CS 251 Spring 2020
Principles of Programming Languages
Ben Wood

WELLESLEY

Structures, Signatures, and Abstract Types

Topics

Hiding implementation details
is the most important strategy
for writing correct, robust, reusable software.

- ML mechanisms:
  - ML structures and signatures
- Abstract Data Types for:
  - robust library and client+library code
  - easy change
- Functions as data structures

Hiding with functions

procedural abstraction

Can you tell the difference?

```
- double 4;
val it : int = 8
```

```
fun double x = x*2

fun double x = x+x

val y = 2
fun double x = x*y

fun double x =
  let fun help 0 y = y
        | help x y =
            help (x-1) (y+1)
  in help x x end
```

"Private", but can't be shared among functions.

structure *(module)*

```
structure Name =
struct bindings end
```

namespace management and code organization

```
structure MyMathLib =
struct
  fun fact 0 = 1
    | fact x = x * fact (x-1)

  val half_pi = Math.pi / 2

  fun doubler x = x * 2
end
```

outside:

```
val facts = List.map MyMathLib.fact [1,3,5,7,9]
```

```
signature NAME =
sig binding-types end
```

signature

type for a structure (module)

List of bindings and their types:

variables, type synonyms, datatypes, exceptions

```
signature MATHLIB =
sig
  val fact    : int -> int
  val half_pi : real
  val doubler : int -> int
end
```



```
structure Name :> NAME =
struct bindings end
```

ascription

(opaque – will ignore other kinds)

Structure must have all bindings/types as declared in signature.

```
signature MATHLIB =
sig
  val fact    : int -> int
  val half_pi : real
  val doubler : int -> int
end

structure MyMathLib :> MATHLIB =
struct
  fun fact 0 = 1
    | fact x = x * fact (x-1)
  val half_pi = Math.pi / 2
  fun doubler x = x * 2
end
```

Real power:
Abstraction and Hiding

Hiding with signatures

`MyMathLib.doubler`
is unbound (not in environment, not visible) outside module.

```
signature MATHLIB2 =
sig
  val fact    : int -> int
  val half_pi : real
end

structure MyMathLib2 :> MATHLIB2 =
struct
  fun fact 0 = 1
    | fact x = x * fact (x-1)
  val half_pi = Math.pi / 2.0
  fun doubler x = x * 2
end
```


Abstract Data Type

type of data and operations on it

Example: rational numbers supporting `add` and `toString`

```
structure Rational =
struct
  datatype rational = Whole of int
                    | Frac  of int*int
  exception BadFrac

  (* see adts.ml for full code *)

  fun make_frac (x,y) = ...
  fun add (r1,r2) = ...
  fun toString r = ...
end
```

Library spec and invariants

External properties *[externally visible **guarantees**, up to library writer]*
- Disallow 0 denominators
- Return strings in reduced form
  ("4" not "4/1", "3/2" not "9/6")
- No infinite loops or exceptions

Implementation invariants *[not in external specification]*
- All denominators > 0
- All `rational` values returned from functions are reduced

Signatures help ***enforce*** internal invariants.

More on invariants

Our code maintains (and relies on) invariants.

Maintain:
- `make_frac` disallows 0 denominator, removes negative denominator, and reduces result
- `add` assumes invariants on inputs, calls `reduce` if needed

Rely:
- `gcd` assumes its arguments are non-negative
- `add` uses math properties to avoid calling `reduce`
- `toString` assumes its argument is in reduced form

A first signature

Helper functions `gcd` and `reduce` not visible outside module.

Attempt #1

```
signature RATIONAL_OPEN =
sig
  datatype rational = Whole of int
                    | Frac  of int*int
  exception BadFrac
  val make_frac : int * int -> rational
  val add       : rational * rational -> rational
  val toString  : rational -> string
end

structure Rational :> RATIONAL_OPEN = ...
```


Problem: clients can violate invariants

Create values of type `Rational.rational` directly.

```
signature RATIONAL_OPEN =
sig
  datatype rational = Whole of int
                    | Frac  of int*int
  ...
end
```

```
Rational.Frac(1,0)
Rational.Frac(3,~2)
Rational.Frac(9,6)
```

Solution: hide more!

ADT must hide concrete type definition so clients cannot create invariant-violating values of type.

Attempt #2

```
signature RATIONAL_WRONG =
sig
  exception BadFrac
  val make_frac : int * int -> rational
  val add : rational * rational -> rational
  val toString : rational -> string
end

structure Rational :> RATIONAL_WRONG = ...
```

Too far: type `rational` is not known to exist!

Abstract the type! *(Really Big Deal!)*

Type `rational` exists, but representation *absolutely* hidden.

Client can pass them around, but can manipulate them only through module.

Success! (#3)

```
signature RATIONAL =
sig
  type rational
  exception BadFrac
  val make_frac : int * int -> rational
  val add : rational * rational -> rational
  val toString : rational -> string
end

structure Rational :> RATIONAL = ...
```

Only way to make 1st `rational`.

Only operations on `rational`.

Module controls all operations with `rational`, so client cannot violate invariants.

Abstract Data Type

Abstract **type of data + operations on it**

Outside of implementation:

- Values of type `rational` can be **created and manipulated only through ADT operations.**
- **Concrete representation** of values of type `rational` **is *absolutely* hidden.**

```
signature RATIONAL =
sig
  type rational
  exception BadFrac
  val make_frac : int * int -> rational
  val add       : rational * rational -> rational
  val toString  : rational -> string
end

structure Rational :> RATIONAL = ...
```


Abstract Data Types: two key tools

Powerful ways to use signatures for hiding:

1. **Deny bindings exist.**
   Especially val bindings, fun bindings, constructors.

2. **Make types abstract.**
   Clients cannot create or inspect values of the type directly.

A cute twist

Exposing the `Whole` constructor is no problem.

Expose it as a function:

- Still hiding the rest of the datatype
- Still does not allow using `Whole` as a pattern

```
signature RATIONAL_WHOLE =
sig
  type rational
  exception BadFrac
  val Whole     : int -> rational
  val make_frac : int * int -> rational
  val add       : rational * rational -> rational
  val toString  : rational -> string
end
```


Signature matching rules

`structure Struct :> SIG`
type-checks if and only if **all** of the following hold:

1. Every **non-abstract type** in `SIG` is provided in `Struct`, as specified
2. Every **abstract type** in `SIG` is provided in `Struct`, in some way
3. Every **`val` binding** in `SIG` is provided in `Struct`, possibly with a *more general* and/or *less abstract* internal type
4. Every **exception** in `SIG` is provided in `Struct.`

`Struct` can have more bindings (implicit in above rules)

Allow *different implementations* to be *equivalent / interchangeable*

A key purpose of abstraction:

- *No* client can tell which you are using
- Can improve/replace/choose implementations later
- Easier with more abstract signatures (reveal only what you must)

`UnreducedRational` in `adts.sml`.

- Same concrete datatype.
- **Different invariant:** reduce fractions only in `toString`.
- Equivalent under `RATIONAL` and `RATIONAL_WHOLE`, but not under `RATIONAL_OPEN`.

`PairRational` in `adts.sml`.

- **Different concrete datatype.**
- Equivalent under `RATIONAL` and `RATIONAL_WHOLE`, but cannot ascribe `RATIONAL_OPEN`.

`PairRational` (alternative concrete type)

```
structure PairRational =
struct
  type rational = int * int
  exception BadFrac

  fun make_frac (x,y) = …
  fun Whole i = (i,1) (* for RATIONAL_WHOLE *)
  fun add ((a,b)(c,d)) = (a*d + b*c, b*d)
  fun toString r = ... (* reduce at last minute *)
end
```

Some interesting details

`make_frac`

Internally: `int * int -> int * int`

Externally: `int * int -> rational`

- *Client cannot tell if we return argument unchanged*

`Whole`

Internally: `'a -> 'a * int`

Externally: `int -> rational`

- Specialize `'a` to `int`
- abstract `int * int` to `rational`
- Type-checker just figures it out

Cannot have types

```
'a -> int * int
'a -> rational
```


Cannot mix and match module bindings

Different modules with the *same signatures* define ***different types***.

These do not type-check:

```
Rational.toString(UnreducedRational.make_frac(9,6))

PairRational.toString(UnreducedRational.make_frac(9,6))
```

Crucial for type system and module properties:

- **Different modules have different internal invariants!**
  ... and different type definitions:
  - `UnreducedRational.rational` **looks like** `Rational.rational`, **but clients and type-checker do not know**
  - `PairRational.rational` is `int*int`, not a datatype!

Later: contrast with Object-Oriented techniques.

Set ADT (`set.sml`)

```
signature SET =
sig
  type ''a t
  val empty     : ''a t
  val singleton : ''a -> ''a t
  val fromList  : ''a list -> ''a t
  val toList    : ''a t -> ''a list
  val fromPred  : (''a -> bool) -> ''a t
  val toPred    : ''a t -> ''a -> bool
  val toString  : (''a -> string) -> ''a t -> string
  val isEmpty   : ''a t -> bool
  val member    : ''a -> ''a t -> bool
  val insert    : ''a -> ''a t -> ''a t
  val delete    : ''a -> ''a t -> ''a t
  val union     : ''a t -> ''a t -> ''a t
  val intersect : ''a t -> ''a t -> ''a t
  val diff      : ''a t -> ''a t -> ''a t
end
```

Common idiom: if module provides one externally visible type, name it `t`. Then outside references are `Set.t`.

Implementing the `SET` signature

`ListSet` structure

Represent sets as lists of their elements.

Invariants?

- Duplicates?
- Ordering?

`FunSet` structure

Represent sets as predicate function closures (!!!)

that return true when applied to a member of the set, and false otherwise.

Sets are fun!

English: "the set of all multiples of 3"

Math: $\{ x \mid x \bmod 3 = 0 \}$

SML: `fn x => x mod 3 = 0`

```
structure FunSet :> SET =
struct
  type ''a t = ''a -> bool
  val empty = fn _ => false
  fun singleton x = fn y => x=y
  fun member x set = set x
  fun insert x set = fn y => x=y orelse set y
  ...
end
```

Are all set operations possible?