (WhateverStack.(empty |> push 1 |> peek) = 1)
  ```

- Too much code duplication!
- Especially if you imagine they are large OUnit test suites, not just single assertions
Using functor to eliminate duplication

module StackTester (S:StackSig) = struct
    assert (S.(empty |> push 1 |> peek) = 1)
end

module MyStackTester = StackTester(MyStack)

module ListStackTester = StackTester(ListStack)

StackTester does not define any values: it is not a stack module: this is not Java extension

Can pass ListStack to StackTester even though ListStack not explicitly annotated with :StackSig: this is not Java subtyping
"Extension" with a functor

module type Sig = sig ... end

module Ext (M:Sig) = struct
  include M
  let f = ...
end

(see notes for detailed example)
“Subtyping” with structures

A structure `Struct` matches a signature `Sig` if:

- `Struct` defines every declaration in `Sig`
- The type of each definition in `Struct` meets the requirement for that type in `Sig`
  - Usually, that means they’re the same types
  - But type of definition could be more general than type of declaration, e.g.

```plaintext
module M
  : sig val f : int -> int end
=
  struct let f x = x end
```
STANDARD LIBRARY: MAP
Map

(* maps over totally ordered keys *)

module Map : sig

(* the input type of Make *)
module type OrderedType = sig type t ... end

(* the output type of Make *)
module type S = sig type key ... end

(* functor that makes a module *)
module Make (Ord : OrderedType) : S with type key = Ord.t
end
module type S =

sig

  type key

  type 'a t

  val empty : 'a t

  val mem : key -> 'a t -> bool

  val add : key -> 'a -> 'a t -> 'a t

  ...

end
Map

module type OrderedType = sig
  type t
  val compare : t -> t -> int
end

Must return 0 if equal, negative if first argument is lesser, positive if second argument is lesser
(* maps over totally ordered keys *)
module Map : sig
  (* the input type of Make *)
  module type OrderedType = sig type t ... end

  (* the output type of Make *)
  module type S = sig type key ... end

  (* functor that makes a module *)
  module Make (Ord : OrderedType)
    : S with type key = Ord.t
end

sharing constraint: the output of Make additionally knows that the key type and the OrderedType are the same
module type S with type key = Ord.t = sig
  type key = Ord.t
  type 'a t
  val empty : 'a t
  val mem : key -> 'a t -> bool
  val add : key -> 'a -> 'a t -> 'a t
...
end
Why does this work? The String module already provides a type `t` and a function `compare`.

```ocaml
# module StringMap = Map.Make(String) ;;

module StringMap : sig
  type key = string
  ...
end

# let sm = StringMap.(
  empty |> add "Alice" 4.0 |> add "Bob" 3.7)

# StringMap.find "Bob" sm
- : float = 3.7
```
What if we wanted a map with keys that are int's?
There's no standard library module that gives us a type \( t \) and function `compare` for ints.
So we build our own...

```ocaml
module Int = struct
    type t = int
    let compare = Pervasives.compare
end

module IntMap = Map.Make(Int)
let im = IntMap.(empty |> add 1 "one" |> add 2 "two")
```
What if we wanted a map over records that sorts in a custom order? Again, build our own module...

```ocaml
type name = {first:string; last:string}

module Name = struct
  type t = name
  let compare {first=first1;last=last1}
  {first=first2;last=last2} =
      match Pervasives.compare last1 last2 with
      | 0 -> Pervasives.compare first1 first2
      | c -> c
end

module NameMap = Map.Make(Name)
```

Sort by last name then by first name
let k1 =
   {last="Kardashian"; first="Kourtney"}
let k2 =
   {last="Kardashian"; first="Kimberly"}
let k3 =
   {last="Kardashian"; first="Khloe"}
let k4 =
   {last="West"; first="Kanye"}

let nm = NameMap.(  
   empty   |> add k1 1979   |> add k2 1980   
   |> add k3 1984   |> add k4 1977)
Map

let print_entry {first;last} v
    = print_string (first ^ " " ^ last ^ " : ");
    print_int v;
    print_newline ()

let () = NameMap.iter print_entry nm

Khloe Kardashian: 1984
Kimberly Kardashian: 1980
Kourtney Kardashian: 1979
Kanye West: 1977
Code reuse with Map

• The Map implementer built all the tricky parts of maps: adding keys and values, iterating over them, etc.

• As clients, all we have to provide is a description of our keys and how to sort them; then we get to reuse everything the implementer already built.

• Solves a similar problem as Java does with interfaces+subtyping: see Java's TreeMap constructor that takes a Comparator.

• OCaml's Set module is quite similar to Map in its functorial interface.
Recap

• Functors are "functions" from structures to structures
• Functors make the OCaml module system higher-order
• Functors enable code reuse
Upcoming events

• N/A

This is higher-order funk.

THIS IS 3110