Reminder

The take-home midterm exam has been posted.

You can use any course materials but it is an individual exercise. It is “closed friends” ”closed TAs” and “closed rest of the internet”

See Piazza for instructions on how to download it.

You have 24 hours to do the exam.
The latest start time is Tuesday 11:59PM
The latest end time is Wednesday 11:59PM.
(i.e: like an assignment, hand it in before midnight on Wednesday)
The Reality of Development

We rarely know the *right* algorithms or the *right* data structures when we start a design project.

  – When implementing a search engine, what data structures and algorithms should you use to build the index? To build the query evaluator?

Reality is that *we often have to go back and change our code*, once we’ve built a prototype.

  – Often, we don’t even know what the *user wants* (requirements) until they see a prototype.

  – Often, we don’t know where the *performance problems* are until we can run the software on realistic test cases.

  – Sometimes we just want to change the design -- come up with *simpler* algorithms, architecture later in the design process.
Given that we know the software will change, how can we write the code so that doing the changes will be easier?
Given that we know the software will change, how can we write the code so that doing the changes will be easier?

The primary trick: use *data and algorithm abstraction*. 
Given that we know the software will change, how can we write the code so that doing the changes will be easier?

The primary trick: use *data and algorithm abstraction*.  
- *Don’t* code in terms of *concrete representations* that the language provides.  
- *Do* code with *high-level abstractions* in mind that fit the problem domain.  
- Implement the abstractions using a *well-defined interface*.  
- Swap in *different implementations* for the abstractions.  
- *Parallelize* the development process.
Example

Goal: Implement a query engine.

Requirements: Need a scalable *dictionary* (a.k.a. index)

- maps words to *set* of URLs for the pages on which words appear.
- want the index so that we can efficiently satisfy queries
  - e.g., all links to pages that contain “Dave” and “Jill”.

Wrong way to think about this:

- Aha! A *list* of pairs of a word and a *list* of URLs.
- We can look up “Dave” and “Jill” in the *list* to get back a *list* of URLs.
Example

```ml
type query =
  Word of string
| And of query * query
| Or of query * query

type index = (string * (url list)) list

let rec eval (q:query) (h:index) : url list =
  match q with
  | Word x ->
    let (_,urls) = List.find (fun (w,urls) -> w = x) h in
    urls
  | And (q1,q2) ->
    merge_lists (eval q1 h) (eval q2 h)
  | Or (q1,q2) ->
    (eval q1 h) @ (eval q2 h)
```
Example

type query =
    Word of string
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        urls
    | And (q1,q2) ->
        merge_lists (eval q1 h) (eval q2 h)
    | Or (q1,q2) ->
        (eval q1 h) @ (eval q2 h)

merge expects to be passed sorted lists.
**Example**

```ocaml
type query =  
  Word of string  
| And of query * query  
| Or of query * query

type index = (string * (url list)) list

let rec eval (q:query) (h:index) : url list =  
  match q with  
  | Word x ->  
      let (_,urls) = List.find (fun (w,urls) -> w = x) in 
      urls  
  | And (q1,q2) ->  
      merge_lists (eval q1 h) (eval q2 h)  
  | Or (q1,q2) ->  
      (eval q1 h) @ (eval q2 h)
```

*merge expects to be passed sorted lists.*

Oops!
I find out there's a better hashtable implementation.

type query =
    Word of string
  | And of query * query
  | Or of query * query

type index = string (url list) hashtable

let rec eval (q:query) (h:index) : url list =
  match q with
  | Word x ->
      let i = hash_string x in
      let l = Array.get h [i] in
      let urls = assoc_list_find l x in
      urls
  | And (q1,q2) -> ...
  | Or (q1,q2) -> ...
type query =
  Word of string
| And of query * query
| Or of query * query

type index = string url_set dictionary

let rec eval(q:query)(d:index) : url_set =
  match q with
  | Word x -> Dict.lookup d x
  | And (q1,q2) -> Set.intersect (eval q1 h) (eval q2 h)
  | Or (q1,q2) -> Set.union (eval q1 h) (eval q2 h)
The problem domain talked about an abstract type of *dictionaries* and *sets of URLs*.

```ocaml
let rec eval (q:query) (d:index) : url_set =
  match q with
  | Word x -> Dict.lookup d x
  | And (q1,q2) -> Set.intersect (eval q1 h) (eval q2 h)
  | Or (q1,q2) -> Set.union (eval q1 h) (eval q2 h)
```
The problem domain talked about an abstract type of dictionaries and sets of URLs.

Once we’ve written the client, we know what operations we need on these abstract types.
A Better Way

The problem domain talked about an abstract type of *dictionaries* and *sets of URLs*.

Once we’ve written the client, we know what operations we need on these abstract types.

Later on, when we find out linked lists aren’t so good for sets, we can replace them with balanced trees.

So we can define an interface, and send a pal off to implement the *abstract types* dictionary and set.
Abstract Data Types

Barbara Liskov
Assistant Professor, MIT
1973

Invented CLU language that enforced data abstraction

Barbara Liskov
Professor, MIT
Turing Award 2008

“For contributions to practical and theoretical foundations of programming language and system design, especially related to data abstraction, fault tolerance, and distributed computing.”
OCaml has mechanisms for building new abstract data types:

- **signature**: an interface.
  - specifies the abstract type(s) without specifying their implementation
  - specifies the set of operations on the abstract types

- **structure**: an implementation.
  - a collection of type and value definitions
  - notion of an implementation matching or satisfying an interface
    - gives rise to a notion of sub-typing

- **functor**: a parameterized module
  - really, a function from modules to modules
  - allows us to factor out and re-use modules
The Abstraction Barrier

Rule of thumb: Use the language to enforce the abstraction barrier.

- Reveal little information about *how* something is implemented
- Provide maximum flexibility for change moving forward.
- Murphy’s Law: What is not enforced, will be broken

But rules are meant to broken: Exercise judgement.

- may want to reveal more information for debugging purposes
  - eg: conversion to string so you can print things out

ML gives you precise control over how much of the type is left abstract

- different amounts of information can be revealed in different contexts
- type checker helps you detect violations of the abstraction barrier
Recall assignment #2:

**query.ml**

```ml
type movie = { ... };

let sort_by_studio = ...
let sort_by_year = ...
```

**main.ml**

```ml
open Io
open Query

let main () = ...
let _ = main ()
```
Simple Modules

Recall assignment #2:

```
query.ml

type movie = { ... }
let sort_by_studio = ...
let sort_by_year = ...
```

```
main.ml

open Io
open Query
let main () = ... sort_by_studio ...
let _ = main ()
```

Each .ml file actually defines an ML module.

Convention: the file foo.ml or Foo.ml defines the module named Foo.
Recall assignment #2:

**query.ml**

```ml
type movie = { ... };
let sort_by_studio = ...;
let sort_by_year = ...;
```

**main.ml**

```ml
open Io;
open Query;
let main () = ... sort_by_studio ...;
let _ = main ();
```
Simple Modules

Recall assignment #2:

query.ml

```ml
type movie = { ... }
let sort_by_studio = ...
let sort_by_year = ...
```

main.ml

```ml
open Io
open Query
let main () =
... Query.sort_by_studio ...
```

Can refer to module components using dot notation
Simple Modules

query.ml

```ml
type movie = { ... }
let sort_by_studio = ...
let sort_by_year = ...
```

main.ml

```ml
open Io
open Query
let main () =
... Query.sort_by_studio ...
```

query.mli

```ml
type movie

val sort_by_studio : movie list -> movie list
val sort_by_year : movie list -> movie list
```

You can add interface files (.mli) (also called *signatures* in ML)

These interfaces can hide module components or render types abstract.
**Simple Modules**

query.ml

```ml
type movie = { ... }

let sort_by_studio = ...
let sort_by_year = ...
```

main.ml

```ml
open Io
open Query

let main () =
    ...
    Query.sort_by_studio ...
```

query.mli

```ml
type movie

val sort_by_studio : movie list -> movie list
val sort_by_year : movie list -> movie list
```

If you have no signature file, then the default signature is used: all components are fully visible to clients.
Simple Modules

Simple summary:

– file Name.ml is a *structure* implementing a module named Name
– file Name.mli is a *signature* for the module named Name
  • if there is no file Name.mli, OCaml infers the default signature
At first glance: OCaml modules = C modules?

C has:
- .h files (signatures) similar to .mli files?
- .c files (structures) similar to .ml files?

But ML also has:
- tighter control over type abstraction
  - define abstract, transparent or translucent types in signatures
    - i.e.: give none, all or some of the type information to clients
- more structure
  - modules can be defined within modules
  - i.e.: signatures and structures can be defined inside files
- more reuse
  - multiple modules can satisfy the same interface
  - the same module can satisfy multiple interfaces
  - modules take other modules as arguments (functors)
- fancy features: dynamic, first class modules
module type INT_STACK =

  sig
    type stack
    val empty : unit -> stack
    val push : int -> stack -> stack
    val is_empty : stack -> bool
    val pop : stack -> stack
    val top : stack -> int option
  end
module type INT_STACK =

  sig
    type stack
    val empty : unit -> stack
    val push : int -> stack -> stack
    val is_empty : stack -> bool
    val pop : stack -> stack option
    val top : stack -> int option
  end

empty and push are abstract constructors: functions that build our abstract type.
module type INT_STACK =
  sig
    type stack
    val empty : unit -> stack
    val push : int -> stack -> stack
    val is_empty : stack -> bool
    val pop : stack -> stack
    val top : stack -> int option
  end

is_empty is an observer – useful for determining properties of the ADT.
module type INT_STACK =

sig

  type stack
  val empty : unit -> stack
  val push : int -> stack -> stack
  val is_empty : stack -> bool
  val pop : stack -> stack
  val top : stack -> int option

end

pop is sometimes called a mutator (though it doesn’t really change the input)
module type INT_STACK =

sig

  type stack

  val empty : unit -> stack

  val push : int -> stack -> stack

  val is_empty : stack -> bool

  val pop : stack -> stack

  val top : stack -> int option

end

*top* is also an *observer*, in this functional setting since it doesn’t change the stack.
module type INT_STACK =
  sig
    type stack

    (* create an empty stack *)
    val empty : unit -> stack

    (* push an element on the top of the stack *)
    val push : int -> stack -> stack

    (* returns true iff the stack is empty *)
    val is_empty : stack -> bool

    (* pops top element off the stack; returns empty stack if the stack is empty *)
    val pop : stack -> stack

    (* returns the top element of the stack; returns None if the stack is empty *)
    val top : stack -> int option
  end
Signature Comments

Signature comments are for clients of the module

- explain what each function should do
  - how it manipulates abstract values (stacks)
- *not* how it manipulates concrete values
- don’t reveal implementation details that should be hidden behind the abstraction

Don’t copy signature comments into your structures

- your comments will get out of date in one place or the other
- an extension of the general rule: don’t copy code

Place implementation comments inside your structure

- comments about implementation invariants hidden from client
- comments about helper functions
Module List

module List: sig . . end

List operations.

Some functions are flagged as not tail-recursive. A tail-recursive function uses constant stack space, while a non-tail-recursive function uses stack space proportional to the length of its list argument, which can be a problem with very long lists. When the function takes several list arguments, an approximate formula giving stack usage (in some unspecified constant unit) is shown in parentheses.

The above considerations can usually be ignored if your lists are not longer than about 10000 elements.

val length : 'a list -> int
Return the length (number of elements) of the given list.

val compare_lengths : 'a list -> 'b list -> int
Compare the lengths of two lists. compare_lengths \( l_1 \) \( l_2 \) is equivalent to compare (length \( l_1 \)) (length \( l_2 \)), except that the computation stops after iterating on the shortest list.
Since 4.05.0

val compare_length_with : 'a list -> int -> int
Compare the length of a list to an integer. compare_length_with \( l \) \( n \) is equivalent to compare (length \( l \)) \( n \), except that the computation stops after at most \( n \) iterations on the list.
Since 4.05.0

val cons : 'a -> 'a list -> 'a list
cons \( x \) \( xs \) is \( x :: xs \)
Since 4.03.0

val hd : 'a list -> 'a
Return the first element of the given list. Raise Failure "hd" if the list is empty.

val tl : 'a list -> 'a list
Return the given list without its first element. Raise Failure "tl" if the list is empty.

val nth : 'a list -> int -> 'a
Return the \( n \)-th element of the given list. The first element (head of the list) is at position 0. Raise Failure "nth" if the list is too short. Raise Invalid_argument "List.nth" if \( n \) is negative.

val nth_opt : 'a list -> int -> 'a option
Return the \( n \)-th element of the given list. The first element (head of the list) is at position 0. Return None if the list is too short. Raise Invalid_argument "List.nth" if \( n \) is negative.
Since 4.05

val rev : 'a list -> 'a list
module ListIntStack : INT_STACK =
  struct
    type stack = int list
  let empty () : stack = []
  let push (i:int) (s:stack) : stack = i::s
  let is_empty (s:stack) =
    match s with
    | [] -> true
    | _:::_ -> false
  let pop (s:stack) : stack =
    match s with
    | [] -> []
    | _::t -> t
  let top (s:stack) : int option =
    match s with
    | [] -> None
    | h::_ -> Some h
end
Inside the module, we know the **concrete type** used to implement the abstract type.

```ocaml
module ListIntStack : INT_STACK =
  struct
    type stack = int list
    let empty () : stack = []
    let push (i:int) (s:stack) = i::s
    let is_empty (s:stack) =
      match s with
      | [] -> true
      | _:::_ -> false
    let pop (s:stack) : stack =
      match s with
      | [] -> []
      | _::t -> t
    let top (s:stack) : int option =
      match s with
      | [] -> None
      | h::_ -> Some h
  end
```
module ListIntStack : INT_STACK =

struct
  type stack = int list
  let empty () : stack = []
  let push (i:int) (s:stack) = i::s
  let is_empty (s:stack) =
    match s with
    | [] -> true
    | _::_ -> false
  let pop (s:stack) : stack =
    match s with
    | [] -> []
    | _::t -> t
  let top (s:stack) : int option =
    match s with
    | [] -> None
    | h::_ -> Some h
end

But by giving the module the INT_STACK interface, which does not reveal how stacks are being represented, we prevent code outside the module from knowing stacks are lists.
module ListIntStack : INT_STACK =
    struct
        ...
    end

let s0 = ListIntStack.empty ()
let s1 = ListIntStack.push 3 s0
let s2 = ListIntStack.push 4 s1
let x = ListIntStack.top s2
module ListIntStack : INT_STACK =

struct
  ...
end

let s0 = ListIntStack.empty ()
let s1 = ListIntStack.push 3 s0
let s2 = ListIntStack.push 4 s1
let x = ListIntStack.top s2

s0 : ListIntStack.stack
s1 : ListIntStack.stack
s2 : ListIntStack.stack
module ListIntStack : INT_STACK =
    struct
        ...
    end

let s0 = ListIntStack.empty ()
let s1 = ListIntStack.push 3 s0
let s2 = ListIntStack.push 4 s1
let x = ListIntStack.top s2
x : option int = Some 4
module ListIntStack : INT_STACK =
  struct
    ...
  end

let s0 = ListIntStack.empty ()
let s1 = ListIntStack.push 3 s0
let s2 = ListIntStack.push 4 s1
let x = ListIntStack.top s2
x : option int = Some 4
let x = ListIntStack.top (ListIntStack.pop s2)
x : option int = Some 3
module ListIntStack : INT_STACK =
    struct
        ...
    end

let s0 = ListIntStack.empty ()
let s1 = ListIntStack.push 3 s0
let s2 = ListIntStack.push 4 s1
let x = ListIntStack.top s2
x : option int = Some 4
let x = ListIntStack.top (ListIntStack.pop s2)
x : option int = Some 3
open ListIntStack
module ListIntStack : INT_STACK =
    struct
        ...
    end

let s0 = ListIntStack.empty ()
let s1 = ListIntStack.push 3 s0
let s2 = ListIntStack.push 4 s1
let x = ListIntStack.top s2
x : option int = Some 4
let x = ListIntStack.top (ListIntStack.pop s2)
x : option int = Some 3
open ListIntStack
let x = top (pop (pop s2))
x : option int = None
An Example Client

module type INT_STACK =
  sig
    type stack
    val push : int -> stack -> stack
    ...
  end
module ListIntStack : INT_STACK

let s2 = ListIntStack.push 4
...
List.rev s2

Error: This expression has type stack but an expression was expected of type 'a list.

Notice that the client is not allowed to know that the stack is a list.
module ListIntStack (* : INT_STACK *) =
  struct
    type stack = int list
  let empty () : stack = []
  let push (i:int) (s:stack) = i::s
  let is_empty (s:stack) =
    match s with
    | [] -> true
    | _:::_ -> false
  exception EmptyStack
  let pop (s:stack) =
    match s with
    | [] -> []
    | _::t -> t
  let top (s:stack) =
    match s with
    | [] -> None
    | h::_ -> Some h
end

Note that when you are debugging, you may want to comment out the signature ascription so that you can access the contents of the module.
The Client without the Signature

module ListIntStack (* : INT_STACK *) =
  struct
    ...
  end

let s = ListIntStack.empty()
let s1 = ListIntStack.push 3 s
let s2 = ListIntStack.push 4 s1
...
let x = List.rev s2
x : int list = [3; 4]

If we don’t seal the module with a signature, the client can know that stacks are lists.
When you put the signature on here, you are restricting client access to the information in the signature (which does not reveal that stack = int list.) So clients can only use the stack operations on a stack value (not list operations.)
Another technique:
Add testing components to your signature.
Or have 2 signatures, one for testing and one for the rest of the code)
DESIGN CHOICES FOR CORNER CASES
module type INT_STACK =
  sig
    type stack
    (* create an empty stack *)
    val empty : unit -> stack

    (* push an element on the top of the stack *)
    val push : int -> stack

    (* returns true if the stack is empty *)
    val is_empty : stack -> bool

    (* pops top element off the stack; returns empty stack if the stack is empty *)
    val pop : stack -> stack

    (* returns the top element of the stack; returns None if the stack is empty *)
    val top : stack -> int option
  end

Is this a good idea?
Design choices

sig
  type stack
  (* pops top element;
     returns empty if empty *)
  val pop : stack -> stack
end

sig
  type stack
  (* pops top element;
     returns arbitrary stack if empty *)
  val pop : stack -> stack
end

sig
  type stack
  (* pops top element;
     returns option *)
  val pop : stack -> stack option
end

sig
  type stack
  exception EmptyStack
  (* pops top element;
     raises EmptyStack if empty *)
  val pop : stack -> stack
end
For some functions, there are some input values outside the domain of the function & the domain is not easily described by a simple type.

Say the function returns an arbitrary result on those inputs.

When proving things about the program, there’s an extra proof obligation: Prove that the input is in the domain of the function.
For some functions, there are some input values outside the \textit{domain} of the function & the domain is not easily described by a simple type.

Say the function returns an arbitrary result on those inputs.

When proving things about the program, there’s an extra proof obligation: Prove that the input is in the domain of the function.

But when a programmer forgets to do this proof (or makes a mistake), such silent errors can be hard to track down.
Design choices

For some functions, there are some input values outside the domain of the function.

This is not completely crazy. One might still be able to guarantee that the input is always in the domain of the function.

It’s what the C language does, for example.

```
sig
  type stack
  (* pops top element; crashes the program if empty *)
  val pop : stack -> stack
end
```
For some functions, there are some input values outside the *domain* of the function.

This is not *completely* crazy. One might still be able to guarantee that the input is always in the domain of the function.

It’s what the C language does, for example.

But it’s *almost completely* crazy. This is the biggest source of security vulnerabilities ever. It’s why the hackers can drive your car, steal your money, read your e-mails, ...
Design choices

It’s also reasonable to say the function returns a specified, convenient, result on those inputs. This is pretty much the same thing, in practice.

Consider: If supplying an empty stack to pop is probably a mistake on the part of the caller, it is better to stop the program right away (by raising an exception) than to let the error silently slip by. In the long run, finding the real error is tougher.
Design choices

For some functions, there are some input values outside the *domain* of the function.

That’s what exceptions are for! Raise an exception for values not in the domain.

```ml
sig
  type stack
  exception EmptyStack
  (* pops top element; raises EmptyStack if empty *)
  val pop : stack -> stack
end
```
Finally, you can just use option types in the obvious way.

Using an option has the advantage of forcing the caller to consider what to do on the “error” condition every time the function is called. They can’t forget to handle this situation.

```plaintext
sig
  type stack
  (* pops top element;  
     returns option *)
  val pop:  
    stack -> stack option
end
```
All of these are reasonable design choices!
Design choices

All of these are reasonable design choices!

But use these two with extreme care

But use the bottom two are more common. Options are the “safest.” They force consideration of the error condition every time.
ANOTHER EXAMPLE
module type QUEUE =
  sig
    type 'a queue
    val empty : unit -> 'a queue
    val enqueue : 'a -> 'a queue -> 'a queue
    val is_empty : 'a queue -> bool
    exception EmptyQueue
    val dequeue : 'a queue -> 'a queue
    val front : 'a queue -> 'a
  end
module type QUEUE =

sig
  type 'a queue
  val empty : unit -> 'a queue
  val enqueue : 'a -> 'a queue -> 'a queue
  val is_empty : 'a queue -> bool
  exception EmptyQueue
  val dequeue : 'a queue -> 'a queue
  val front : 'a queue -> 'a
end

These queues are re-usable for different element types.

Here's an exception that client code might want to catch.
module AppendListQueue : QUEUE =
  struct
    type 'a queue = 'a list
    let empty() = []
    let enqueue(x:'a)(q:'a queue) : 'a queue = q @ [x]
    let is_empty(q:'a queue) =
      match q with
      | [] -> true
      | _:::_ -> false

    ...
  end
module AppendListQueue : QUEUE =

  struct
    type 'a queue = 'a list
    let empty() = []
    let enqueue(x:'a)(q:'a queue) : 'a queue = q @ [x]
    let is_empty(q:'a queue) = ...

  exception EmptyQueue
  let deq(q:'a queue) : ('a * 'a queue) =
    match q with
    | [] -> raise EmptyQueue
    | h::t -> (h,t)
  let dequeue(q:'a queue) : 'a queue = snd (deq q)
  let front(q:'a queue) : 'a = fst (deq q)
  end
module AppendListQueue : QUEUE =

    struct
        type 'a queue = 'a list
        let empty() = []
        let enqueue(x:'a)(q:'a queue) : 'a queue = q @ [x]
        let is_empty(q:'a queue) = ...

    exception EmptyQueue

    let deq(q:'a queue) : ('a * 'a queue) =
        match q with
        | [] -> raise EmptyQueue
        | h::t -> (h,t)

    let dequeue(q:'a queue) : 'a queue = snd (deq q)
    let front(q:'a queue) : 'a = fst (deq q)

end

Notice deq is a helper function that doesn’t show up in the signature.

You can't use it outside the module.
module AppendListQueue : QUEUE =

struct
    type 'a queue = 'a list
    let empty() = []
    let enqueue(x:'a)(q:'a queue) : 'a queue = q @ [x]
    let is_empty(q:'a queue) = ...

exception EmptyQueue

let deq(q:'a queue) : ('a * 'a queue) =
    match q with
    | [] -> raise EmptyQueue
    | h::t -> (h,t)

let dequeue(q:'a queue) : 'a queue = snd (deq q)
let front(q:'a queue) : 'a = fst (deq q)
end

Dequeue runs in constant time 😊
enqueue takes time proportional to the length of the queue 😞
module DoubleListQueue : QUEUE =
    struct
        type 'a queue = {front:'a list; rear:'a list}
    end
In Pictures

abstraction

\[ \text{a, b, c, d, e} \]

implementation

\[ \{ \text{front=[a; b]; rear=[e; d; c]} \} \]

```
let q0 = empty {front=[]; rear=[]}
let q1 = enqueue 3 q0 {front=[]; rear=[3]}
let q2 = enqueue 4 q1 {front=[]; rear=[4; 3]}
let q3 = enqueue 5 q2 {front=[]; rear=[5; 4; 3]}
let q4 = dequeue q3 {front=[4; 5]; rear=[]}
let q5 = dequeue q4 {front=[5]; rear=[]}
let q6 = enqueue 6 q5 {front=[5]; rear=[6]}
let q7 = enqueue 7 q6 {front=[5]; rear=[7; 6]}
```
module DoubleListQueue : QUEUE =

  struct
    type 'a queue = {front:'a list;
                    rear:'a list}
    let empty() = {front=[]; rear=[]}

    let enqueue x q = {front=q.front; rear=x::q.rear}

    let is_empty q =
      match q.front, q.rear with
      | [], [] -> true
      | _, _ -> false

    ...
  end
module DoubleListQueue : QUEUE =

struct
  type 'a queue = {front:'a list;
                  rear:'a list}

exception EmptyQueue

let deq (q:'a queue) : 'a * 'a queue =
  match q.front with
  | h::t -> (h, {front=t; rear=q.rear})
  | [] -> match List.rev q.rear with
         | h::t -> (h, {front=t; rear=[]})
         | [] -> raise EmptyQueue

let dequeue (q:'a queue) : 'a queue = snd(deq q)
let front (q:'a queue) : 'a = fst(deq q)
end

dequeue runs in amortized constant time 😊
How would we design an abstraction?

Think:

- what data do you want?
  - define some types for your data
- what operations on that data do you want?
  - define some types for your operations

Write some test cases:

- example data, operations

From this, we can derive a signature

- list the types
- list the operations with their types
- don’t forget to provide enough operations that you can debug!

Then we can build an implementation

- when prototyping, build the simplest thing you can.
- later, we can swap in a more efficient implementation.
- (assuming we respect the abstraction barrier.)
The stack and queue interfaces are quite similar:

```ocaml
module type STACK =
  sig
    type 'a stack
    val empty : unit -> 'a stack
    val push : int -> 'a stack -> 'a stack
    val is_empty : 'a stack -> bool
    exception EmptyStack
    val pop : 'a stack
    val top : 'a stack
  end

module type QUEUE =
  sig
    type 'a queue
    val empty : unit -> 'a queue
    val enqueue : 'a -> 'a queue -> 'a queue
    val is_empty : 'a queue -> bool
    exception EmptyQueue
    val dequeue : 'a queue
    val front : 'a queue -> 'a
  end
```
It’s a good idea to factor out patterns

Stacks and Queues share common features.

Both can be considered “containers”

Create a reuseable container interface!

```ocaml
module type CONTAINER =
  sig
    type 'a t
    val empty : unit -> 'a t
    val insert : 'a -> 'a t -> 'a t
    val is_empty : 'a t -> bool
    exception Empty
    val remove : 'a t -> 'a t
    val first : 'a t -> 'a
  end
```
It’s a good idea to factor out patterns

module type CONTAINER = sig ... end

module Queue : CONTAINER = struct ... end
module Stack : CONTAINER = struct ... end

module DepthFirstSearch : SEARCHER =
  struct
    type to_do : Graph.node Stack.t
  end

module BreadthFirstSearch : SEARCHER =
  struct
    type to_do : Graph.node Queue.t
  end

Still repeated code!
Breadth-first and depth-first search code is the same!
Just use different containers!
Need parameterized modules!
FUNCTORS

David MacQueen
Bell Laboratories 1983-2001
U. of Chicago 2001-2012

Designer of ML module system, functors, sharing constraints, etc.
Suppose I ask you to write a generic package for matrices.
   – e.g., matrix addition, matrix multiplication

The package should be *parameterized* by the element type.
   – Matrix elements may be ints or floats or complex ...
   – And the elements still have a collection of operations on them:
     • addition, multiplication, zero element, etc.

What we'll see:
   – **RING**: a signature for matrix elements
   – **MATRIX**: a signature for operations on matrices
   – **DenseMatrix**: a functor that will generate a MATRIX with a specific RING as an element type
module type RING =

  sig
    type t
    val zero : t
    val one : t
    val add : t -> t -> t
    val mul : t -> t -> t
  end
Some Rings

module IntRing =
  struct
    type t = int
    let zero = 0
    let one = 1
    let add x y = x + y
    let mul x y = x * y
  end

module FloatRing =
  struct
    type t = float
    let zero = 0.0
    let one = 1.0
    let add = (+.)
    let mul = ( *. )
  end

module BoolRing =
  struct
    type t = bool
    let zero = false
    let one = true
    let add x y = x || y
    let mul x y = x && y
  end
module type MATRIX =
  sig
  type elt
  type matrix
  val matrix_of_list : elt list list -> matrix
  val add : matrix -> matrix -> matrix
  val mul : matrix -> matrix -> matrix
  end
module DenseMatrix (R:RING) : (MATRIX with type elt = R.t) =
struct
  ...
end
The DenseMatrix Functor

module DenseMatrix (R:RING) : (MATRIX with type elt = R.t) =

struct...

end

Argument R must be a RING
Result must be a MATRIX
Specify Result.elt = R.t
module DenseMatrix (R:RING) : (MATRIX with type elt = R.t) =
struct
  ...
end

module IntMatrix = DenseMatrix(IntRing)
module FloatMatrix = DenseMatrix(FloatRing)
module BoolMatrix = DenseMatrix(BoolRing)
The Type of IntMatrix

module DenseMatrix (R:RING) : (MATRIX with type elt = R.t) =
struct ... end

module IntMatrix = DenseMatrix(IntRing)

What is the signature of IntMatrix?
module DenseMatrix (R:RING) : (MATRIX with type elt = R.t) =
struct ... end

module IntMatrix = DenseMatrix(IntRing)

What is the signature of IntMatrix?

It depends on both the signatures of DenseMatrix and of its argument IntRing.
The Type of IntMatrix

module DenseMatrix (R:RING) : (MATRIX with type elt = R.t) =
struct ... end

module IntMatrix = DenseMatrix(IntRing)

module type MATRIX =
sig
  type elt
  type matrix
  val matrix_of_list : elt list list -> matrix
  val add : matrix -> matrix -> matrix
  val mul : matrix -> matrix -> matrix
end

type elt = R.t
The Type of IntMatrix

module DenseMatrix (R:RING) : (MATRIX with type elt = R.t) =
struct ... end

module IntMatrix = DenseMatrix(IntRing)

module type MATRIX =
sig
  type elt
  type matrix
  val matrix_of_list : elt list list -> matrix
  val add : matrix -> matrix -> matrix
  val mul : matrix -> matrix -> matrix
end

module IntRing =
struct
  type t = int
  let zero = 0
  ...
end

Recall:
The Type of IntMatrix

module DenseMatrix (R:RING) : (MATRIX with type elt = R.t) =
struct ... end

module IntMatrix = DenseMatrix(IntRing)

module type MATRIX =
sig
type elt
type matrix
val matrix_of_list : elt list list -> matrix
val add : matrix -> matrix -> matrix
val mul : matrix -> matrix -> matrix
end

module type MATRIX =
sig
type elt = int
type matrix
...
end

module IntRing =
struct
type t = int
...
end
module DenseMatrix (R:RING) : (MATRIX with type elt = R.t) =

struct

...

end

module IntMatrix = DenseMatrix(IntRing)
module FloatMatrix = DenseMatrix(FloatRing)
module BoolMatrix = DenseMatrix(BoolRing)
module DenseMatrix (R:RING) : (MATRIX with type elt = R.t) =
struct
...
end

module type MATRIX =
sig
  type elt
  type matrix

  val matrix_of_list : elt list list -> matrix
  val add : matrix -> matrix -> matrix
  val mul : matrix -> matrix -> matrix
end

module IntMatrix = DenseMatrix(IntRing)
module FloatMatrix = DenseMatrix(FloatRing)
module BoolMatrix = DenseMatrix(BoolRing)
module DenseMatrix (R:RING) : (MATRIX with type elt = R.t) =
  struct
  module type MATRIX =
    sig
      type elt
      type matrix

      val matrix_of_list : elt list list list -> matrix

      val add : matrix -> matrix -> matrix
      val mul : matrix -> matrix -> matrix
    end
  end

module IntMatrix = DenseMatrix(IntRing)
module FloatMatrix = DenseMatrix(FloatRing)
module BoolMatrix = DenseMatrix(BoolRing)
The DenseMatrix Functor

```plaintext
module DenseMatrix (R:RING) : (MATRIX with type elt = R.t) =
struct
  ...
end

module type MATRIX =
sig
  type elt = int
  type matrix

  val matrix_of_list : elt list list -> matrix
  val add : matrix -> matrix -> matrix
  val mul : matrix -> matrix -> matrix
end

module IntMatrix = DenseMatrix(IntRing)
module FloatMatrix = DenseMatrix(FloatRing)
module BoolMatrix = DenseMatrix(BoolRing)
```

- **sharing constraint**: known to be int when R.t = int like when R = IntRing
- **list of list of ints**: elt list list -> matrix
- **known to be int when R.t = int like when R = IntRing**: elt list list -> matrix
- **module type MATRIX**
  - type elt = int
  - type matrix
  - val matrix_of_list : elt list list -> matrix
  - val add : matrix -> matrix -> matrix
  - val mul : matrix -> matrix -> matrix

```
The DenseMatrix Functor

module DenseMatrix (R:RING) : (MATRIX with type elt = R.t) =
struct

The "with" clause makes IntMatrix.elt equal to int -- we can build a matrix from any int list list

module type MATRIX =
sig
  type elt = int
  type matrix

  val matrix_of_list : elt list list -> matrix

  val add : matrix -> matrix -> matrix
  val mul : matrix -> matrix -> matrix
end

module IntMatrix = DenseMatrix(IntRing)
module FloatMatrix = DenseMatrix(FloatRing)
module BoolMatrix = DenseMatrix_BoolRing

sharing constraint

known to be int when R.t = int like when R = IntRing

list of list of ints
Matrix Functor

module DenseMatrix (R:RING) : (MATRIX with type elt = R.t) =
struct
  type elt = ...
  type matrix = ...
  let matrix_of_list = ...
  let add m1 m2 = ...
  let mul m1 m2 = ...
end

To define a functor, just write down a module as its body.

That module has to match the result signature (MATRIX).

This module may refer to the functor arguments, like R.

module IntMatrix = DenseMatrix(IntRing)
module FloatMatrix = DenseMatrix(FloatRing)
module BoolMatrix = DenseMatrix(BoolRing)
module DenseMatrix (R:RING) : (MATRIX with type elt = R.t) =
struct
  type elt = R.t
  type matrix = (elt list) list
let matrix_of_list rows = rows
let add m1 m2 =
  List.map (fun (r1,r2) ->
    List.map (fun (e1,e2) -> R.add e1 e2))
    (List.combine r1 r2))
  (List.combine m1 m2)
let mul m1 m2 = (* good exercise *)
end

module IntMatrix = DenseMatrix(IntRing)
module FloatMatrix = DenseMatrix(FloatRing)
module BoolMatrix = DenseMatrix(BoolRing)
ANONYMOUS STRUCTURES
module type UNSIGNED_BIGNUM =

sig
  type ubignum
  val fromInt : int -> ubignum
  val toInt : ubignum -> int
  val plus : ubignum -> ubignum -> ubignum
  val minus : ubignum -> ubignum -> ubignum
  val times : ubignum -> ubignum -> ubignum
...
end
module My_UBignum_1000 : UNSIGNED_BIGNUM =
struct
    let base = 1000

type ubignum = int list

let toInt(b:ubignum):int = ...

let plus(b1:ubignum)(b2:ubignum):ubignum = ...

let minus(b1:ubignum)(b2:ubignum):ubignum = ...

let times(b1:ubignum)(b2:ubignum):ubignum = ...
...
end

What if we want to change the base? Binary? Hex? 2^32? 2^64?
module type BASE =
  sig
    val base : int
  end

module UbignumGenerator(Base:BASE) : UNSIGNED_BIGNUM =
  struct
    type ubignum = int list
    let toInt(b:ubignum):int =
      List.fold_left (fun a c -> c*Base.base + a) 0 b ...
  end

module Ubignum_10 =
  UbignumGenerator(struct let base = 10 end) ;;

module Ubignum_2 =
  UbignumGenerator(struct let base = 2 end) ;;
SIGNATURE SUBTYPING
A module matches any interface as long as it provides \textit{at least} the definitions (of the right type) specified in the interface.

But as we saw earlier, the module can have more stuff.
- e.g., the \texttt{deq} function in the \texttt{Queue} modules

Basic principle of subtyping for modules:
- wherever you are expecting a module with signature \texttt{S}, you can use a module with signature \texttt{S'}, as long as all of the stuff in \texttt{S} appears in \texttt{S'}.
- That is, \texttt{S'} is a bigger interface.
module type GROUP =
   sig
   type t
   val zero : t
   val add : t → t → t
   end
module type RING =
   sig
   type t
   val zero : t
   val one : t
   val add : t → t → t
   val mul : t → t → t
   end
module IntGroup : GROUP = IntRing
module FloatGroup : GROUP = FloatRing
module BoolGroup : GROUP = BoolRing
module type GROUP =
  sig
    type t
    val zero : t
    val add : t -> t -> t
  end
module type RING =
  sig
    type t
    val zero : t
    val one : t
    val add : t -> t -> t
    val mul : t -> t -> t
  end
module IntGroup : GROUP = IntRing
module FloatGroup : GROUP = FloatRing
module BoolGroup : GROUP = BoolRing

RING is a sub-type of GROUP.
Groups versus Rings

module type GROUP =
  sig
    type t
    val zero : t
    val add : t -> t -> t
  end
module type RING =
  sig
    type t
    val zero : t
    val one : t
    val add : t -> t -> t
    val mul : t -> t -> t
  end
module IntGroup : GROUP = IntRing
module FloatGroup : GROUP = FloatRing
module BoolGroup : GROUP = BoolRing
module type GROUP =
  sig
    type t
    val zero : t
    val add : t -> t -> t
  end
module type RING =
  sig
    type t
    val zero : t
    val one : t
    val add : t -> t -> t
    val mul : t -> t -> t
  end
module IntGroup : GROUP = IntRing
module FloatGroup : GROUP = FloatRing
module BoolGroup : GROUP = BoolRing

Any module expecting a GROUP can be passed a RING.
module type GROUP =
  sig
    type t
    val zero : t
    val add : t -> t -> t
  end
module type RING =
  sig
    include GROUP
    val one : t
    val mul : t -> t -> t
  end
module IntGroup : GROUP = IntRing
module FloatGroup : GROUP = FloatRing
module BoolGroup : GROUP = BoolRing
Groups versus Rings

module type GROUP =
  sig
    type t
    val zero : t
    val add : t -> t -> t
  end

module type RING =
  sig
    include GROUP
    val one : t
    val mul : t -> t -> t
  end

module IntGroup : GROUP = IntRing
module FloatGroup : GROUP = FloatRing
module BoolGroup : GROUP = BoolRing

That ensures we will be a sub-type of the included signature.
MODULE EVALUATION
Evaluating the contents of a module

A structure is a series of declarations

- How does one evaluate a type declaration? We’ll ignore it.
- How does one evaluate a let declaration?

let x = e

evaluate the expression e
bind the value to x

How does one evaluate an entire structure?

- evaluate each declaration in order from first to last
let x = 326

let main () =
    Printf.printf "Hello COS %d\n" x

let foo =
    Printf.printf "Byeee!\n"

let _ =
    main ()
Evaluating the contents of a module

**main.ml**

```ml
let x = 326
let main () = 
  Printf.printf "Hello COS %d\n" x
let foo = 
  Printf.printf "Byeee!\n"
let _ = 
  main ()
```

**Step 1:**
evaluate the 1\textsuperscript{st} declaration

but the RHS (326) is already a value so there’s nothing to do except remember that \(x\) is bound to the integer 326
Evaluating the contents of a module

main.ml

let x = 326

let main () = 
  Printf.printf “Hello COS %d
” x

let foo = 
  Printf.printf “Byeee!
”

let _ = 
  main ()

Step 2: evaluate the 2\textsuperscript{nd} declaration
this is slightly trickier:

let main () = ...

really declares a function.
It’s equivalent to:

let main = fun () -> ...

“fun () -> ...” is already a value, like 326.
So there’s nothing to do again.
Evaluating the contents of a module

**main.ml**

```ml
let x = 326
let main () =  
    Printf.printf "Hello COS %d\n" x
let foo =  
    Printf.printf "Byeee!\n"
let _ = 
    main ()
```

**Step 3:** evaluate the 3\textsuperscript{rd} declaration

```
let foo = ...
```

evaluation of this expression has an effect – it prints out "Byeee!\n" to the terminal.

the resulting value is () which is bound to foo
main.ml

let x = 326
let main () =
  Printf.printf "Hello COS %d\n" x
let foo =
  Printf.printf "Byeee!\n"
let _ =
  main ()

Step 4:
evaluate the 4th declaration

let _ = ... 

evaluation main ()
causes another effect.

"Hello ..." is printed

the resulting value is () again.
the "_" indicates we don’t care to bind () to any variable
A Variation

This evaluates exactly the same way.

We just replaced

let main () = ... with the equivalent

let main = fun () -> ...

let x = 326

let main =
  (fun () ->
    Printf.printf "Hello COS %d\n" x)

let foo =
  Printf.printf "Byeee!\n"

let _ =
  main ()
This rewrite does something different.

On the 2\textsuperscript{nd} step, it prints because that’s what evaluating this expression does:

\begin{verbatim}
Printf.printf “Hello COS %d\n” x;
(func () -> ())
\end{verbatim}

The result of the expression is:

\begin{verbatim}
fun () -> ()
\end{verbatim}

which is bound to main. This is a pretty silly function.
module C326 =
struct
  let x = 326

  let main =
    Printf.printf "Hello COS %d\n" x;
    (fun () -> ())

  let foo = Printf.printf "Byeee!\n"

  let _ = main ()
end

let _ =
  Printf.printf "Done\n"
Now what happens?

The entire file contains 2 decls:
• module C326 = ...
• let done = ...

We execute both of them in order.

```ml
module C326 =
struct
  let x = 326

  let main =
    Printf.printf "Hello COS %d\n" x;
    (fun () -> ())

  let foo = Printf.printf "Byeee!\n"

  let _ = main ()
end

let done =
  Printf.printf "Done\n"
```
A Variation

main.ml

module C326 = 
struct
  let x = 326

  let main = 
    Printf.printf "Hello COS %d\n" x; 
    (fun () -> ()

  let foo = Printf.printf "Byeee!\n"

  let _ = main ()
end

let done = 
  Printf.printf "Done\n"

Now what happens?

The entire file contains 2 decls:
• module C326 = ...
• let done = ...

We execute both of them in order.

Executing the module declaration has the effect of executing every declaration within it in order.

Executing let done = ... is as before
A Variation

main.ml

module C326 =
struct
  exception Unimplemented
  let x = raise Unimplemented

  let main =
    Printf.printf "Hello COS %d\n" x;
    (fun () -> ())

  let foo = Printf.printf "Byeee!\n"

  let _ = main ()
end

let done =
  Printf.printf "Done\n"
main.ml

module C326 =
struct
  exception Unimplemented
let x = raise Unimplemented

let main =
  Printf.printf "Hello COS %d\n" x;
  (fun () -> ()
let foo = Printf.printf "Byeee!\n"

let _ = main ()
end

let done =
  Printf.printf "Done\n"

Now what happens?

The entire file contains 2 decls:
• module C326 = ...
• let done = ...

We execute both of them in order.

Executing the module declaration has the effect of executing every declaration within it in order.

The first declaration within it raises an exception which is not caught! That is the only result.
Now what happens?

The entire file contains 2 decls:
• module type = ...
• module F (M:S) : S = ...
• let done = ...

```plaintext
module type S =
sig
    type t = int
    val x : t
end

module F (M:S) : S =
struct
    let wow = Printf.printf "%d\n" M.x
    let t = M.t
    let x = M.x
end

let done = Printf.printf "Done\n"
```
module type S =
 sig
   type t = int
   val x : t
 end

module F (M:S) : S =
 struct
   let wow = Printf.printf "%d\n" M.x
   let t = M.t
   let x = M.x
 end

let done = Printf.printf "Done\n"

The signature declaration has no (run-time) effect.

The functor declaration is like declaring a function value.

The body of the functor is not executed until it is applied.

The functor is not applied here so M.x is not printed.

Only “Done\n” is printed.
module type S = sig ... end

module F (M:S) : S =
struct
  let wow = Printf.printf "%d\n" M.x
  let t = M.t
  let x = M.x
end

let module M1 = F (struct
  type t = int
  val x = 3
end)

let done = Printf.printf "Done\n"
What happens now?

When M1 is declared, F is applied to an argument.

This creates a new structure and its components are executed.

This has the effect of printing 3.
OCaml’s linguistic mechanisms include:

– signatures (interfaces)
– structures (implementations)
– functors (functions from modules to modules)

We can use the module system

– provides support for name-spaces
– hiding information (types, local value definitions)
– code reuse (via functors, reuseable interfaces, reuseable modules)

Information hiding allows design in terms of abstract types and algorithms.

– think “sets” not “lists” or “arrays” or “trees”
– think “document” not “strings”
– the less you reveal, the easier it is to replace an implementation
– use linguistic mechanisms to implement information hiding
  • invariants written down as comments are easy to violate
  • use the type checker to guarantee you have strong protections in place
It is often tempting to break the abstraction barrier.
  – e.g., during development, you want to print out a set, so you just call a convenient function you have lying around for iterating over lists and printing them out.

But the barrier supports future change of implementations.
  – e.g., moving from unsorted invariant to sorted invariant.
  – or from lists to balanced trees.

Languages often allow information to leak through the barrier.
  – “good” clients should not take advantage of this.
  – but they always end up doing it.
  – so you end up having to support these leaks when you upgrade, else you’ll break the clients.
Wrap up and Summary

It is often tempting to break the abstraction barrier.

- e.g., during development, you want to print out a set, just call a convenient function you have lying around iterating over lists and printing them out.

But the barrier supports future changes in implementations.

- e.g., moving from unsorted invariant to sorted invariant.
- or from lists to balanced trees.

Languages often allow information to leak through the barrier.

- “good” clients should not take advantage of this.
- but you always end up doing it.

Hence, having to support these leaks when you upgrade, else you’ll break the clients.