CSE583: Programming Languages

David Notkin
25 January 2000
notkin@cs.washington.edu
http://www.cs.washington.edu/education/courses/583

Functional programming: 2+ weeks

Last Two Weeks' Lectures!

- *Scheme*
  - *Gives a strong, langua...-bas... f... for functio...al ...*
  - *May be mo...*
- Some theor...
  - Theoretica... ...ons and issues in functional programming
- ML
  - A modern basis for discussing key issues in functional programming

---

Tonight: a final set of topics on functional languages

- ML types
  - user-defined datatypes, variant records, recursive types, polymorphic types, exceptions, streams, …
- Haskell
  - lazy evaluation
    - purely side-effect free, infinite lists
  - type classes for added flexibility in polymorphism

Then, with luck, on to types

ML concrete user-defined datatypes

- Users can define their own (polymorphic) data structures
- Simple example: ML's version of enumerated types
  - `datatype sign = Positive | Zero | Negative;`
- Introduces constants
  - Can be used in patterns

Example

```
- fun signum(x) =
    if x > 0 then positive
    else if x = 0 then Zero
    else Negative;
val signum = fn : int -> sign;
- fun signum_val(Positive) = 1
    | signum_val(Zero)     = 0
    | signum_val(Negative) = -1;
val signum = fn : sign -> int;
```

Variant records/tagged unions

- Each component of a datatype declaration can have information
  - constructors act as functions to create values with that tag
  - can be used in patterns to take apart values of a tag

```
datatype Sexpr =
   Nil |
   Integer of int |
   Symbol of string |
   Cons of Sexpr * Sexpr;
```


Example

```
- Nil;
Nil : Sexpr;
- Integer;
Integer : int -> Sexpr;
- Symbol;
Symbol : string -> Sexpr;
- Cons;
Symbol : Sexpr * Sexpr -> Sexpr;
```


Using datatypes

```
- val wuss =Cons(Integer(3),Cons(Symbol("hi"),Nil));
Cons(Integer 3,Cons(Symbol "hi",Nil)) : Sexpr;  (*
  '(3 hi)   *)
- fun car Nil        = Nil
    | car (Cons(x,_) = x;
val car = fn : Sexpr -> Sexpr;
- fun cdr Nil         = Nil
    | cdr (Cons(_,xs) = xs;
val car = fn : Sexpr -> Sexpr;
- cdr wuss;
Cons(Symbol "hi",Nil) : Sexpr;
- car wuss = Integer 3;
true : bool;
```


Recursive user-defined datatypes

```
- datatype int_tree =
     Empty |
     Node of int * int_tree * int_tree;
- fun insert x Empty = Node(x,Empty,Empty)
    | insert x (n as Node(y,t1,t2)) =
        if x = y then n
        else if x < y then Node(y,insert x t1,t2)
        else Node(y,t1,insert x t2);
val insert = fn : int -> int_tree -> int_tree;
- fun member x Empty            = false
    | member x (Node(y,t1,t2))  =
        if x = y then true
        else if x < y then member x t1
        else member x t2;
val member = fn : int -> int_tree -> bool;
```


But what about a polymorphic version?

- It should be polymorphic with respect to `=` and `<`
- `int_tree` is an equality type
  - Does `=` do the right thing?
- Define using explicit type variables

Polymorphic binary trees

```
- datatype 'a tr =
     Empty |
     Node of 'a * 'a tr * 'a tr;
- fun ins eq lt x Empty = Node(x,Empty,Empty)
    | ins eq lt x (n as Node(y,t1,t2)) =
        if eq(x,y) then n
        else if lt(x,y) then
          Node(y,ins eq lt x t1,t2)
        else Node(y,t1,ins eq lt x t2);
val ins = fn : ('a*'a->bool) -> ('a*'a->bool)
                 -> 'a -> 'a tr -> 'a tr;
```

That’s a mouthful: use a wrapper

```
- datatype ‘a tree =
     Tree of {tree: ‘a tr,
              eq: ‘a* ‘ a -> bool,
              lt: ‘a* ‘ a -> bool};
- fun make_tree eq_fn lt_fn =
      Tree{tree=Empty,eq=eq_fn,lt=lt_fn};
val make_tree = fn : (‘a*‘a->bool) -> (‘a*‘a->bool)
                  -> ‘a tree;
- fun insert x (Tree {tree=tr,eq_fn=fn,lt_fn=lt}) =
      Tree{tree=ins eq_fn lt_fn x tr,
                     eq=eq_fn,lt=lt_fn};
val insert = fn : ‘a -> ‘a tree -> ‘a tree;
```


A problem

- **In Scheme we can use “distinguished values” to handle exceptional cases**
  - **(define (find pred x)**
    (cond ((null? x) *#f*)
    ((pred (car x)) (car x))
    (else (find pred (cdr x)))))
  - **(find is-positive? ‘(-3 3 5)) => 3**
  - **(find is-positive> ‘(-3 -5)) => *#f***

In ML it doesn’t work

```
- fun find pred nil     = false
    | find pred (x::xs) =
        if pred x then x else find pred xs;
val find = fn : (bool->bool) -> bool list -> bool

- find is_positive [~3,3,5];
...type error...
```


Use exceptions

- **Exceptions can be returned from functions without affecting the normal return type**

```
- exception NotFound;
- fun find pred nil     = raise NotFound
    | find pred (x::xs) =
        if pred x then x else find pred xs;
val find = fn : (‘a->bool) -> ‘a list -> ‘a
- find is_positive [~3,3,5];
3 : int
- find is_positive [~3,~5];
uncaught exception NotFound
```


Handling exceptions

- **Add handler clause to expressions to handle (some) exceptions raised in that expression**
  - **Must return same type as handled expression**

```
- (find is_positive [~3,~5])
     handle NotFound => 0
0 : int
```


Exceptions can have arguments

```
- exception IOError of int;
- (…raise IOError(-3) …)
     handle IOError(code) => code ...
```

Streams

- Streams are (in essence) infinite lists
- Streams are a good model for I/O (and other things)
  - Unix pipes are basically streams
- But it's hard to have an infinite list in an eager-evaluation language
  - Think about appending an element to a list
  - First you evaluate the element and the list, and then you append … whoops!

Streams in ML

- Instead, represent a stream cons cell as a pair of
  - a head value and
  - a function that will return the next element in the stream

```
- datatype 'a stream =
     Stream of 'a * (unit -> 'a stream);
```


Basic functions

```
- fun cons_stream(x,f) = Stream(x,f);
- fun hd_stream(Stream(x,f)) = x;
- fun tl_stream(Stream(x,f)) = f();

- fun ints_from(x) =
      cons_stream(x, fn() => ints_from(x+1));
- val nats = ints_from(0);

- fun map_stream(g,s) =
      cons_stream(g(hd_stream(s)),
                  fn() => map_stream(g,tl_stream(s)));
- val squares = map_stream(fn(x)=>x*x,nats);
```


References

- ML allows side-effects through explicit reference values
  - Completely non-functional

```
- ref      : 'a -> 'a ref
- !        : 'a ref -> a
- (op :=)  : 'a ref * 'a -> unit
```


Examples

```
- val v = ref 0;
val v = ref 0 : int ref
- v := !v + 1;
() : unit
- !v;
1 : int
```

- A major difference from Scheme is that the mutable objects are stated explicitly
  - In Scheme, `set!` can be used anywhere, anytime

Modules

- `datatype`s were cool, but they exposed their representation
  - Helped with pattern matching, etc.
- ML modules support *encapsulated* abstract data types
  - hidden operations, values, types, and some kinds of polymorphism

Note

- The module system in ML is clearly intended to try to make the language more industrial strength and feasible for practical use
- A challenge is balancing the software engineering needs with the type system in ML

Overview

- `structure` defines module implementation
- `signature` defines module interface
  - hides other aspects of underlying structure
- `open` imports a module for naming convenience
  - We won't cover this
- `functor` supports parameterized module implementations

Structures

- Package a set of declarations

```
structure Queue1 = struct
  type 'a T = 'a list;  (* T is conventional name *)
  (* constructors)
  val empty = nil;
  fun enq x q = a @ [x]; (* @ is append *)
  (* accessors *)
  exception empty_queue;
  fun head (x::q) = x
    | head nil = raise empty_queue;
  fun deq (x::q) = (x,q)
    | deq nil = raise empty_queue;
```


Accessing members

```
- val q = Queue1.enq 3 Queue1.empty;
val q = [3] : int list
- val q2 = Queue1.enq 4 q;
val q2 = [3,4] : int list
- Queue1.head q2;
3 : int
```


Signatures

- Construct for encapsulating representations
- Define a public external interface with `signature`
- Then apply the signature to restrict the interface to a structure

Example

```
signature QUEUE = sig
  type 'a T;
  val empty : 'a T;
  val enq: `a -> `a T -> `a T;
  exception empty_queue;
  val head: `a T -> `a;
  val deq: `a T -> `a * `a T;
end;
structure Queue2: QUEUE = struct … end;
```

- Any operations in `struct` that aren't in `sig` are inaccessible

Holes in encapsulation

- Signatures don't completely hide module implementation
- Types defined using type are not hidden

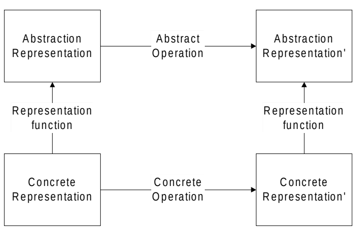
```
- Queue.empty = nil;
true : bool;
```

- If you want to hide types, use `datatype` instead of `type`

Another hole

- Built-in equality (=) function operates over the representation, not the abstraction
- That is, two values that are abstractly the same can be revealed to be different using =
- There are various proposals to try to fix these holes in ML

Aside: abstract/concrete data



Functors

- You can parameterize structures by other structures
- Then instantiate the functors to build regular structures

```
functor QueueUser(Q:QUEUE) =
  struct … Q.enq … Q.deq …
end;
```

- This only knows the aspects of Q that are defined by QUEUE

```
structure QU1 = QueueUser(Queue1);
structure QU2 = QueueUser(Queue3);
```


Example

```
signature ORDERED = sig
  type T;
  val eq: T * T -> bool;
  val lt: T * T -> bool;
end;
functor Sort(O;ORDERED) = struct
  fun min(x,y) =
     if O.lt(x,y) then x else y;
  fun sort(lst) = … O.lt(x,y) …
```


Example con't

```
structure IntOrder = struct
  type T = int;
  val eq = (op =);
  val lt = (op <);
end;
structure IntSort = Sort(IntOrder);
IntSort.sort([3,5,~2]);
```

Signature "subtyping"

- (A quick preview of one of the Cardelli-Wegner ideas)
- How can we have subtyping in a language that doesn't even have inheritance?
- The question is: under what conditions can we treat an instance of one type as an instance of another type?
- Roughly: If all possible instances of type ***S*** can be treated as instances of type ***T***, then we can view ***S*** as a subtype of ***T***

In ML

- A signature defines a particular interface
- Any structure that satisfies that interface can be used where that interface is expected
  - For instance, in a functor application
- A structure can have more than is required by the signature
  - More operations, more general/polymorphic operations, more details of implementation of the types

Limitations in ML

- structures and signatures are not first-class values
  - They must be named
  - They must be declared at the top-level or nested inside another structure or signature
- You cannot instantiate functors at run-time to create "objects"
  - This implies you cannot simulate classes and object-oriented programming

Modules vs. ADTs in ML

- ML abstract data types implicitly define a single type
  - With associated constructors, observers and mutators
- Modules can define 0, 1 or many types in the same module with associated operations over several types
  - Multiple types can share private data and operations
- Functors are similar to parameterized ADTs
- Modules are more general, but clumsier for the common case

Haskell

- A "competitor" to ML
- We won't do a full language description, but will focus on "interesting" differences
  - Lazy evaluation instead of eager
    - Purely side-effect-free
  - Type classes for more flexible polymorphic type checking
  - Unparameterized modules

A bit of history

- Main design completed in 1992
  - By committee
- Attempted to merge the many different lazy-evaluation-based functional languages into one common thrust
  - Miranda, HOPE, …

A few quick, minor examples

```
map f []       = []
map f (x::xs) = f x : map f xs
<<fn>> :: (a->b) -> [a] -> [b]
lst = map square [3,4,5]
[9,16,25] :: [Int]
(3,4,\x y -> x+y)
(3,4,<<fn>>) : (Int,Int,Int->Int->Int)
```


List comprehensions

- **A nice syntax for constructing lists from *generators* and *guards***
  - ***[expr | var <- expr, …, … boolExpr, …]***

```
[ f x | x <- xs ]
[(x,y) | x <- xs, y <- ys)]
[y | y <- ys, y > 10 ]
```


quicksort

```
quicksort []      = []
quicksort (x:xs) =
    quicksort [y | y <- xs, y < x] ++
    [x] ++
    quicksort [y | y <- xs, y >=  x]
```


Easy to construct arithmetic sequences

- `[1..8]       -- [1,2,3,4,5,6,7,8]`
- `[2,4..8]     -- [2,4,6,8]`
- `[2,4..]      -- [2,4,6,8,10,12,…]`
- `[1..]        -- [1,2,3,4,5,6,7,…]`

Sections

- **Can call an infix operator on 0 or 1 of its arguments to create a curried function**

```
(+)
<<fn>> :: Int -> Int -> Int
(+ 1)    --increment function
<<fn>> :: Int -> Int
(0 -)    --negate function
<<fn>> :: Int -> Int
```


Lazy vs. eager evaluation

- **Eager, applicative-order, strict**
  - **Before passing value to function**
- **Lazy, normal-order, nonstrict, call-by-need, demand-driven**
  - **When/if first needed**
- **Again, Haskell is lazy**

Example

```
my_if test then_val else_val =
   if test then then_val else else_val

my_if True 3 4
3 : Int
my_if False 3 4
4 : Int
x = 3
y = 12
my_if (x /= 0) (y `div` x) (-1)
4 : Int
```

Different than in Scheme and ML, which would require a special form

Streams in Haskell

- **All lists are automatically streams!**
  - **head, tail fields of a list structure won't be evaluated until they are demanded by some client of the list**
- **Lazy evaluation holds for all data structures in the same way**

Examples

```
ints_from n = n : ints_from (n+1)
  --same as [n..]
nats = ints_from 0;
squares = map (^2) nats
[0,1,4,9,16,25…]
fibs = 0 : 1 :
        [a+b | (a,b) <- zip fibs
                            (tail fibs)]
[0,1,1,2,3,5,8,13,21,34,55,…]
```


Lazy programming paradigm

- **There is a programming style that exploits lazy evaluation**
  - **May lead to more reusable components**
- **Construct a toolkit of operations to generate interesting streams**
  - **Ex: Scanner produces a stream of tokens**
  - **Ex: Input produces a stream of characters**
  - **Ex: Event-driven simulations produce streams of events**
- **Independently produce operations to manipulate and extract the interesting subset of the generated streams**

Polymorphic functions

- **ML allows functions to be**
  - **Completely polymorphic**
    - `length: 'a list -> int`
  - **Polymorphic over types that admit `=`**
    - `eq_pair: (``a*``b)*(``a*``b)->bool`
  - **Monomorphic**
    - `fun square n = n * n`
    - `int` or `real`, **but not both**
- **With the singular exception of equality types, ML supports *universal* or *unbounded* parametric polymorphism**

Bounded polymorphism

- **It is also possible to support forms of bounded polymorphism, where constraints are expressing on possible instantiating types; examples:**
  - **polymorphic over all types that support `=`**
  - **polymorphic over all types that support `+` , `*`**
  - **polymorphic over all types that support `print`**
  - **polymorphic over all tuples with at least two components**
  - **polymorphic over all records with `hd` and `tl` fields**
  - **…**

More

- Constraints on type parameters let the body know what operations can be performed on expressions of those types
  - Unbounded type values can be passed around, but with no constraints on the operations
- How to express constraints?

Subtype constraints

- In OO languages, we can often express constraints such as "polymorphic over all types that are subtypes of *T*"
  - subtypes have all the operations of *T* (and maybe more)
  - body can perform all operations listed in *T*

Type classes in Haskell

- Haskell supports a similar idea, within a lazy, function, type-inferencing-based language framework
  - Similar to OO classes, but not identical

Example

```
class Eq a where
  (==) :: a -> a -> Bool
  (/=) :: a -> a -> Bool
```

- `Eq` is the name of the new type class
- `==` and `/=` are the newly declared names of operations on this class
- `a` is the dummy name of a type that's in this class
  - used in the type signatures of operations of the class
  - roughly like a formal type parameter

Instances of type classes

- Types explicitly declared as members of particular type classes
  - Use `instance` construct
  - They must provide implementations of the type class' operations

```
instance Eq Int where
  x == y = intEq x y
  x /= y = intNeq x y
instance Eq Float where
  x == y = floatEq x y
  x /= y = floatNeq x y

3    == 4       --allowed
3.4  /= 5.6     --allowed
3    == 4.5     --type error
"hi" == "there" --type error
```


Type classes as polymorphic constraints

- Can use a type class to constrain legal instantiations

```
eq_pair (x1,y1) (x2,y2) = x1==x2 and y1==y2
eq_pair :: (Eq a,Eq b)=>(a,b)->(a,b)->Bool
```

- `(eq a,Eq b)` is a *context* that constrains the polymorphic type variables `a` and `b` to be instances of the `Eq` class

Defining contexts

- Can be implicitly defined by the type inference system based on operations used in the body
  - Requires that operations are defined in only one class
  - Cannot overload signatures in multiple classes
- Contexts can also be defined explicitly

```
member :: (Eq a)=> a -> [a] -> Bool
member _ []      = False
member x (y:ys) = x==y or member x ys
```


Conditional instances

- "A pair supports `==` if its component types do"

```
instance (Eq a,Eq b)=> Eq(a,b) where
   (x1,y1)==(x2,y2) = x1=x2 and y1=y2
   x /= y           = not (x==y)
```

- A list of a supports `==` if a does"

```
instance (Eq a)=> Eq [a] where
   []      == []      = True
   (x:xs)  == (y:ys)  = x==y and xs==ys
   _       == _       = False
```

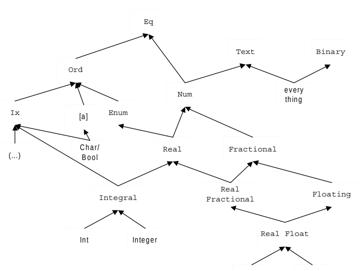

Default implementations in type classes

- Add a `/=` operation, which defaults to negation
  - `class Eq a where`
    ```
    (==), (/=) :: a -> a -> Bool
    x /= y   = not (x==y)
    ```
- ```
  instance (Eq a,Eq b)=> Eq(a,b) where
    (x1,y1) == (x2,y2) =
             x1==x2 and y1 == y2
    --inherits default /=,
    --  but could override
  ```


Type subclasses

- Can define new type classes that extend existing type classes, adding new operations and/or defaults
  - Define the superclass(es) as contexts
    - Instantiate each of a type's superclasses top-down to satisfy context
  - Multiple inheritance allowed
    - No name clashes, since operations can not be overloaded

Hierarchy of predefined type classes in Haskell



Type classes vs. OO subtypes

- Type classes do not support run-time heterogeneous collections
  - Cannot have functions that accept lists of mixed ints and reals
  - (Roughly) no run-time subtyping, only compile-time subtyping
- The constraints defined using type classes are not straightforward to define in most OO languages
  ```

Type classes vs. ML polymorphism

- ML polymorphism simple with warts
  - equality-bounded polymorphism
  - overloaded operators block some kinds of polymorphism
- Haskell type classes subsume and unify unbounded, equality-bounded, and general bounded polymorphism
  - Default implementations are nice, too
- Type classes
  - Big part of standard library and reference manual
  - Temptation is high to go overboard in refining class hierarchy

Whew

- Next week, on to some more discussion of types
- Leading into object-oriented programming languages
- Watch for a new assignment and some readings