CS 3110

Testing

Prof. Clarkson
Fall 2016

Today's music: Wrecking Ball by Miley Cyrus

Review

Previously in 3110:

- architecture and design of large programs
- specification of modules

Today:

- finish up specification
- testing

Review: Sets without duplicates

```
module ListSetNoDup : Set = struct
  (* the list may never have duplicates *)
  type 'a set = 'a list
  let empty = []
  let mem = List.mem
  let add x l =
    if mem x l then l else x :: l
  let size = List.length
end
```

Review: Sets with duplicates

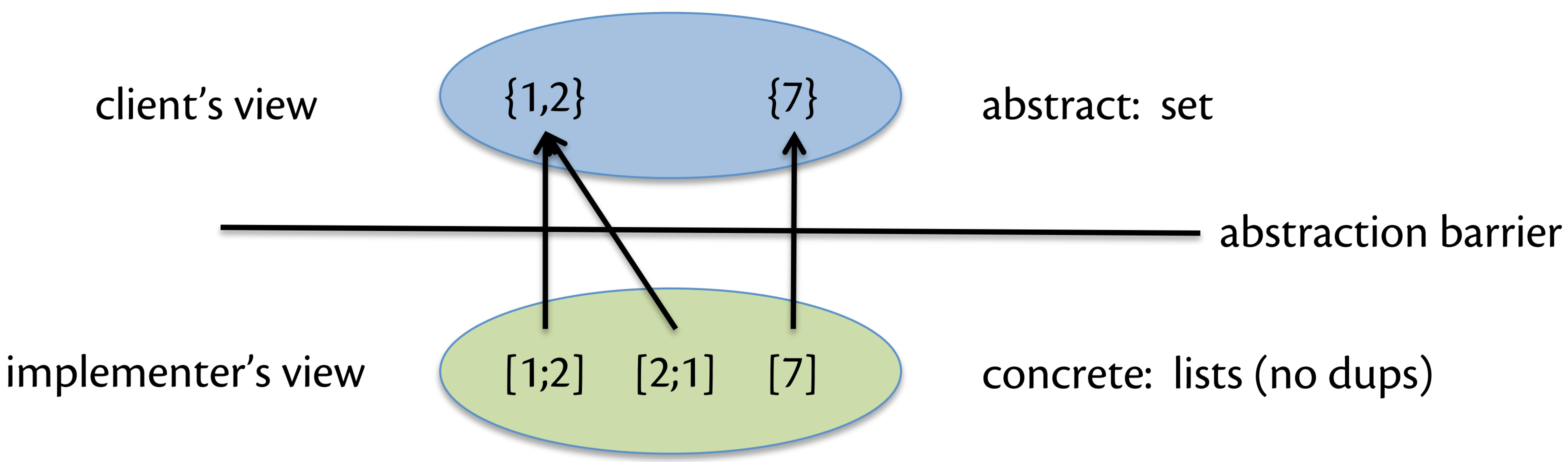
```
module ListSetDup : Set = struct
  (* the list may have duplicates *)
  type 'a set = 'a list
  let empty = []
  let mem = List.mem
  let add x l = x :: l
  let rec size = function
  | [] -> 0
  | h::t -> size t +
              (if mem h t then 0 else 1 )
end
```

Review: Set implementations

- Same representation type: **`'a list`**
- Different interpretations:
  - **`[1;1;2]`** is {1,2} in **`ListSetDup`**
  - **`[1;1;2]`** is not meaningful in **`ListSetNoDup`**
  - In both, **`[1;2]`** and **`[2;1]`** are {1,2}

Review: Abstraction function

- **Abstraction function** (AF) captures designer's intent in choosing a particular representation of a data abstraction
- Not actually an OCaml function, but a mathematical function
- Maps *concrete values* to *abstract values*



Review: Documenting AFs

```
module ListSetNoDup : Set = struct
  (* AF: the list [a1; ...; an] represents
   *    the set {a1,...,an}.  [] represents
   *    the empty set. *)
  type 'a set = 'a list
  ...
end
module ListSetDup : Set = struct
  (* AF: the list [a1; ...; an] represents
   *    the smallest set containing the
   *    elements a1, ..., an.  [] represents
   *    the empty set. *)
  type 'a set = 'a list
  ...
end
```

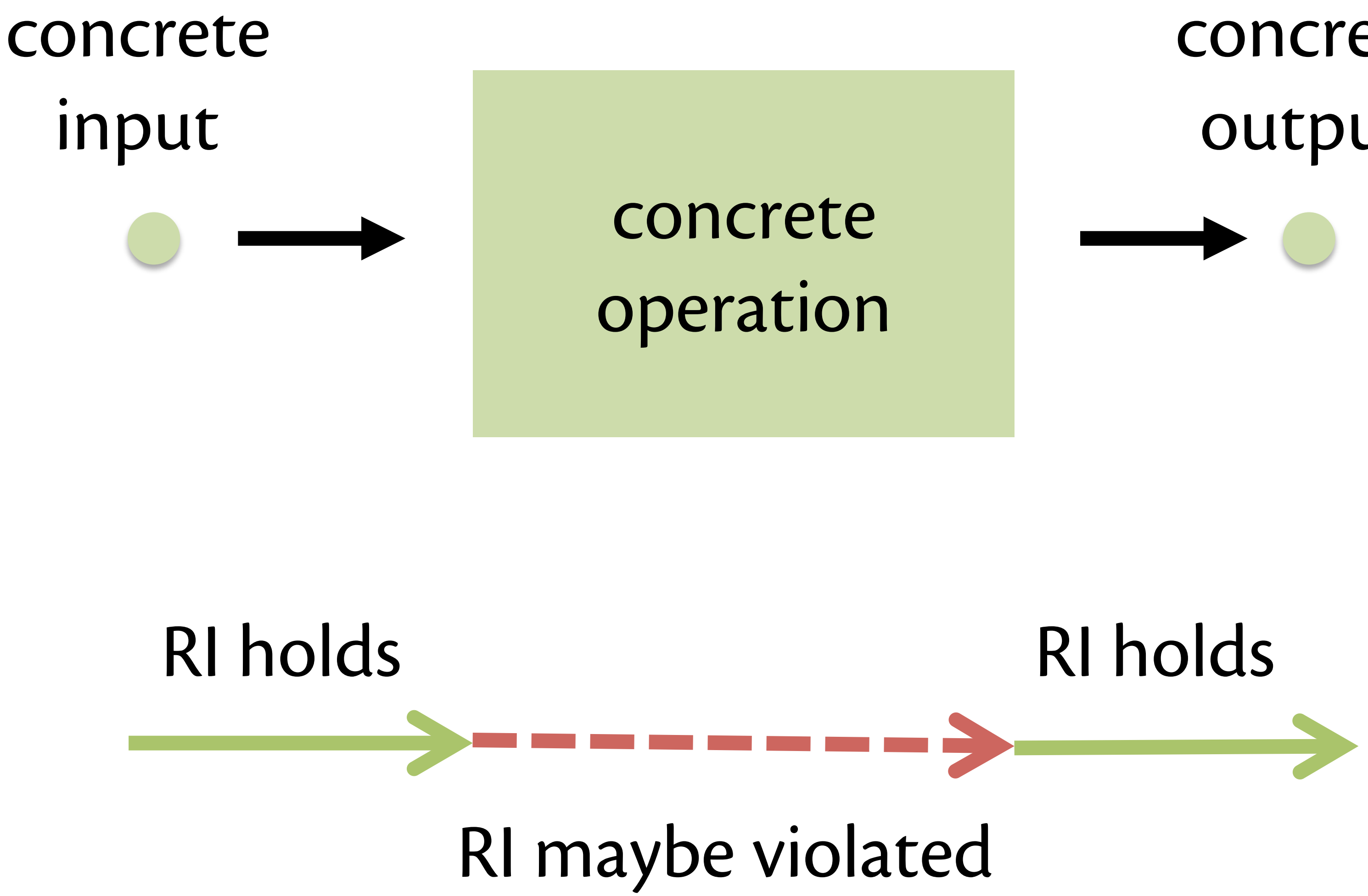
So far nothing other than module name specifies whether duplicates are allowed...

REPRESENTATION INVARIANT

Representation invariant

- **Representation invariant** characterizes which concrete values are *valid* and which are *invalid*
  - “Rep invariant” or "RI" for short
  - Valid concrete values mapped by AF to abstract values
  - Invalid concrete value not mapped by AF to any abstract values
  - Closely related to *class invariants* that you saw in 2110
- RI is a fact whose truth is *invariant* except for limited blocks of code
  - (much like loop invariants from 2110)
  - RI is implicitly part of pre- and post-conditions
  - operations may violate it temporarily (e.g., construct a list with duplicates then throw out the duplicates)

Representation invariant



Documenting RI

```
module ListSetNoDup : Set = struct
  (* AF: the list [a1; ...; an] represents
   *   the set {a1,...,an}.  [] represents
   *   the empty set. *)
  (* RI: the list contains no duplicates *)
  type 'a set = 'a list
end
module ListSetDup : Set = struct
  (* AF: the list [a1; ...; an] represents
   *   the smallest set containing the
   *   elements a1, ..., an.  [] represents
   *   the empty set.
   * RI: none *)
  type 'a set = 'a list
end
```

Implementing the RI

- Implement it early, before any operations are implemented

- Common **idiom**: if RI fails then raise exception, otherwise return concrete value

```
let rep_ok (x:'a list) : 'a list =
    if has_dups x then failwith "RI"
    else x
```

- When debugging, check **`rep_ok`** on every input to an operation and on every output...

Checking the RI

```
module ListSetNoDup : Set = struct
  (* AF: ... *)
  (* RI: ... *)
  type 'a set = 'a list
  let rep_ok = ...
  let empty = rep_ok []
  let mem x l = List.mem x (rep_ok l)
  let add x l =
    let l' = rep_ok l in
    if mem x l' then l'
    else rep_ok(x :: l')
  let size l = List.length (rep_ok l)
end
```

Funny story...this saved a CS 3110 tournament one year

Checking the RI

- Can be expensive!
- For production code, options include...
  - only check "cheap parts" of RI
  - comment out "real" implementation, change **`rep_ok`** to identity function, let compiler optimize call away
  - use language features for condition compilation (in OCaml, CamlP4 or PPX)

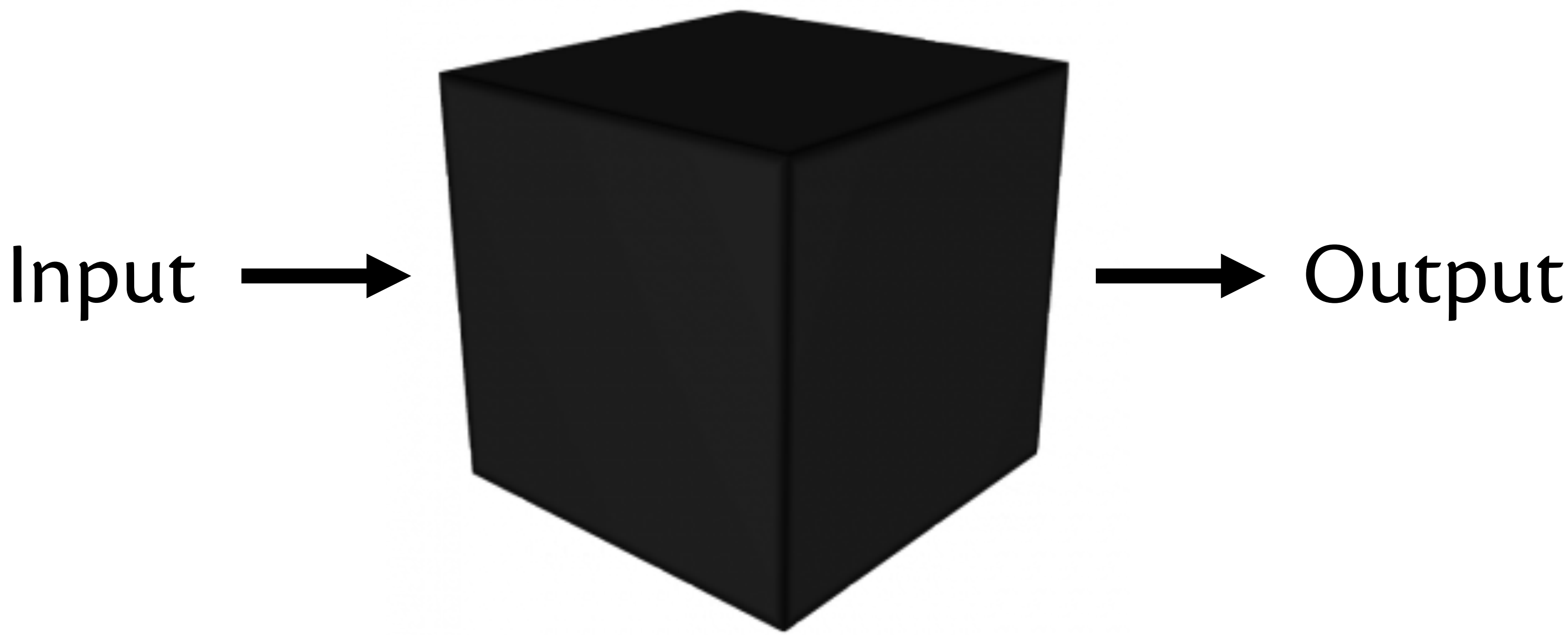
Recap: Specifying rep. types

- **Q:** How to *interpret* the representation type as the data abstraction?
- **A:** Abstraction function

- **Q:** How to determine which values of representation type are *meaningful*?
- **A:** Representation invariant

TESTING

Black box testing



tester knows nothing about internals of functionality being tested

Black box testing

Input →

→ Output

tester knows nothing about internals of functionality being tested

Glass box testing

Input →

→ Output

tester knows internals of functionality being tested

Glass box testing

Input →  → Output

tester knows internals of functionality being tested

Black box testing

- Tests are based on the specification
- **Advantages:**
  - Tester is not biased by assumptions made in implementation
  - Tests are robust w.r.t. changes in implementation
  - Tests can be read and evaluated by reviewers who are not implementers
- Main kinds of black box tests:
  - Typical inputs
  - Boundary cases
  - Paths through spec

Typical inputs

- Common, simple values of a type
  - `int`: small integers like 1 or 10
  - `char`: alphabetic letters, digits
  - `string`: whose length is a small integer and whose characters are typical
  - `'a list`: a small integer number of elements, each of which is a typical value of type `'a`
  - **records/tuples:** each field/component with a typical value
  - **variants:** typical constructors, if there is such a thing
- Any example inputs provided by specification

Boundary cases

Boundary cases

- aka *corner cases* or *edge cases*
- Atypical or extremal values of a type, and values nearby
  - **`int`**: **`0`**, **`1`**, **`-1`**, **`min_int`**, **`max_int`**
  - **`char`**: **`'\000'`**, **`'\255'`**, **`'\032'`** (space), **`'\127'`** (delete)
  - **`string`**: empty string, string with a single character, unreasonably long string
  - **`'a list`**: empty list, list with a single element, list with enough elements to trigger stack overflow on non-tail-recursive functions
  - **records/tuples:** combinations of atypical values
  - **variants:** all constructors

Paths through spec

Representative inputs for classes of outputs

```
(* [is_prime n] is true iff [n] is prime *)
val is_prime: int -> bool
```

two classes of output:

- true: representative input: n=13
- false: representative input: n=42

other examples:

- **`compare`** functions have three classes of output
- functions that return variants have several classes of output

Paths through spec

Representative inputs for each way of satisfying the precondition

```
(* [sqrt x n] is the square root of [x]
 * computed to an accuracy of [n]
 * significant digits
 * requires: x >= 0 and n >= 1 *)
val sqrt : float -> int -> float
```

(i) x=0.0, n=1,   (ii) x=1.0, n=1,
(iii) x=0.0, n=2,   (iv) x=1.0, n=2

Paths through spec

Representative inputs for each way of (not) raising exception

```
(* [pos x lst] is the 0-based position of
 * the first element of [lst] that equals [x].
 * raises:  Not_found if [x] is not in [lst]. *)
val pos: 'a -> 'a list -> int
```

(i) x=1, lst=[1],   (ii) x=0, lst[1]

Glass box testing

- aka *white box testing*
- **Advantages:**
  - can determine whether a new test case really yields additional information about correctness of implementation
  - can address likely errors that are not apparent from specification
- **Supplements** black-box testing; does not **replace** examination of specification
- Main kind of glass box test cases:
  - *paths through implementation* aka *path coverage*

Paths through implementation

All execution paths through implementation are tested

```
let max3 x y z =
  if x>y then
    if x>z then x else z
  else
    if y>z then y else z
```

Testing according to black-box specification might lead to all kinds of inputs

But there are really only four paths through implementation!
Representatives: (i) 3 2 1, (ii) 3, 2, 4, (iii) 1, 2, 1, (iv) 1, 2, 3

Achieving path coverage

- Include test cases for:
  - each branch of each (nested) if expression
  - each branch of each (nested) pattern match
- Particularly watch out for:
  - base cases of recursive function
  - recursive calls in recursive function
  - every place where an exception might be raised

Testing data abstractions

- Some functions of a data abstraction *produce* a value of it
  - **`empty`** produces an empty set
  - **`union`** produces a set
- Other functions *consume* a value
  - **`size`** consumes a dictionary and produces an integer
  - **`bindings`** consumes a dictionary and produces a list
- For every possible path through spec and impl of producers... test how a consumer handles it
  - e.g. if producers of a set handle sets of size 0, 1, and >1 differently...
  - then test each such set with every consumer
- For every value returned by abstraction, check the RI

Randomized testing

- *"It was a dark and stormy night..."*
- Generate random inputs and feed them to programs:
  - Crash? hang? terminate normally?
  - Of ~90 utilities in '89, crashed about 25-33% in various Unixes
  - Crash => buffer overflow potential
- Since then, "fuzzing" has become a standard practice for security testing
- Results have been repeated for X-windows system, Windows NT, Mac OS X
  - Results keep getting **worse** in GUIs but better on command line

Debugging

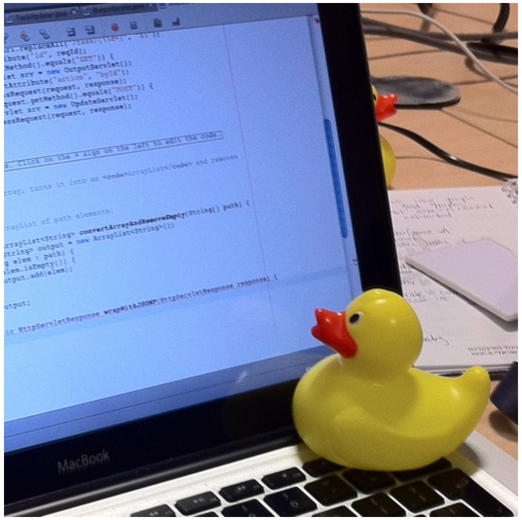
- *Testing* reveals a fault in program
- *Debugging* reveals the cause of that fault
- "Bug" is misleading
  - it didn't just crawl into program
  - **you or I put it there**
- Debugging takes more time than programming
  - get it right the first time!
  - understand exactly why you expect code to work before testing/debugging it

Debugging advice

- Follow the scientific method:
  - formulate a falsifiable hypothesis
  - create an experiment that can refute that hypothesis
  - run that experiment
  - keep a lab notebook
- Find the simplest possible input that causes fault
- Find the first manifestation of inappropriate behavior

Debugging advice

- Invest effort in writing code to help you understand intermediate results
- The bug is probably not where you think it is…ask yourself where it cannot be
- Get someone else to help you



Debugging advice

- If all else if failing, doubt your sanity: do you have the right compiler? the right source code
- Don't debug when angry or tired: give it a break; come back refreshed
- Think through the fix carefully: "fixing" a bug often leads to new bugs

Upcoming events

- [next Wed] A3 due
- [Oct 13, two weeks from today] Prelim 1, look for Piazza post soon

This is tested.

THIS IS 3110

Acknowledgment

Parts of this lecture are based on *Program Development in Java: Abstraction, Specification, and Object-Oriented Design* by Barbara Liskov with John Guttag.