Haskell

Many similarities with ML

- functions are first-class values
- strongly, statically typed
  - polymorphic type system
  - automatic type inference
- expression-oriented, recursion-oriented
- garbage-collected heap
- pattern matching
- **highly regular and expressive**

Key differences:

- **lazy evaluation** instead of eager evaluation
  - purely side-effect-free
  - **modads** for controlled side-effects, I/O, etc.
- **type classes** for more flexible polymorphic typechecking
- simpler module system
- some interesting syntactic clean-ups and conveniences

Main design completed in 1992, by a committee,
to unify many earlier lazy functional languages

- most recent version: Haskell 98

Some syntactic differences with ML

ML:

```
- fun map f nil     = nil
    | map f (x::xs) = f x :: map f xs;
val map = fn : ('a->'b) -> 'a list -> 'b list
- val lst = map square [3,4,5];
[9,16,25] : int list
- (3, 4, fn x y => x+y)
(3,4,fn) : int * int * (int->int->int)
```

Haskell (decls vs. exprs & output depends on implementation):

```
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] :: [Integer]

(3, 4, \x y -> x+y)
  (3,4,<fn>) :: (Integer, Integer,
                 Integer->Integer->Integer)
```


More examples

ML:

```
- datatype 'a Tree =
    Empty | Node of 'a * 'a Tree * 'a Tree;
- fun size Empty = 0
    | size (Node(_,t1,t2)) = 1+size t1+size t2;
- Node(3,Empty,Empty);
Node(3,Empty,Empty) : int Tree
```

Haskell:

```
data Tree a = Empty | Node a (Tree a) (Tree a)

size Empty = 0
size (Node _ t1 t2) = 1 + size t1 + size t2

Node 3
  <fn> ::
    Tree Integer -> Tree Integer -> Tree Integer

size (Node 4 (Node 3 Empty Empty) Empty)
  2 :: Integer
```


General syntactic principles

Expressions and types use similar syntax

- `(3,"hi") :: (Int,String)`
- `[3,4,5] :: [Int]`

Upper-case letters for constructor constants and known types
Lower-case letters for variables and type variables

Functions and variables defined in same way,
with no leading keyword

- variables have no arguments
- functions have 1 or more arguments

Uniform use of curried functions,
including infix operators and data constructors

Type constructors use prefix notation, just like other functions

Layout & indentation are significant,
and imply grouping and nesting

- can use `{ ... }` to explicitly control grouping

Sections

Can call an infix operator on 0 or 1 of its arguments to create a curried function that takes the remaining argument(s)

```
3 + 4
  7 :: Integer

(+)
  <fn> :: Integer -> Integer -> Integer

(+ 1)   -- the increment function
  <fn> :: Integer -> Integer

(1 /)   -- the inverse function
  <fn> :: Double -> Double
```

Parentheses convert an infix operator into a prefix fn expression

Can treat a prefix fn name as an infix operator by bracketing with backquotes

```
6 `div` 2
  3 :: Integer
```


List comprehensions

Nice syntax for constructing a list from **generators** and **guards**:

[*expr* | *var* <- *expr*, ..., *boolExpr*, ...]

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

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

Arithmetic sequences easy to construct, too

```
[1..10]     → [1,2,3,4,5,6,7,8,9,10]
[2,4..10]   → [2,4,6,8,10]
[2,4..]     → [2,4,6,8,10,12,...
[1..]       → [1,2,3,4,5,6,7,...
```


Lazy vs. eager evaluation

When is a function argument evaluated?

- eager, applicative-order, strict:
  before passing value to function
- lazy, normal-order, nonstrict, call-by-need, demand-driven:
  when/if first needed

When is an expression's value needed?

- when it's being called as a function
- when it's being used as the test of an `if`
- when it's an operand of + (or some other primitive that can't compute its result without looking at the value of its argument)
- when it's being pattern-matched against
  (but then only enough to get the constructor tag;
  the components don't need to be evaluated until they're needed)
- if it's the final result of the program

When is an expression not needed?

- when it's not used
- when it's just bound to another variable, e.g. a formal
- when it's an argument of a data constructor

Example

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

my_if True 3 4     → 3
my_if False 3 4    → 4

x = 3
y = 12
my_if (x /= 0) (y `div` x) (-1)  → 4
  -- different than in ML or Scheme!
```

A call to `my_if` doesn't evaluate its arguments first

The test is always evaluated, since it's needed to progress

Either the `then_val` or the `else_val` is evaluated, but not both

Needed "special form" in Scheme & ML to achieve this

Unnecessary in a lazy language

Issues with lazy evaluation

Only computations needed for getting the result need to be evaluated
- can avoid useless work
- can write programs that look inefficient but need not be
  - generator + transformer style
  - "infinite" data structures, of which only a finite amount is ever actually used

Can always replace variable with defined expression
⇒ better equational reasoning

Evaluation order depends on what caller of function demands
⇒ hard to determine
- disallow side-effects, I/O, exceptions, etc. in (lazy) expressions
- use **monads** at outer level to get effects, in a specific order

Streams

Lists can be viewed as (possibly infinite) streams of values
- `head`, `tail` fields of a list structure won't be evaluated until & unless they're demanded

Lazy evaluation holds for all data structures in same way

```
-- an infinite list of ascending integers, starting with n:
ints_from n = n : ints_from (n + 1)
  -- shorthand: [n..]

-- the natural numbers:
nats = ints_from 0  -- shorthand: [0..]

-- the perfect squares:
squares = map (^ 2) nats
  → [0, 1, 4, 9, 16, 25, ...

-- the fibonacci numbers:
fibs = 0 : 1 :
       [ a+b | (a,b) <- zip fibs (tail fibs)]
  → [0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, ...
```


Simulating streams using first-class functions

Can simulate streams by wrapping lazy part(s) in function(s)

E.g. a lazy list: pair of **functions** to produce the head and the tail on demand

```
- datatype 'a lazy_list =
=    lazy_nil |
=    lazy_cons of (unit -> 'a) *
=                 (unit -> 'a lazy_list);

- fun lazy_hd(lazy_cons(fh,_)) = fh();
val lazy_hd = fn : 'a lazy_list -> 'a

- fun lazy_tl(lazy_cons(_,ft)) = ft();
val lazy_tl = fn : 'a lazy_list -> 'a lazy_list

- fun first(0, _) = []
=   | first(n, lazy_cons(fh,ft)) =
=                   fh() :: first(n-1, ft());
val first = fn : int * 'a lazy_list -> 'a list
```


A client

```
- fun ints_from n =
=   lazy_cons(fn()=>n, fn()=>ints_from(n+1));
val ints_from = fn : int -> int lazy_list

- val nats = ints_from 0;
val nats = lazy_cons(fn,fn) : int lazy_list

- val single_digits = first(10, nats);
[0,1,...,9] : int list
```

Will re-evaluate body of function each time head/tail of a particular lazy list is referenced, unlike real lazy evaluation
- Scheme builds in `delay` and `force` to avoid this

Have to have multiple versions of list operations like `map`, `fold`, etc., for eager vs. lazy lists, unlike real lazy evaluation

Generators and transformers

Programming style exploiting lazy evaluation,
leading to more reusable components

Construct a toolkit of operations to generate interesting streams

- lots of list processing functions, e.g.
  mapping & filtering & combining & (un)zipping streams
- scanner produces a stream of tokens
- input produces a stream of characters
- event-driven simulations produce streams of events
- ....

Don't worry about controlling how much to generate;
generate everything that might possibly be useful

Independently produce operations to manipulate and extract interesting **subset** of generated data

- only portion needed in final result will actually be generated

Example

Implement scanner as a generator of a stream of tokens

Implement utility that checks which functions have been changed since last compile

- generate streams of tokens on both versions
- compares two streams to find difference
- if difference found, rest of tokens won't be demanded, therefore won't be generated

Implement parser to produce a stream of possible parses, if grammar has type-dependent ambiguities (like C++)

- consumes stream of tokens, until first syntax error

Implement typechecker to
consume possible parse trees,
filter for those that typecheck

I/O

How can a purely functional program interact with the outside world, e.g. read any (mutable) input or produce any output?

Idea:

- introduce a special `IO` type,
  whose values are I/O **actions** that could be performed
- top-level `main` function yields an I/O action,
  which is performed only "when main returns"
  - but lazy evaluation makes this happen "as soon as possible"

`IO` data type is a special case of a **monad**

- very powerful mechanism for controlling & encapsulating effects of many sorts, including mutable state, exceptions, resource consumption, etc.

IO actions

`IO a`: the type of actions that have some I/O effect and then yield a value of type a

`main :: IO ()`

- `main` returns an I/O action that has no result
  - the system runs a program by demanding the result of main, and executing the actions that are computed

Some basic I/O actions:

- `getChar :: IO Char`
- `putChar :: Char -> IO ()`
- `openFile :: String -> IOMode -> IO Handle`
- `hClose :: Handle -> IO ()`
- `stdin, stdout :: IO Handle`
- `hGetChar :: Handle -> IO Char`
- `hPutChar :: Handle -> Char -> IO ()`
- `hGetContents :: Handle -> IO String`

A no-op action:
`return` *`expr`* `::` `IO` *`typeOfExpr`*

- does no I/O but yields a value

Composite actions

Can combine actions together, in sequences:

```
do v1 <- action1
   v2 <- action2
   ...
   actionn
```

- yields an action that, if performed,
  first performs $action_1$, binding the result value to v_1,
  then peforms $action_2$, binding the result value to v_2,
  ...,
  then performs $action_n$ and returns its result value
- any of the v_i are optional

Example: a program that copies its input to its output, twice

```
hPutString :: Handle -> String -> IO ()
hPutString h []     = return ()
hPutString h (x:xs) = do hPutChar h x
                         hPutString h xs
main :: IO ()
main = do contents <- hGetContents stdin
          hPutString stdout contents
          hPutString stdout contents
```


The magic

Key property of the IO data type:
there are no functions to perform an action, yielding something without `IO` in its result type

- the only way to perform an action is to have `main` return (an action containing) it

Corollary: can't embed I/O (or any other kind of side-effect) in an expression that doesn't yield an I/O action!

Type structure enforces a strict separation between
purely effect-free computations (result type != `IO` *a*)
and (potentially) effect-full computations (result type == `IO` *a*)

- effect-full computations are at the "top level" of the computation
  - effect-free computations are its subexpressions
- effect-full computations are explicitly sequenced using `do`

Effects and lazy evaluation

Lazy evaluation doesn't interact badly with effects, since none of the effects are actually performed until `main` returns

- but nothing is computed until it's demanded...

Operation of a Haskell program:

- Haskell runtime system demands result I/O action of `main` be computed and performed
- This demands evaluation & performance of e.g. a `do` block action
- This demands evaluation & performance of the first action in the `do` block
- Etc., until some primitive action is reached, at which point Haskell's runtime system performs it, and then proceeds to the next action subexpression

Polymorphic and overloaded functions

In ML, functions may either be

- completely polymorphic (e.g. `length:'a list→int`) or
- polymorphic over types that admit equality (e.g. `eq_pair:(''a*''b)*(''a*''b)→bool`) or
- completely monomorphic (e.g. `square:int→int`)

Can't define more restricted forms of polymorphism,
e.g. a function that is polymorphic over numbers

E.g.

```
fun square n = n * n;
```

requires n either to be `int` or `real`, but not either

* refers to two different **overloaded** functions,
not one **polymorphic** function

- can't define functions polymorphic over the different overloadings

With the one oddball exception of equality types,
ML supports only **unbounded** parametric polymorphism

Bounded polymorphism

Would like to allow **bounded** polymorphism,
constraining possible instantiating types
in order to be able to call specialized operations on them

E.g.:

- polymorphic over all types that support = (equality types)
- polymorphic over all types that support * and +
- polymorphic over all types that support `print`
- polymorphic over all tuples with at least 3 components
- polymorphic over all records with `hd` and `tl` fields
- ...

Constraints on type parameters let body know what operations can be performed on expressions of those types

- unbounded type variables: can only pass around

How to express constraints?

Subtype constraints

In object-oriented languages, can often express constraints 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*

E.g.

```
- class number {
    method +:(number)→number;
    method *:(number)→number;
    ...
  };
- class int subtypes number { ... };
- class float subtypes number { ... };

- fun square n = n * n;
val square = fn : number → number;
- square 3;
9 : number
- square 3.4;
11.5 : number
```

[How to get result type to be as precise as argument?]

Type classes in Haskell

Haskell supports a similar idea, within a lazy, functional, type-inference-based language framework

- similar to OO classes
- some key differences that limit its expressive power

Example: the class `Eq` of types a that implement ==

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

- `Eq` is the name of the new **type class**
- == and `/=` are newly declared names of operations on this class
  - global names ⇒ cannot overload with other global names
- a is a placeholder name for a type that's in this class, used in the type signatures of operations of the class

Instances of type classes

Types must be explicitly declared to be members of particular type classes

- must provide implementations of type class's operations

```
-- Int, Float are previously declared types
instance Eq Int where    -- Int ∈ Eq
  x == y  = intEq x y
  x /= y  = intNeq x y
instance Eq Float where  -- Float ∈ Eq
  x == y  = floatEq x y
  x /= y  = floatNeq x y
```

Now can invoke type class operations on member types:

```
3    == 4       -- allowed; calls intEq
3.4  /= 5.6     -- allowed; calls floatNeq
3    == 4.5     -- type error
"hi" == "there" -- type error
```

Type classes as constraints on polymorphism

Use a type class to constrain legal instantiations

E.g.:

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

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

Contexts can be inferred 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 given explicitly (as can regular types)

Another example:

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


Conditional instances

Can use context to place constraints on type variables for when something is a type class instance

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

```
instance (Eq a,Eq b)=> Eq (a,b) where
  (x1,y1) == (x2,y2)  =  x1==x2 && 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 && xs==ys
  _      == _       =  False
  x /= y            =  not (x == y)
```


Default implementations in type classes

Add a `/=` operation, which defaults to negating ==

```
class Eq a where
  (==), (/=) :: a -> a -> Bool
  x /= y  =  not (x == y)
```

Instances can "inherit" this default implementation, or provide their own

```
instance Eq Int where
  x == y  = intEq  x y
  x /= y  = intNeq x y   -- override default

instance (Eq a, Eq b)=> Eq (a,b) where
  (x1,y1) == (x2,y2)  =  x1==x2 && y1==y2
  -- inherit default /=
```


Type subclasses

Can define new type classes that extend existing type classes & add new operations

- define the superclass(es) as contexts
  - for a type to be an instance of a subclass, it must already be an instance of all its superclasses
- multiple inheritance allowed
  - name clashes can't happen since operations not overloadable

Example: `Ord` class of totally ordered things, subclassing `Eq`

```
class Eq a => Ord a where
  -- Ord "inherits" Eq operations == and /=
  (<), (<=), (>=), (>) :: a -> a -> Bool
  min, max :: a -> a -> a
  x <= y  =  x == y or x < y
  min x y =  if x < y then x else y
  ... (>=, >, and max defaulted too) ...
```

A client function:

```
member_sorted :: Ord a => a -> [a] -> Bool
member_sorted _ []      =  False
member_sorted x (y:ys)  =
    x==y || x<y && member_sorted x ys
```

`Ord` instances

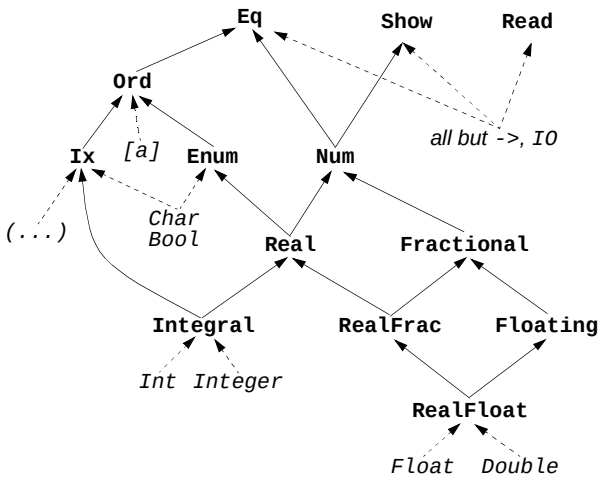
(assume Eq instances already declared)

```
instance Ord Int where
  x < y   = intLt  x y
  x <= y  = intLeq x y
  ...  -- other operations implemented or inherited
```

```
instance (Ord a, Ord b)=> Ord (a,b) where
  (x1,y1) < (x2,y2) = x1<x2 || x1==x2 && y1<y2
  -- all other operations inherited
```

```
instance Ord a => Ord [a] where
  []     < (y:ys)  = True
  (x:xs) < (y:ys)  = x<y || x==y && xs<ys
  _      < _       = False
  -- all other operations inherited
```


Hierarchy of some predefined type classes



Type classes vs. ML polymorphism

ML polymorphism is simple, but has warts:

- "equality-bounded" polymorphism
- overloaded operators, not polymorphism

Haskell's type classes subsume and unify
unbounded polymorphism, equality-bounded polymorphism, and general bounded polymorphism

- default implementations are a nice feature, too

But type classes take over the language

- big part of standard library
- big part of reference manual
- temptation to go overboard with refining class hierarchy
- [just like OO languages]

Type classes vs. OO classes

Type classes do not support run-time heterogeneous collections

- can have functions that are polymorphic over lists of ints and lists of reals
- cannot have functions that accept lists of mixed ints and reals
- no run-time subtyping, just compile-time subtyping (roughly)
- [Haskell extensions with existential types can do this]

No inheritance, other than single default method

Type classes support binary operations like == and + well, where the arguments and result are all of same type

```
(==) :: Eq a  => a -> a -> Bool
(+)  :: Num a => a -> a -> a
```

- hard to do in an OO language without **F-bounded subtype polymorphism** or similar feature

Retain type inference, unlike OO languages