Modules
and Abstract Data Types

COS 326
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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?
Engineering for Change

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• The primary trick: use data and algorithm abstraction.
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• 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

```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)
```

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

Oops!
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 h in
    let l = Array.get h [i] in
    let urls = assoc_list_find ll x in
    urls
  | And (q1,q2) -> ...
  | Or (q1,q2) -> ...

I find out there’s a better hash-table implementation
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)
A Better Way

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

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

define type index = string url_set dictionary

define 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)
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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.
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 =  
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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.

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

- We can use the module system of Ocaml to build 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
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
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 option
  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 option
    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 option

  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 None
       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
  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) =
        match s with
        | [] -> None
        | _::t -> Some t
    let top (s:stack) =
        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) =
        match s with
        | [] -> None
        | _::t -> Some t
    let top (s:stack) =
        match s with
        | [] -> None
        | h:::_ -> Some h
end

Inside the module, we know the **concrete type** used to implement the abstract type.
Example Structure

```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) =
        match s with
        | [] -> None
        | _::_t -> Some t

    let top (s:stack) =
        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;;
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 ;;
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;;
ListIntStack.top s2;;
- : 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;;
ListIntStack.top s2 ;;
- : option int = Some 4
ListIntStack.top (ListIntStack.pop s2) ;;
- : 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;;
ListIntStack.top s2 ;;
- : option int = Some 4
ListIntStack.top (ListIntStack.pop s2) ;;
- : 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;;
ListIntStack.top s2 ;;
- : option int = Some 4
ListIntStack.top (ListIntStack.pop s2) ;;
- : option int = Some 3
open ListIntStack ;;
top (pop (pop s2)) ;;
- : option int = None
module type INT_STACK =
  sig
    type stack
    val push : int -> stack -> stack
...

module ListIntStack : INT_STACK

let s2 = ListIntStack.push 4 s1
...
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
    | [] -> raise EmptyStack
    | _::t -> t
  let top (s:stack) =
    match s with
    | [] -> raise EmptyStack
    | h:::_ -> 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.
module ListIntStack (* : INT_STACK *) =
  struct
    ...
  end

let s = ListIntStack.empty();;
let s1 = ListIntStack.push 3 s;;
let s2 = ListIntStack.push 4 s1;;

... List.rev s2 ;;
- : int list = [3; 4]

If we don’t seal the module with a signature, the client can know that stacks are lists.
module ListIntStack : INT_STACK =
struct
  type stack = int list
  let empty () : stack = []
  let push (i:int) (s:stack) =
  let is_empty (s:stack) =
    match s with
    | [ ] -> true
    | _:::_ -> false
  exception EmptyStack
  let pop (s:stack) =
    match s with
    | [] -> raise EmptyStack
    | _::t -> t
  let top (s:stack) =
    match s with
    | [] -> raise EmptyStack
    | h:::_ -> h
end

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.)
Summary

- Design in terms of *abstract* types and algorithms.
  - think “sets” not “lists” or “arrays” or “trees”
  - think “document” not “strings”

- In OCaml, we have a powerful *module system* with:
  - *signatures* (interfaces)
  - *structures* (implementations)
  - *functors* (functions from modules to modules)

- We can use the module system
  - to support name spaces
  - to hide information (concrete types, local value definitions)
  - to make it easy to reuse code (via parameterization, functors)