Principles of Programming Languages

http://www.di.unipi.it/~andrea/Didattica/PLP-14/

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Lesson 28

- Type classes in Haskell

Polymorphism vs Overloading

- Parametric polymorphism
  - Single algorithm may be given many types
  - Type variable may be replaced by any type
  - if `f::t→t` then `f::Int→Int`, `f::Bool→Bool`, ...
- Overloading
  - A single symbol may refer to more than one algorithm.
  - Each algorithm may have different type.
  - Choice of algorithm determined by type context.
  - `+` has types `Int → Int → Int` and `Float → Float → Float`, but not `t→t→t` for arbitrary `t`.

Why Overloading?

- Many useful functions are not parametric
- Can list membership work for any type?

```
member :: [w] -> w -> Bool
```

  – No! Only for types w for that support equality.
- Can list sorting work for any type?

```
sort :: [w] -> [w]
```

  – No! Only for types w that support ordering.

Why Overloading?

- Many useful functions are not parametric.
- Can serialize work for any type?

```
serialize:: w -> String
```

  – No! Only for types w that support serialization.
- Can sumOfSquares work for any type?

```
sumOfSquares:: [w] -> w
```

  – No! Only for types that support numeric operations.

Overloading Arithmetic, Take 1

- Allow functions containing overloaded symbols to define multiple functions:

```
square x = x * x          -- legal
-- Defines two versions:
-- Int -> Int and Float -> Float
```

- But consider:

```
squares (x,y,z) =
    (square x, square y, square z)
-- There are 8 possible versions!
```

- This approach has not been widely used because of exponential growth in number of versions.

Overloading Arithmetic, Take 2

- Basic operations such as + and * can be overloaded, but not functions defined from them

```
3 * 3                -- legal
3.14 * 3.14          -- legal
square x = x * x     -- Int -> Int
square 3             -- legal
square 3.14          -- illegal
```

- Standard ML uses this approach.
- Not satisfactory: Programmer cannot define functions that implementation might support

Overloading Equality, Take 1

- Equality defined only for types that admit equality: types not containing function or abstract types.

```
3 * 3 == 9                -- legal
'a' == 'b'                -- legal
\x->x == \y->y+1          -- illegal
```

- Overload equality like arithmetic ops + and * in SML.
- But then we can't define functions using '==':

```
member [] y      = False
member (x:xs) y = (x==y) || member xs y

member [1,2,3] 3         -- ok if default is Int
member "Haskell" 'k'     -- illegal
```

- Approach adopted in first version of SML.

Overloading Equality, Take 2

- Make type of equality fully polymorphic

```
(==) :: a -> a -> Bool
```

- Type of list membership function

```
member :: [a] -> a -> Bool
```

- Miranda used this approach.
  - Equality applied to a function yields a runtime error
  - Equality applied to an abstract type compares the underlying representation, which violates abstraction principles

Only provides overloading for ==

Overloading Equality, Take 3

- Make equality polymorphic in a limited way:

```
(==) :: a(==) -> a(==) -> Bool
```

where a(==) is type variable restricted to types with equality

- Now we can type the member function:

```
member :: a(==) -> [a(==)] -> Bool
member  4           [2,3] :: Bool
member 'c'          ['a', 'b', 'c'] :: Bool
member (\y->y *2) [\x->x, \x->x + 2]  -- type error
```

- Approach used in SML today, where the type a(==) is called an “eqtype variable” and is written ``a.

Type Classes

- Type classes solve these problems
  - Provide concise types to describe overloaded functions, so no exponential blow-up
  - Allow users to define functions using overloaded operations, eg, square, squares, and member
  - Allow users to declare new collections of overloaded functions: equality and arithmetic operators are not privileged built-ins
  - Generalize ML's eqtypes to arbitrary types
  - Fit within type inference framework

Intuition

- A function to sort lists can be passed a comparison operator as an argument:

```
qsort:: (a -> a -> Bool) -> [a] -> [a]
qsort cmp [] = []
qsort cmp (x:xs) = qsort cmp (filter (cmp x) xs)
              ++ [x] ++
                  qsort cmp (filter (not.cmp x) xs)
```

  – This allows the function to be parametric

- We can built on this idea …

Intuition (continued)

- Consider the "overloaded" parabola function

```
parabola x = (x * x) + x
```

- We can rewrite the function to take the operators it contains as an argument

```
parabola' (plus, times) x = plus (times x x) x
```

  - The extra parameter is a "dictionary" that provides implementations for the overloaded ops.
  - We have to rewrite all calls to pass appropriate implementations for plus and times:

```
y = parabola'(intPlus,intTimes) 10
z = parabola'(floatPlus, floatTimes) 3.14
```

Systematic programming style

```
-- Dictionary type
data MathDict a = MkMathDict (a->a->a) (a->a->a)

-- Accessor functions
get_plus :: MathDict a -> (a->a->a)
get_plus (MkMathDict p t) = p

get_times :: MathDict a -> (a->a->a)
get_times (MkMathDict p t) = t

-- "Dictionary-passing style"
parabola :: MathDict a -> a -> a
parabola dict x = let plus  = get_plus  dict
                      times = get_times dict
                  in plus (times x x) x
```

Type class declarations will generate Dictionary type and selector functions

Systematic programming style

Type class **instance declarations** produce instances of the Dictionary

```
-- Dictionary type
data MathDict a = MkMathDict (a->a->a) (a->a->a)

-- Dictionary construction
intDict   = MkMathDict intPlus   intTimes
floatDict = MkMathDict floatPlus floatTimes

-- Passing dictionaries
y = parabola intDict   10
z = parabola floatDict 3.14
```

Compiler will add a dictionary parameter and rewrite the body as necessary

Type Class Design Overview

- Type class declarations
  - Define a set of operations, give the set a name
  - Example: `Eq a` type class
    - operations `==` and `\=` with `type a -> a -> Bool`
- Type class instance declarations
  - Specify the implementations for a particular type
  - For `Int` instance, `==` is defined to be integer equality
- Qualified types (or Type Constraints)
  - Concisely express the operations required on otherwise polymorphic type

```
member:: Eq w => w -> [w] -> Bool
```

“for all types w that support the Eq operations”

Qualified Types

```
Member :: Eq w => w -> [w] -> Bool
```

If a function works for every type with particular properties, the type of the function says just that:

```
sort      :: Ord a  => [a] -> [a]
serialise :: Show a => a -> String
square    :: Num n  => n -> n
squares   ::(Num t, Num t1, Num t2) =>
                 (t, t1, t2) -> (t, t1, t2)
```

Otherwise, it must work for any type whatsoever

```
reverse :: [a] -> [a]
filter  :: (a -> Bool) -> [a] -> [a]
```

Type Classes

Works for any type 'n' that supports the Num operations

```
square :: Num n => n -> n
square x = x*x
```

FORGET all you know about OO classes!

```
class Num a where
  (+)    :: a -> a -> a
  (*)    :: a -> a -> a
  negate :: a -> a
  ...etc...
```

The class declaration says what the Num operations are

```
instance Num Int where
  a + b    = intPlus  a b
  a * b    = intTimes a b
  negate a = intNeg a
  ...etc...
```

An instance declaration for a type T says how the Num operations are implemented on T's

```
intPlus  :: Int -> Int -> Int
intTimes :: Int -> Int -> Int
etc, defined as primitives
```

Compiling Overloaded Functions

When you write this...

```
square :: Num n => n -> n
square x = x*x
```

...the compiler generates this

```
square :: Num n -> n -> n
square d x = (*) d x x
```

The "Num n =>" turns into an extra value argument to the function. It is a value of data type Num n and it represents a dictionary of the required operations.

A value of type (Num n) is a dictionary of the Num operations for type n

Compiling Type Classes

When you write this...

```
square :: Num n => n -> n
square x = x*x
```

```
class Num n where
  (+)    :: n -> n -> n
  (*)    :: n -> n -> n
  negate :: n -> n
  ...etc...
```

The class decl translates to:
A data type decl for Num
A selector function for each class operation

...the compiler generates this

```
square :: Num n -> n -> n
square d x = (*) d x x
```

```
data Num n
  = MkNum (n -> n -> n)
          (n -> n -> n)
          (n -> n)
          ...etc...
...
(*) :: Num n -> n -> n -> n
(*) (MkNum _ m _ ...) = m
```

A value of type (Num n) is a dictionary of the Num operations for type n

Compiling Instance Declarations

When you write this...

```
square :: Num n => n -> n
square x = x*x
```

...the compiler generates this

```
square :: Num n -> n -> n
square d x = (*) d x x
```

```
instance Num Int where
  a + b     = intPlus  a b
  a * b     = intTimes a b
  negate a = intNeg a
  ...etc...
```

```
dNumInt :: Num Int
dNumInt = MkNum intPlus
                intTimes
                intNeg
                ...
```

An instance decl for type T translates to a value declaration for the Num dictionary for T

A value of type (Num n) is a dictionary of the Num operations for type n

Implementation Summary

- The compiler translates each function that uses an overloaded symbol into a function with an extra parameter: **the dictionary**.
- References to overloaded symbols are rewritten by the compiler to lookup the symbol in the dictionary.
- The compiler converts each type class declaration into a dictionary type declaration and a set of selector functions.
- The compiler converts each instance declaration into a dictionary of the appropriate type.
- The compiler rewrites calls to overloaded functions to pass a dictionary. It uses the static, qualified type of the function to select the dictionary.

Functions with Multiple Dictionaries

```
squares :: (Num a, Num b, Num c) => (a, b, c) -> (a, b, c)
squares(x,y,z) = (square x, square y, square z)
```

Note the concise type for the squares function!

```
squares :: (Num a, Num b, Num c) -> (a, b, c) -> (a, b, c)
squares (da,db,dc) (x, y, z) =
                 (square da x, square db y, square dc z)
```

Pass appropriate dictionary on to each square function.

Compositionality

Overloaded functions can be defined from other overloaded functions:

```
sumSq :: Num n => n -> n -> n
sumSq x y = square x + square y
```

```
sumSq :: Num n -> n -> n -> n
sumSq d x y = (+) d (square d x)
                    (square d y)
```

Extract addition operation from d

Pass on d to square

Compositionality

Build compound instances from simpler ones:

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

instance Eq Int where
   (==) = intEq       -- intEq primitive equality

instance (Eq a, Eq b) => Eq(a,b)
   (u,v) == (x,y)     = (u == x) && (v == y)

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

Compound Translation

Build compound instances from simpler ones.

```
class Eq a where
   (==) :: a -> a -> Bool
instance Eq a => Eq [a] where
   (==) []     []     = True
   (==) (x:xs) (y:ys) = x==y && xs == ys
   (==) _      _      = False
```

```
data Eq = MkEq (a->a->Bool)      -- Dictionary type
(==) (MkEq eq) = eq              -- Selector
dEqList :: Eq a -> Eq [a]        -- List Dictionary
dEqList d = MkEq eql
  where
    eql []     []     = True
    eql (x:xs) (y:ys) = (==) d x y && eql xs ys
    eql _      _      = False
```

Many Type Classes

- **Eq**: equality
- **Ord**: comparison
- **Num**: numerical operations
- **Show**: convert to string
- **Read**: convert from string
- **Testable**, **Arbitrary**: testing.
- **Enum**: ops on sequentially ordered types
- **Bounded**: upper and lower values of a type
- Generic programming, reflection, monads, …
- And many more.

Subclasses

- We could treat the Eq and Num type classes separately

```
memsq :: (Eq a, Num a) => a -> [a] -> Bool
memsq x xs = member (square x) xs
```

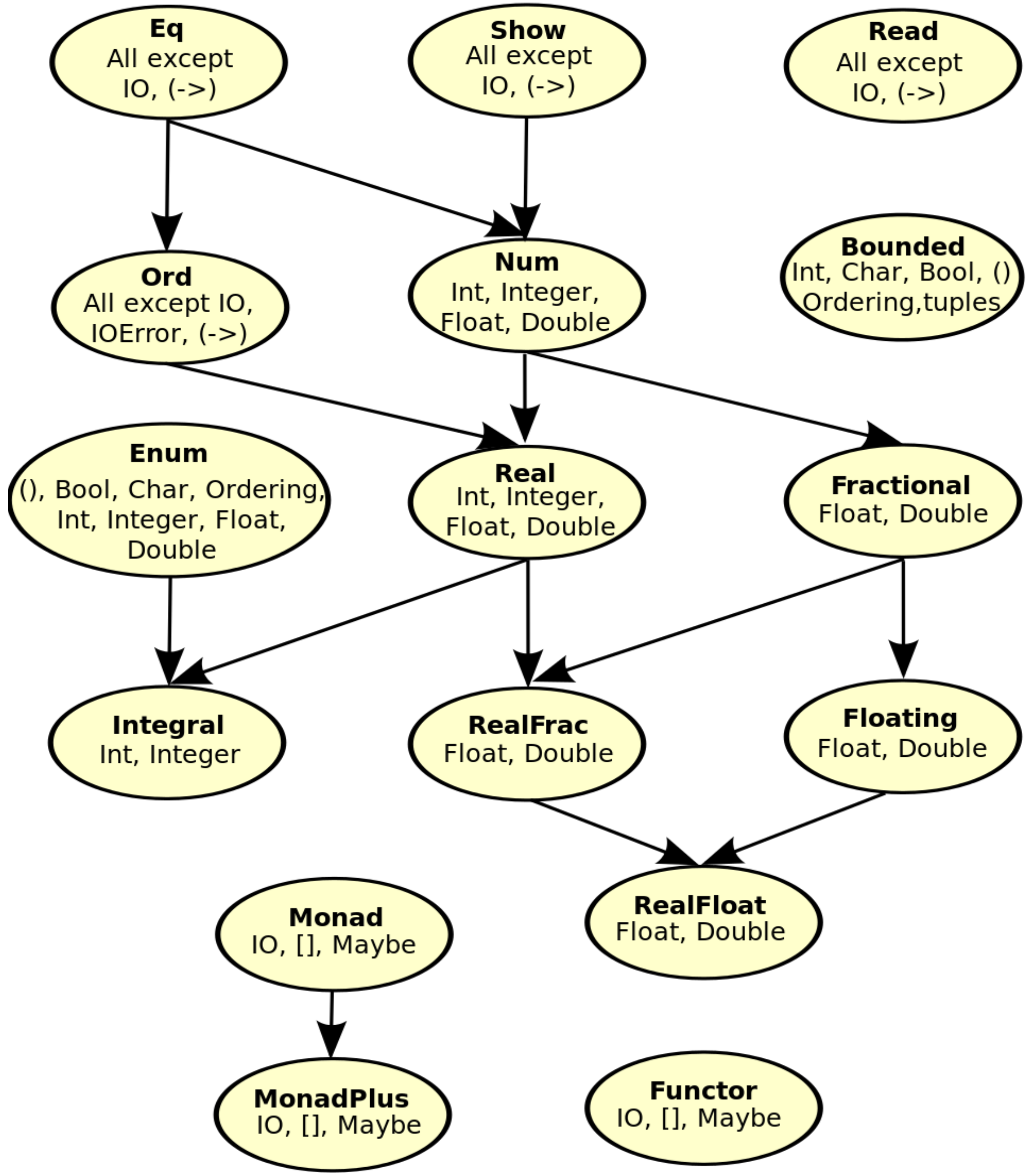
  – But we expect any type supporting Num to also support Eq

- A subclass declaration expresses this relationship:

```
class Eq a => Num a where
   (+) :: a -> a -> a
   (*) :: a -> a -> a
```

- With that declaration, we can simplify the type of the function

```
memsq :: Num a => a -> [a] -> Bool
memsq x xs = member (square x) xs
```


Eq
All except
IO, (->)
Show
All except
IO, (->)
Read
All except
IO, (->)
Ord
All except IO,
IOError, (->)
Num
Int, Integer,
Float, Double
Bounded
Int, Char, Bool, ()
Ordering,tuples
Enum
(), Bool, Char, Ordering,
Int, Integer, Float,
Double
Real
Int, Integer,
Float, Double
Fractional
Float, Double
Integral
Int, Integer
RealFrac
Float, Double
Floating
Float, Double
Monad
IO, [], Maybe
RealFloat
Float, Double
MonadPlus
IO, [], Maybe
Functor
IO, [], Maybe

Default Methods

- Type classes can define “default methods”

```
-- Minimal complete definition:
--      (==) or (/=)
class Eq a where
    (==) :: a -> a -> Bool
    x == y    =  not (x /= y)
    (/=) :: a -> a -> Bool
    x /= y    =  not (x == y)
```

- Instance declarations can override default by providing a more specific definition.

Deriving

- For Read, Show, Bounded, Enum, Eq, and Ord, the compiler can generate instance declarations automatically

```
data Color = Red | Green | Blue
     deriving (Show, Read, Eq, Ord)
```

```
Main> show Red
"Red"
Main> Red < Green
True
Main>let c :: Color = read "Red"
Main> c
Red
```

  - *Ad hoc* : derivations apply only to types where derivation code works

Numeric Literals

```
class Num a where
  (+) :: a -> a -> a
  (-) :: a -> a -> a
  fromInteger :: Integer -> a
  ...

inc :: Num a => a -> a
inc x = x + 1
```

Even literals are overloaded.
1 :: (Num a) => a

"1" means "fromInteger 1"

Advantages:

- Numeric literals can be interpreted as values of any appropriate numeric type
- Example: 1 can be an Integer or a Float or a user-defined numeric type.

Example: Complex Numbers

- We can define a data type of complex numbers and make it an instance of **Num**.

```
class Num a where
  (+) :: a -> a -> a
  fromInteger :: Integer -> a
  ...
```

```
data Cpx a = Cpx a a
  deriving (Eq, Show)

instance Num a => Num (Cpx a) where
  (Cpx r1 i1) + (Cpx r2 i2) = Cpx (r1+r2) (i1+i2)
  fromInteger n = Cpx (fromInteger n) 0
  ...
```

Example: Complex Numbers

- And then we can use values of type **`Cpx`** in any context requiring a **`Num`**:

```
data Cpx a = Cpx a a

c1 = 1 :: Cpx Int
c2 = 2 :: Cpx Int
c3 = c1 + c2

parabola x = (x * x) + x
c4 = parabola c3
i1 = parabola 3
```

Type Inference

- Type inference infers a qualified type Q => T
  - T is a Hindley Milner type, inferred as usual
  - Q is set of type class predicates, called a constraint
- Consider the example function:

```
example z xs =
   case xs of
     []      -> False
     (y:ys) -> y > z || (y==z && ys == [z])
```

  - Type T is a -> [a] -> Bool
  - Constraint Q is { Ord a, Eq a, Eq [a]}

Ord a	because	y>z
Eq a	because	y==z
Eq [a]	because	ys == [z]

Type Inference

- Constraint sets Q can be simplified:
  - Eliminate duplicates
    - {Eq a, Eq a} simplifies to {Eq a}
  - Use an **instance declaration**
    - If we have instance Eq a => Eq [a],
    - then {Eq a, Eq [a]} simplifies to {Eq a}
  - Use a **class declaration**
    - If we have class Eq a => Ord a where ...,
    - then {Ord a, Eq a} simplifies to {Ord a}
- Applying these rules,
  - {Ord a, Eq a, Eq[a]} simplifies to {Ord a}

Type Inference

- Putting it all together:

```
example z xs =
   case xs of
     []      -> False
     (y:ys) -> y > z || (y==z && ys ==[z])
```

  – T = a -> [a] -> Bool
  – Q = {Ord a, Eq a, Eq [a]}
  – Q simplifies to {Ord a}
  – `example :: {Ord a} => a -> [a] -> Bool`

Detecting Errors

- Errors are detected when predicates are known not to hold:

```
Prelude> ‘a’ + 1
 No instance for (Num Char)
      arising from a use of `+' at <interactive>:1:0-6
    Possible fix: add an instance declaration for (Num Char)
    In the expression: 'a' + 1
    In the definition of `it': it = 'a' + 1
```

```
Prelude> (\x -> x)
 No instance for (Show (t -> t))
      arising from a use of `print' at <interactive>:1:0-4
    Possible fix: add an instance declaration for (Show (t -> t))
    In the expression: print it
    In a stmt of a 'do' expression: print it
```

More Type Classes: Constructors

- **Type Classes** are predicates over **types**
- **Constructor Classes** are predicates over **type contstructors**
- Example: Map function useful on many Haskell types
- Lists:

```
map:: (a -> b) -> [a] -> [b]
map f  [] = []
map f (x:xs) = f x : map f xs

result = map (\x->x+1) [1,2,4]
```

Constructor Classes

- More examples of map function

```
data Tree a = Leaf a | Node(Tree a, Tree a)
    deriving Show

mapTree :: (a -> b) -> Tree a -> Tree b
mapTree f (Leaf x) = Leaf (f x)
mapTree f (Node(l,r)) = Node (mapTree f l, mapTree f r)

t1 = Node(Node(Leaf 3, Leaf 4), Leaf 5)
result = mapTree (\x->x+1) t1
```

```
data Opt a = Some a | None
 deriving Show

mapOpt :: (a -> b) -> Opt a -> Opt b
mapOpt f None = None
mapOpt f (Some x) = Some (f x)

o1 = Some 10
result = mapOpt (\x->x+1) o1
```

Constructor Classes

- All map functions share the same structure

```
map     :: (a -> b) -> [a] -> [b]
mapTree :: (a -> b) -> Tree a -> Tree b
mapOpt  :: (a -> b) -> Opt a -> Opt b
```

- They can all be written as:

```
fmap:: (a -> b) -> g a -> g b
```

  - where **g** is:

    [-] for lists, **Tree** for trees, and **Opt** for options

- Note that **g** is a function from types to types, i.e. a **type constructor**

Constructor Classes

- Capture this pattern in a constructor class,

```
class Functor g where
  fmap :: (a -> b) -> g a -> g b
```

A type class where the predicate is over type constructors

Constructor Classes

```
class Functor f where
  fmap :: (a -> b) -> f a -> f b

instance Functor [] where
  fmap f [] = []
  fmap f (x:xs) = f x : fmap f xs

instance Functor Tree where
  fmap f (Leaf x) = Leaf (f x)
  fmap f (Node(t1,t2)) = Node(fmap f t1, fmap f t2)

instance Functor Opt where
  fmap f (Some s) = Some (f s)
  fmap f None = None
```

Constructor Classes

- Or by reusing the definitions map, mapTree, and mapOpt:

```
class Functor f where
  fmap :: (a -> b) -> f a -> f b

instance Functor [] where
  fmap = map

instance Functor Tree where
  fmap = mapTree

instance Functor Opt where
  fmap = mapOpt
```

Constructor Classes

- We can then use the overloaded symbol **fmap** to map over all three kinds of data structures:

```
*Main> fmap (\x->x+1) [1,2,3]
[2,3,4]
it :: [Integer]

*Main> fmap (\x->x+1) (Node(Leaf 1, Leaf 2))
Node (Leaf 2,Leaf 3)
it :: Tree Integer

*Main> fmap (\x->x+1) (Some 1)
Some 2
it :: Opt Integer
```

- The `Functor` constructor class is part of the standard Prelude for Haskell

Type classes /= OOP

- **Dictionaries** and **method suites** are similar
  - In OOP, a value carries a method suite.
  - With type classes, the dictionary travels separately
- Method resolution is static for type classes, dynamic for objects.
- Dictionary selection can depend on result type

```
fromInteger :: Num a => Integer -> a
```

- Based on polymorphism, not subtyping.
- Old types can be made instances of new type classes but objects can't retroactively implement interfaces or inherit from super classes.